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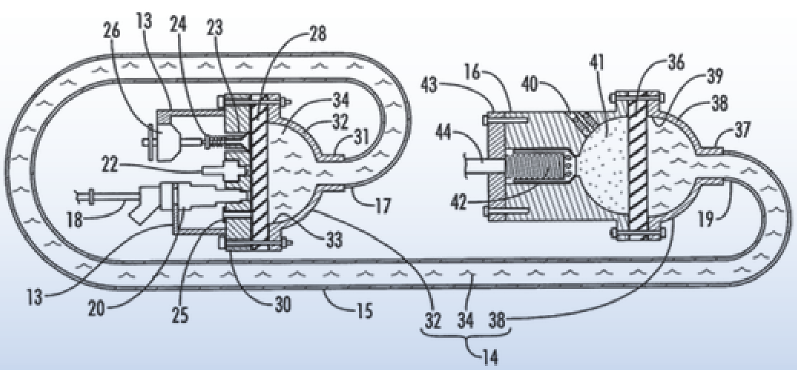
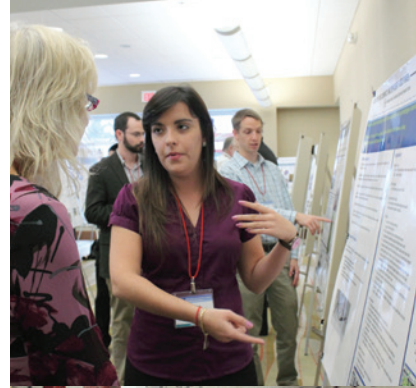
7th Annual Report

Volume 1

COOPERATIVE AGREEMENT #EEC 0540834 / DUE DATE: APRIL 19, 2013





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

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Dr. Kim Stelson, Director

Dr. Perry Li, Deputy Director

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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	

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REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$ 8,475,600	36 months	6/1/13	

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

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PI/PD DEPARTMENT Mechanical Engineering	PI/PD POSTAL ADDRESS 111 Church Street SE 1100 Mechanical Engineering Building Minneapolis, MN 55455
PI/PD FAX NUMBER 612-626-7165	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME Kim A. Stelson	Sc. D	1982	612-626-7168	kstelson@me.umn.edu
CO-PI/PD				
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Volume I Table of Contents — Page

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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). 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 more than twenty 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 40 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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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
Deputy Director	Perry Li	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
Administrative Specialist	Cherie Bandy	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	Tom Chase	Mechanical Engineering	University of Minnesota
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	Ashlie Martini	Mechanical Engineering	Univeristy of California, Merced
Faculty Researcher	Paul Michael	Fluid Power Institute	Milwaukee School of Engineering
Faculty Researcher	Zongxuan Sun	Mechanical Engineering	University of Minnesota

THRUST 2: COMPACTNESS

Faculty Researcher	Eric Barth	Mechanical Engineering	Vanderbilt University
Researcher	Doug Cook	Applied Technology Center	Milwaukee School of Engineering
Faculty Researcher	Vito Gervasi	Applied Technology Center	Milwaukee School of Engineering
Faculty Researcher	Michael Leamy	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Chris Paredis	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Pietro Valdastri	Mechanical Engineering	Vanderbilt University
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	Eui Park	Industrial and Systems Eng.	North Carolina A & T
Faculty Researcher	Richard Salant	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Silvanus Udoka	Industrial and Systems Eng.	North Carolina A & T
Faculty Researcher	Jun Ueda	Mechanical Engineering	Georgia Institute of Technology

TEST BEDS

Faculty Researcher, Test Bed 6	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

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
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
J. Newlin	Education Partner	Physical Sciences & Tech.	Science Museum of Minnesota
Holly Pellerin	gidaa Program Director	ERC Staff	University of Minnesota
James Van De Ven	Faculty Researcher	Mechanical Engineering	University of Minnesota

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1. SYSTEM VISION AND VALUE ADDED OF THE CENTER

Transforming fluid power into a compact, efficient and effective method of energy transmission remains the vision of the Engineering Research Center for Compact and Efficient Fluid Power (CCEFP). The Center's work continues to make progress towards reducing our Nation's energy usage and increasing the ways in which fluid power—through human-scale applications—will improve our quality of life. This will spawn entirely new industries in the process.

While the CCEFP strategy has continued to evolve and mature, the vision has remained constant. The needs that inspired it and the accuracy of the course in pursuing it are affirmed by the international fluid power research community and by industry.

As it completes its seventh year, the CCEFP continues to transform fluid power. The Center has become the catalyst in energizing the Nation's fluid power industry and research community. For the first time in decades, the fluid power industry in the U.S. is undertaking 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.

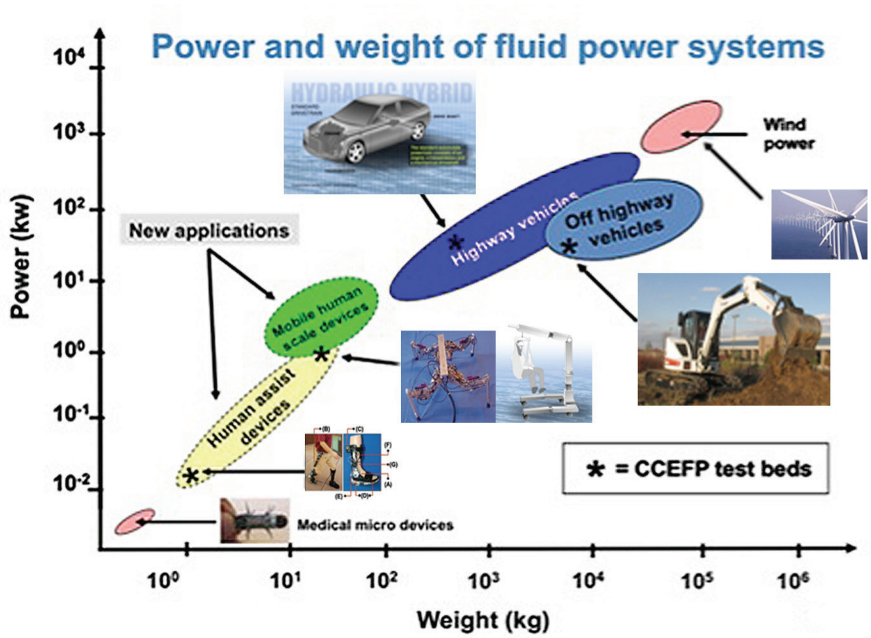
The CCEFP has turned its undivided attention towards sustainability. A full report on sustainability is included in Appendix xx. We envision revenues coming from three major sources: industry membership fees, associated projects and one or more large grants from federal agencies. The most promising near term opportunity for a large grant is from the Energy Efficiency and Renewable Energy Office of the DOE. This effort is supported by an official DOE report issued in December 2012 (http://info.ornl.gov/sites/publications/Files/Pub28014.pdf) documenting the opportunities for fluid power to significantly reduce energy consumption, reduce emissions and spur economic growth.

1.1 SYSTEMS VISION

The CCEFP systems vision has been continuously modified and refined over the last seven years. The test beds demonstrate the systems vision. The current test beds are based on the observation that it is not well known how 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 the entire range of power and weight of interest.

The figure below shows the range of power and weight for fluid power applications. Six families can be identified, as listed below. The six test beds are 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 and lower): Precision Pneumatics for MRI Guided Surgery (Test Bed Beta)



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. In the past year a decision was made to alter the direction of test bed 4. The previous Rescue Robot has been replaced with a Patient Transfer Device (PTD). The justification behind this change was two-fold: 1) the rescue robot was not a good match for our existing industry members, and 2) it was not possible to match the resources available to competing research teams in the defense industry. The new PTD test bed has several attractions. It is a better match to our industry base, it provides an opportunity for collaboration with the Quality of Life Technology ERC and it creates a critical mass of projects and test beds that will be attractive to prospective biomedical industry members.

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.

Doubling the efficiency in current off-road applications has been commercially demonstrated on the recently announced Caterpillar hydraulic hybrid excavator. 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. 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.

Why Fluid Power Is Transformational

Society benefits as the transformational work of the CCEFP leads to the reduction of energy consumption and the creation of new human-scale fluid power devices. Savings will be realized by reducing energy use in current fluid power applications. The DOE energy study mentioned previously 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.

Just as important as the fuel savings, 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 shear 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.

In the last year, a major reorganization of research efforts toward medical applications is creating the critical mass needed to generate research funding and industry interest in this area. Of the four core test beds, only the orthosis is medically related. As was documented in the last few previous reports, an associated test bed on precision pneumatics for MRI guided surgery has been established at Vanderbilt, creating a second medically related test bed. In the last year, two new medically related test beds have been created. The rescue robot test bed has been redirected as a patient handler. Further, 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.

Theory and Science

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. Even so, the results of our efforts will translate directly into benefits for these areas. 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. Nevertheless, CCEFP research results will lead to important improvements in these 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 the table below. Improving these attributes define the technical barriers of the Center. All are important to attaining our systems vision; of these nine, three are transformational.

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

Achieving the CCEFP vision is a strategic challenge. The organization has many member universities and companies spread over a wide geographical area with many differing points of view. Clear communication of the strategy is essential and the three-thrust structure stood the test of time for clearly, concisely and accurately guiding 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.

As was revealed in last year's site visit, the emphasis on the efficiency thrust has increased over time relative to the emphasis on the compactness or effectiveness thrusts. But classifying projects as purely belonging to one of the three thrust seriously overstates the imbalance. Nearly all of the projects in the Center, regardless of how they are classified, 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.

To improve our research management process, more attention must be given to the transformational barriers identified in the previous table. We must focus our attention on overcoming transformational barriers because these barriers would dramatically change the look and feel of fluid power. 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 energy storage in the electric grid. Follow-on research 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. Negotiations are underway for licensing and increased funding from a major hydraulics company that is also a CCEFP member. Unfortunately, the potential of the flywheel accumulator for a ten-fold increase in energy storage density was not recognized in our last proposal selection round. Having later recognized the oversight, the project is now being funded with CCEFP matching funds from the University of Minnesota.

The HCCI free-piston engine-pump solves the energy storage problem by controlling power rather than energy. It epitomizes the system-oriented approach that ERCs strive to create. The major way that hybridization saves energy in the hybrid passenger vehicles is by running the engine under nearly optimal conditions, that is, heavily loaded. Since engines are designed to meet the most demanding power requirements, efficient operation produces more power than typically needed. Hybridization can allow this excess power to be stored for later use when the engine is turned off, 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.

CCEFP recognizes the need for more energy storage research. There are two parts to increasing the research, creating more potential energy storage ideas that become the basis for proposals, and recognizing and supporting the most promising of those ideas in the proposal selection process. It is recognized that finding new approaches to the energy storage problem is difficult and will require explicit effort to find new solutions. Ideation summits are a facilitated process used in industry to generate new approaches to problems. We will implement such a process in the future to generate new proposal ideas. The second aspect requires more discipline in the project selection process. It is imperative that the Executive Committee consciously discerns those projects with the most transformational promise and supports them. This will require an iterative and more refined proposal selection and redirection process.

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. The injection-molding machine was eliminated early on because, as a stationary manufacturing process, there was less transformation potential. The fluid power hand tools were also eliminated to focus resources, recognizing that the orthosis was of similar power and weight. This has caused the mini-engine to become an orphan project. Because of its transformational potential, the project has been continued in spite of its not fitting well with the orthosis. Although not fitting neatly in the strategic plan, the result has been a great success. We have demonstrated an operating engine smaller than any other with the capability of generating ten watts of compressed air at a standard shop-level pressure level. Such an engine can power a hand tool. Lastly, the rescue robot has been redirected as 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 entre into renewable energy research.

As with projects, the management of test beds continues to be a challenge. The hydraulic hybrid vehicle has an ambitious plan for demonstrating the results of projects. Unfortunately, the project has fallen behind schedule due to technical difficulties. The ambition of the project has been scaled back. The use of two platforms has been reduced to one to focus resources. The F-150 platform is becoming industry led with CCEFP providing a supporting role. The redirection of the rescue robot to the patient transfer device (PTD) provides an opportunity to demonstrate systems engineering principles and project management from scratch on a new project.

To implement the strategy, the Center organization was reorganized two years ago. After a transitional period, the new organization is proving its worth. The recruitment of a new ILO has enhanced the Center's effectiveness.

The future directions of the CCEFP in the post-NSF era are outlined in the Sustainability Plan (see Appendix V). We envision revenues coming from three major sources: industry membership fees, associated projects and one or more large grants from federal agencies. Through a careful collective study attempting to match CCEFP strengths, industry needs and the funding available from mission-oriented federal agencies, five potential areas of support from a large grant have been identified. These are:

- Mobile hydraulics
- Industrial pneumatics
- Advanced manufacturing
- Medical and biomedical applications
- Wind energy

The strategy for obtaining grants in each of the five areas is described in detail in the Sustainability Plan. To maximize the chances of success, it is important to focus on one area at a time. The areas above are listed in the order in which they will be pursued, with mobile hydraulics being identified as the most likely source of a large grant in the near term. It is the objective of the Center to broaden its research portfolio into areas that are complementary to our current research. However, it is not necessary to have success in all or even most of the areas for the Center to be strong and vibrant in its post-NSF phase. A single large grant could be sufficient to provide sustainable funding. What is necessary is to focus our efforts on one initiative at a time, with the timing and choice depending on our own state of readiness to undertake the work, industrial interest, and external events that will inevitably change the funding landscape. The list of opportunities mentioned above is far from exhaustive. There are many other mission-oriented federal agencies that might benefit from fluid power research, most notable the Department of Defense (DOD).

CCEFP is in the middle of the two-year funding cycle for Years 7 and 8. It will be essential to critically focus on the potential to bridge from NSF to non-NSF funds in the allocation of Center funding for Years 9 and 10. Preference must be given to projects and test beds that are transformational. A more thorough process will be required. The gap analysis must be more selective so that only critical projects and test beds are chosen. The proposal process will consist of two phases. The first phase will be a short pre-proposal with a longer proposal being submitted only for those projects that are deemed critical. Center leadership and industry will actively work with the proposers to shape the proposal to better suit the strategic plan. Lastly, the Executive Committee will make funding decisions with more discussion and careful attention to the strategic requirements.

Response to Site Visit Team SWOT Report

SVT: CCEFP strategic research plan is not integrated and forward looking enough to assure sustainability

Response: The Center understands the site visit team's concerns regarding the integration of the projects and test beds and acknowledges that it did a poor job of relating the parts to the overall strategy. During the Year 6 site visit we overemphasized the Center's accomplishments rather than its future direction. Our sustainability plan (see Appendix V) describes in detail the relationship of projects and test beds to the overall strategy and shows how the center plans to make a transition from NSF support to self-sufficiency in the next three years. Key elements of the plan are our strategy for research, education and outreach, industrial collaboration and technology transfer, and funding. This plan provides a compelling vision for the future of the CCEFP.

SVT: CCEFP research portfolio is not balanced between the three thrusts, Efficiency, Compactness and Effectiveness

Response: All thrusts are important, but they do not necessarily need to be equally weighted in the research portfolio to achieve our vision. Over time we envision our research portfolio evolving from an efficiency focus to a compactness and effectiveness focus. We believe efficient systems provide the best opportunity for securing additional funding in the near future. But efficient systems require compactness and effectiveness. For example a successful hydraulic hybrid passenger car requires a more compact accumulator and must be quiet and leak-free. In the longer term system level compactness and effectiveness must be realized to develop fluid power medical devices.

SVT: Mini engine compressor is not suitable for the orthosis

Response: We agree that the mini-engine is not suitable for TB6, the orthosis. Nevertheless, the challenging compactness targets of the orthosis test bed caused the mini-engine research team to rethink their technical approach to small engine design. The result is the smallest internal combustion engine ever made with a capability of producing compressed air at standard shop air pressures. Thus, the mini-engine very effectively demonstrates the potential of small-scale, portable fluid power. It will be demonstrated on another test bed such as a portable tool (e.g., an untethered "jaws of life"). The Stirling compressor is a long-term project and may not be integrated into the test bed by Year 10. In the short term, the best power supply to demonstrate the superiority of fluid power for power transmission at the small scale of TB6 are batteries powering an electric motor driving either a hydraulic pump or pneumatic compressor.

SVT: Insufficient energy storage portfolio

Response: The Center agrees that it would be good to have more projects in energy storage. We recognize the transformative importance of energy storage and continue to actively seek new energy storage approaches. To date the Center has funded four projects that address the energy storage problem. These are the open accumulator, the elastomeric accumulator, the flywheel accumulator and the free piston engine pump. Despite the need for additional energy storage projects, two of the energy storage projects undertaken by CCEFP are already success stories. Both have generated IP, one has been licensed and the other is in negotiation for licensing.

The strain energy accumulator has generated interest from industry. One of the Center's member companies has entered into a technology development agreement with Vanderbilt and is currently in negotiations to license the current intellectual property. This will accelerate the commercialization of the technology. Significant work has already been done to identify the optimal materials in the strain energy accumulator. Since maximizing the energy density and assuring durability for the expected number of cycles is an essential characteristic determining the practical potential of the invention, an extensive investigation of all available materials was conducted. Dr. Sudhin Datta of Exxon-Mobil Corporation, a researcher involved in elastomeric material research, has advised us that with sufficient resources, better materials can be engineered for this application. The proof of concept to TRL 4 has been accomplished without durability tests, patents have been applied for, and a major CCEFP industry member has entered into a technology development agreement with Vanderbilt. The additional funding and cooperation with this CCEFP industry member will enable the project to progress beyond TRL 4.

Although the open accumulator technology was not suitable for the hybrid passenger vehicle, it is showing great promise as an energy storage technology for wind energy. The researchers teamed with an industry partner and procured $2M in NSF funding to continue the research and refocus it on wind energy storage. The research is ongoing and SustainX and Light Sail Energy Inc. recently licensed the core intellectual property.

The flywheel accumulator is a new energy storage project that exploits both compressed air and kinetic energy as energy storage modes. This approach has the potential to increase the energy storage density by a factor of ten compared to conventional accumulators. University matching funds are supporting the graduate student on this project.

By taking a system engineering approach to the hydraulic hybrid vehicle challenges another way around the energy storage barrier can be found. The free piston engine pump accomplishes this by controlling power instead of energy.

SVT: Progress on Test bed 3 is lagging and consuming too many resources

***Response**:* We agree that the progress of Test Bed 3 has lagged. We solicited advice from industry partners with knowledge of the automotive industry and its requirements. The general consensus was that pursuing such a complex test bed as a hydraulic hybrid vehicle with such limited resources is challenging. Some even felt we should abandon the hardware demonstration aspects of the test bed and replace them with validated system simulations. We agree that simulations are important but also believe there is significant value in demonstrating our research on this test bed. We plan to continue, but only with the Gen 1 test bed. Progress on this vehicle has been substantial in the past year. A new hydro-mechanical transmission has been designed, built, and installed in the vehicle. In addition, a new hydrostatic dynamometer capable of providing repeatable test data has been designed and built and tested. The next steps for the Gen 1 vehicle will include demonstration of several research projects on the test bed, the first being a comparison of the efficiency of several hydraulic fluids.

The Gen 2 vehicle, the Ford F150, has been transferred from a CCEFP led project to an industry led project. We believe that much can and will be learned once this vehicle is commissioned, but the kinds of problems facing that commissioning are much better suited for industry than for academic researchers. We have a strong relationship with our industrial partners and will continue to remain engaged on the project, but at a lower level of involvement.

SVT: It is not clear that the new Patient Transfer Device test bed will advance the state of fluid power art

Response: The Center believes that the transition of TB4 from rescue robot to patient transfer device (PTD) will provide opportunities for innovative research, new hydraulic technology and new types of system integration. The PTD must be untethered for convenience and because patients must be transferred over long distances. But energy storage and power supplies are not the only compactness issues; there are also power transmission (e.g., tiny components) and control challenges (e.g., passivity control). 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. To be accepted in the market place a single health care provider must easily operate the PTD. 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. An additional factor in the decision to migrate TB4 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.

SVT: Concerns about project selection and overall strategy

Response: Plans for demonstrating projects on test beds have been somewhat informal to date, but now that some of the test beds have matured, more formal mechanisms are needed to speed up the process of integrating projects into the test beds. The excavator, Gen 1 hydraulic hybrid vehicle and orthosis are now ripe for the demonstration of results from our research projects. The formal mechanism for facilitating this integration requires the use of systems engineering and project management tools, requiring the participation, communication and coordination of the test bed and research project teams. In the next year we will work to make an effective transition from an informal to a formal process for planning and executing the demonstration of projects on test beds.

We believe that the process we are currently using for project solicitation and selection is good, but we are implementing ways to improve it. As was presented at the last site visit, the call for proposals carefully looks at the strategic plan and requested specific projects to align with gaps and needs. The integration with the Center's strategic plan is strongly considered during our existing project solicitation and selection process. All Center projects support the overall research strategy and fit into the three thrusts. But insufficient emphasis was placed on the most transformational elements of the strategy. Of the nine important areas recognized, three are transformational: efficient components and systems, compact energy storage and compact power supplies. Efficient components and systems have been well supported but there has been insufficient support for compact power supplies and energy storage. This is due to two factors, an insufficient number of project proposals in these areas and insufficient discipline in project selection. To address the insufficient number of projects we are planning targeted ideation events to generate new approaches to overcoming the compact storage and power supplies barriers. Since the CCEFP Executive Committee makes the final decision on project funding, the process can be improved by better communication, discussion and discipline adherence to the strategic plan within the Executive Committee.

SVT: CCEFP leadership and organizational concerns

Response: To become more effective the CCEFP was reorganized in late 2010. The Center Director (CD) and Administrative Director (AD) conducted this effort with advice and guidance from an organizational expert from the HR department of the University of Minnesota. The resulting solution redefined the role of the AD, Deputy Director (DD) and Industrial Liaison Officer (ILO) and created a new position, Sustainability Director (SD). In the new organization, the core ILO role remained with that position, but the administrative role was transferred to the AD and the research role was transferred to the SD. The DD position was redefined to be strategic and the day-to-day tasks of the DD were assigned to the SD.

After the inevitable transition period, the reorganized center is working well. A team consisting of the CD, DD, SD and ILO leads the research effort. We believe that we have a strong team in place that is providing the strategic thinking, Center coordination, and leadership necessary for the long-term success of the Center. The ILO has greatly improved the IP process and the improved process is already showing results. The SD has greatly improved the follow-up on semi-annual project performance reviews for projects that are lagging, and the SD has provided a key role in obtaining funding for associated projects. The ILO and SD worked closely with the CD and DD to develop the revised Sustainability Plan. The CD, DD, SD and ILO will also be working to improve the systems engineering and project management of research in the Center including the use of design reviews with industry input where appropriate.

SVT: Increase industrial awareness of Center value proposition

Response: Providing a strong value proposition is critical to maintaining and increasing our industry membership. However, the importance of each element of the value proposition is not the same for all companies. We have worked extensively with the IAB and other industry representatives to understand industry's needs in order to clearly capture our value proposition. (See Appendix3) Key elements of the value proposition that the CCEFP offers to industry include access to students as potential employees, access to researchers as a source of technical knowledge and potential targeted research, networking opportunities to develop market insight and intellectual property. In general these are listed in order of value to our industry members.

SVT: lack of a comprehensive safety program across all CCEFP institutions is concerning

Response: CCEFP at the University of Minnesota (Lead Institution) has formally defined and implemented fluid power safety standards into its existing training as appropriate for CCEFP students (http://www.me.umn.edu/intranet/safety/fp/index.shtml). 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 (see Appendix 2). 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.

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 orthosis, demonstrates the practical limits of miniature fluid power systems.

Test Bed 1, the compact excavator, has been a demonstrator of throttle-less hydraulic actuation technology since the inception of the Center through spring 2012. Beginning February 2012, the test bed has been transitioning to a demonstrator of a novel hydraulic hybrid configuration, called series-parallel hybrid DC system, for which a patent was applied in 2011. The series-hybrid architecture will introduce secondary controlled actuation for the swing drive in combination with the implementation of an energy storage system in parallel to the other DC actuators for the remaining working functions. Such architecture enables energy recovery from all actuators, capture of swing braking energy and 50% engine downsizing. It promises fuel savings beyond those achieved with the prototype non-hybrid DC excavator, as was previously shown through simulation studies in project 1A2 ('Multi-Actuator Hydraulic Hybrid Machine Systems'), which concluded in June, 2012. 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. The prime role of the test bed is to be a demonstrator of energy savings that are possible in multi-actuator machines, through efficient system architectures (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 is well positioned for testing of 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 accumulator, Project 2C.2).

Considerable progress has been demonstrated in the Test Bed 1 in the last year. Effort on the excavator has focused on the optimal sizing of the components of the series-parallel hybrid displacement architecture so that its benefits can be fully realized. Simulation has showed that a 20% improvement in fuels is possible over the previous displacement controlled system. This result can be realized with a 50% downsizing of the engine. The new architecture has been demonstrated in hardware with reasonable tracking, with some control issues yet to be resolved with future testing.

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: (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) meeting California emissions standards; and (v) size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market. Resulting powertrains must demonstrate advantages over electric hybrids to be competitive. 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 designing, constructing and testing a hydrostatic dynamometer. The dynamometer is capable of implementing the EPA urban driving cycle, thus eliminating the need for a test track for experimentation. The dynamometer is capable of motoring as well as braking so that regenerative braking can be experimentally tested. The 1.1L Diesel engine was replaced with a 1.5L Diesel so that the required acceleration of the EPA driving cycle can be obtained, and many hardware and electrical upgrades were implemented. For the Gen 2 vehicle, our industry partners, Ford and Folsom, are responsible for the hardware with CCEFP provide support on controls. The controller will be implemented in three steps, software in the loop (SIL), hardware in the loop (HIL), and full hardware implementation, with a Micro-Autobox unit chosen for control implementation. The SIL control has been finished with the HIL and full hardware implementation to follow.

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. As was reported last year, Test Bed 4 has made a transition from a rescue robot to patient transfer device (PTD), providing opportunities for innovative research, new hydraulic technology and new types of system integration. 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 (all day for typical transfers), produce sufficient force to transfer bariatric patients (up to 500 lbs.), and have precise, 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 undertaken 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. This test bed benefits society by creating human-scaled fluid power devices to assist people with daily activities and is creating new market opportunities for fluid power, including opportunities in medical devices.

Progress was realized on two prototype AFOs in Year 7, a portable pneumatic AFO at UIUC and a hydraulic AFO at Minnesota. To improve efficiency a regenerative scheme was tested on the pneumatic AFO using an accumulator from the elastomeric accumulator project. A bench top investigation by REUs estimated a potential energy savings of up to 30% while follow-on walking experiments showed a 17% energy savings. Efforts of a senior capstone design team at Bradley University focused on continuing to reduce the size and weight of the device with novel rotary and linear actuator schemes designed and tested. Specialized control approaches are being developed with the capability of distinguishing level, ascending and descending walking on steps or ramps with the appropriate control approach applied as required. The current prototype is now capable of being used for gait assistance of patients with Parkinson's disease with possible future extensions to rehabilitation of patients with stroke and partial foot amputations. The hydraulic AFO project continued the work on the design and scaling of components and systems for tiny hydraulics. Elements of the design include the electric motor and gear head, pump and cylinders. It was revealed that the efficiency of O-ring sealing is a crucial element in the design.

Education Outcomes

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 who can create new knowledge and innovate; industry that capitalizes on new knowledge to lead the world in fluid power innovation; and participants in all aspects of fluid power who reflect the gender, racial and ethnic composition of this country.

The strategy of the Education and Outreach 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 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 E&O program is divided into thrusts, each containing several projects that answer to the four aforementioned 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.

The CCEFP is striving to change the face of fluid power by providing opportunities for a diverse population to become involved in fluid power--women, underrepresented minorities and those with disabilities. The CCEFP is committed to recruiting, engaging and retaining these diverse audiences in its programs: university faculty, undergraduate and graduate students; pre-college students and teachers; and students of all ages through its outreach activities. Some of these efforts are conducted through the offices and programs at each of its seven universities; others are realized through the work of the Center's affiliated organizations, including NSBE, LSAMP and AGEP institutions; still the CCEFP staff coordinates others.

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.

The Pre-College Outreach Program answers the three following 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 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.

Industrial Collaboration and Tech Transfer Interactions

Our industry membership changed in year 7 from 48 to 40. This was primarily due to a lack of focus caused by a vacant ILO position for the last quarter of 2012. Other contributing factors were loss of key industry champions due to retirement or job reassignment and a decision by some members to not renew after their initial 5-year commitment was completed. As the center matures, it is most important to focus on strategic members. In the process of identifying these strategic partners, we have identified gaps that are leading us to develop other relationships as detailed in Section 4.

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. These meetings can cover a wide range of topics from research projects 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 and 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 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. These site meetings have proven to be very successful and have greatly increased awareness of our activities on the part of industry.
As the CCEFP research matures, some of our most successful projects are approaching technology readiness level 4. At this point the research is ripe for industry involvement for commercialization. A list of fourteen test beds or projects have been identified that have great commercial potential. We will be working closely with our industry members to identify interested partners for collaboration to move these projects toward commercialization.

- 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
- Test bed 6: Fluid Power Ankle-Foot Orthosis
- Test bed 1: High Efficiency Excavator
- 3B.1: Passive Noise Control in Fluid Power
- 1B.1: New material combinations/surface shapes for the main tribo-systems of piston machines

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 areas once deemed by industry as "weaknesses" by have grown to become strengths. This transformation continues to occur with the IAB providing positive feedback on the new project review process and with 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.

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 and the best way to do so is through active and meaningful participation. The CCEFP is actively working with the National Fluid Power Association (NFPA) to improve our industry engagement. Going forward we envision the CCEFP-NFPA-industry partnership to become a critical cornerstone of our long-term sustainability strategy. We must leverage each organization's strengths while eliminating unnecessary duplication of efforts and associated administration overhead. The CCEFP will take the lead on owning and maintaining the research strategy while NFPA will do so on the workforce development strategy with strong input from one another. 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.

Industry surveys have indicated that one of the most important products of the CCEFP is its 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 CCEFP Fluid Power Scholars industry internship program. Interns participate in a 3-day training course on fluid power at a member university before their internship begins.

Team and Diversity
The interdisciplinary makeup of the CCEFP team is appropriate to achieve its vision. As shown in Figure 1a (section 2.1), most of the faculty members are in mechanical engineering or closely related disciplines. However, mechanical engineering is a very broad field with widely varying disciplines. Efforts continue to broaden the disciplines represented in the CCEFP, and for example, the Center's Education Director, Professor Paul Imbertson is an electrical engineering professor at the University of Minnesota.

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 90% of the respondents. For this group, the representation of women was near or exceeding the national averages in all groups. This is a significant increase in numbers over previous years. Comparing CCEFP with national averages, the percentage of women was 13.8% for faculty with 33.3% for the leadership as compared to 13.8% for faculty nationally and 28.3% for undergraduate non-REU students and 30.0% for REU students compared to 18.7% for undergraduates nationally. Underrepresented racial minorities are near or exceeding national averages for all groups, also a significant improvement. The percentage for underrepresented racial minorities was 13.8% for faculty compared to 3% nationally, 20.0% for doctoral students compared to 4.7% nationally, and 47.5% for non-REU students and 30.0% for REU students compared to 6.3% for undergraduates nationally. Hispanics/Latino and persons with disabilities representation 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 to 22 from 12 last year, showing that we are addressing this concern of the Site Visit Team at the last visit. Improvement in publication is still needed, since the average for this figure is 28 among all ERCs.

Inventing and patenting continues at a steady pace. Patent applications increased from 4 to 6, but disclosures decreased from 12 to 3. The decrease can be attributed to a single inventor who disclosed ten variations on a single invention in the previous year.

Doctoral degrees granted increased from 6 to 12, an encouraging sign. Since it typically takes about six years to earn a doctoral degree this shows that doctoral students are completing their degrees in a timely manner. Education impact is significant with 28 courses containing ERC content, up from 19 last year and well about the ERC average of 16. Because of its extensive K-12 education and outreach activities, CCEFP exceeds most norms in these categories.

Associated projects increased from $2.31 million to $2.42 million, much lower than the ERC average of $4.20 million. Industry dues have decreased from $708K to $577K. While the decrease in member dues is undesirable, the dues received are well about the ERC average of $261K. The downward funding trend must be reversed if the CCEFP is to be sustainable.

The number of industry members has decreased from 48 to 40, a troubling development, but as described in Section 4, the core strategic partners remain in place and efforts to improve engagement are planned. The year-to-year comparison is also somewhat misleading since we have used stricter criteria in deciding who is a continuing or new member. Four of the continuing members are expected to pay their current year dues, but are not listed since they have not yet done so. And four new members have not yet paid their current year dues, but are also expected to do so. These new members are Hitachi Construction Machinery, Idemitsu Kosan, JCB and Pall. In previous years, companies were counted as new members when the signed membership agreement was received even if the first year's dues were not yet paid. 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.

Table 1: Quantifiable Outputs							
Outputs	Early Cumulative Total [1]	Feb-01-2008 - Jan-31-2009	Feb-01-2009 - Jan-31-2010	Feb-01-2010 - Jan-31-2011	Feb-01-2011 - Jan-31-2012	Feb-01-2012 - Jan-31-2013	All Years
Publications Resulting From Center Support							
In Peer-Reviewed Technical Journals	0	12	27	22	12	22	95
In Peer-Reviewed Conference Proceedings	19	57	51	59	52	32	270
In Trade Journals	1	2	23	0	2	0	28
With Multiple Authors:	12	70	101	76	51	54	364
Co-authored With ERC Students	12	51	71	50	51	40	275
Co-authored With Industry	0	2	4	3	2	2	13
With Authors From Multiple Engineering Disciplines	0	4	12	3	6	7	32
With Authors From Both Engineering and Non-Engineering Fields	2	9	7	2	6	2	28
With Authors From Multiple Institutions	0	11	7	10	9	0	37
Publications Resulting From Associated Projects in the Strategic Plan							
In Peer-Reviewed Technical Journals	6	8	16	6	5	7	48
In Peer-Reviewed Conference Proceedings	18	19	23	7	10	13	90
Publications Resulting From Sponsored Projects							
In Peer Reviewed Technical Journals	0	0	6	0	0	0	6
In Peer-Reviewed Conference Proceedings	0	0	24	0	0	0	24
Participating Organizations							
Industrial Practitioner Members	114	58	54	54	48	40	368
Innovation Partners	0	0	0	0	1	1	2
Funders of Sponsored Projects	0	0	0	0	0	0	0
Funders of Associated Projects	8	6	5	15	8	5	47
Contributing Organizations	0	0	2	5	9	5	21
ERC Technology Transfer							
Inventions Disclosed (by researchers or tech transfer office)	7	8	9	7	12	3	46
Total Patent Applications Filed	5	5	6	4	4	6	30
Provisional Patent Applications Filed [1]	N/A	N/A	N/A	N/A	N/A	3	3
Full Patent Applications Filed [1]	N/A	N/A	N/A	N/A	N/A	3	3
Patent Awarded	1	0	0	1	2	1	5
Licenses Issued	0	0	0	2	0	2	4
Spin-off Companies Started	0	0	1	0	0	1	2
Estimated Number of Spin-off Company Employees	0	0	0	0	0	1	1
Building Codes Impacts	0	0	0	0	0	0	0
Technology Standards Impacts	1	1	2	4	1	1	10
New Surgical and Other Medical Procedures Adopted	0	0	0	0	0	0	0
Degrees to ERC Students							
Bachelor's Degrees Granted	6	26	44	18	10	10	114
Master's Degrees Granted	9	15	32	14	10	10	90
Doctoral Degrees Granted	2	6	5	9	6	12	40
Job Sector of ERC Graduates							
Undergraduates Hired by:							
Industry:	N/A	N/A	N/A	N/A	4	0	4
ERC Member Firms	N/A	N/A	N/A	N/A	0	0	0
Other U.S. Firms	N/A	N/A	N/A	N/A	4	0	4
Other Foreign Firms	N/A	N/A	N/A	N/A	0	0	0
Government	N/A	N/A	N/A	N/A	0	0	0
Academic Institutions	N/A	N/A	N/A	N/A	4	3	7
Other	N/A	N/A	N/A	N/A	0	1	1
Undecided/Still Looking/Unknown	N/A	N/A	N/A	N/A	2	6	8
Undergraduate ERC Graduates Total	0	0	0	0	10	10	20
Master's Graduates Hired by:							
Industry:	N/A	N/A	N/A	N/A	8	1	9
ERC Member Firms	N/A	N/A	N/A	N/A	2	1	3
Other U.S. Firms	N/A	N/A	N/A	N/A	6	0	6
Other Foreign Firms	N/A	N/A	N/A	N/A	0	0	0
Government	N/A	N/A	N/A	N/A	0	0	0
Academic Institutions	N/A	N/A	N/A	N/A	2	0	2
Other	N/A	N/A	N/A	N/A	0	2	2
Undecided/Still Looking/Unknown	N/A	N/A	N/A	N/A	0	7	7
Master's ERC Graduates Total	0	0	0	0	10	10	20
Ph.D.s Hired by:							
Industry:	N/A	N/A	N/A	N/A	2	0	2
ERC Member Firms	N/A	N/A	N/A	N/A	1	0	1
Other U.S. Firms	N/A	N/A	N/A	N/A	1	0	1
Other Foreign Firms	N/A	N/A	N/A	N/A	0	0	0
Government	N/A	N/A	N/A	N/A	0	0	0
Academic Institutions	N/A	N/A	N/A	N/A	3	0	3
Other	N/A	N/A	N/A	N/A	0	4	4
Undecided/Still Looking/Unknown	N/A	N/A	N/A	N/A	1	8	9
Ph.D. ERC Graduates Total	0	0	0	0	6	12	18
ERC Influence on Curriculum							
New Courses Based on ERC Research That Have Been Approved by the Curriculum Committee and Are Currently Offered [2]	1	3	2	8	2	0	16
Currently Offered, ongoing Courses With ERC Content	0	15	12	12	19	28	N/A
New Textbooks Based on ERC Research	0	2	1	1	0	0	4
New Textbook Chapter Based on ERC Research	0	0	1	0	0	0	1
Free-Standing Course Modules or Instructional CDs	0	0	0	0	3	5	8
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	0	1	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	0	1710	1700	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

Outputs	Early Cumulative Total [1]	Feb-01-2008 - Jan-31-2009	Feb-01-2009 - Jan-31-2010	Feb-01-2010 - Jan-31-2011	Feb-01-2011 - Jan-31-2012	Feb-01-2012 - Jan-31-2013	All Years
Number of Students Graduated	0	0	0	0	0	0	0
Active Information Dissemination/Educational Outreach							
Workshops, Short Courses, and Webinars [3]	8	23	9	9	83	85	217
Number of Participants That Attended Events	N/A	0	86	135	2322	5189	7732
Innovation-focused Workshops, Short courses, Webinars, and Seminars	N/A	N/A	N/A	5	39	14	58
Number of Participants That Attended Events	N/A	N/A	N/A	25	1172	1120	2317
Seminars, Colloquia, Invited Talks, Etc.	24	44	24	35	18	7	152
ERC Sponsored Educational Outreach Events for K-12 Students	N/A	0	14	28	15	19	76
Number of Students That Attended Events	N/A	0	4365	3251	10926	11000	29542
Number of Teachers That Attended Events	N/A	0	26	30	100	500	656
ERC Sponsored Educational Outreach Events for Community Colleges	0	0	8	9	9	4	30
Number of Community College Students That Attended Events	0	0	244	125	5000	250	5619
Number of Community College Faculty That Attended Events	0	0	24	9	50	4	87
Personnel Exchanges							
Student Internships in Industry	12	11	4	14	12	9	62
Faculty Working at Member Firm	0	0	1	1	1	0	3
Member Firm Personnel Working at ERC	2	2	6	0	0	0	10

[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: 2012 Average Metrics Benchmarked Against All Active ERC's and the Center's Tech Sector					
Metric	**Average All Active ERC's FY 2012**	**Average Advanced Manufacturing Sector FY 2012**	**Average Class of 2006 FY 2012**	**Minnesota Twin Cities-CCEFP Total**	**Minnesota Twin Cities-CCEFP Total**
	(17 ERC's)	**(4 ERC's)**	**(5 ERC's)**	**FY 2012**	**FY 2013**
Organizations Within Non-Industry Sectors	**15**	**14**	**21**	**6**	**7**
Organizations Within Industry Sectors	**22**	**36**	**36**	**60**	**44**
Small	41%	41%	51%	43%	39%
Medium	10%	9%	9%	8%	9%
Large	49%	50%	40%	48%	52%
Industrial/Practitioner Member Firms	**20**	**31**	**31**	**48**	**40**
Innovation Partners	**5**	**4**	**5**	**1**	**1**
Funders of Sponsored Projects	**1**	**1**	**1**	**0**	**0**
Funders of Associated Projects	**10**	**12**	**17**	**8**	**5**
Contributing Organizations	**2**	**3**	**3**	**9**	**5**
Total Number of Organizations	**37**	**50**	**56**	**66**	**51**
Total Membership Fees Received	**$260,944**	**$512,392**	**$369,113**	**$708,817**	**$576,600**

Direct Sources of Support [1]	**$5,226,762**	**$5,878,973**	**$5,080,077**	**$5,793,275**	**$5,451,357**
NSF	69%	72%	76%	70%	74%
Other Federal	0%	0%	0%	0%	0%
State Government	2%	0%	0%	0%	0%
Local Government	0%	0%	0%	0%	0%
Foreign Government	0%	0%	0%	0%	0%
Quasi-Government Research	0%	0%	0%	0%	0%
Industry (U.S. and Foreign)	9%	12%	11%	16%	11%
University (U.S. and Foreign)	19%	15%	13%	14%	15%
Other	1%	0%	0%	0%	0%

Associated Project Support	**$4,197,141**	**$5,533,829**	**$7,592,064**	**$2,311,570**	**$2,111,345**

ERC Personnel and Educational Participants	**4,772**	**6,692**	**8,201**	**16,363**	**12,057**
Leadership Team [2]	15	13	14	10	9
Faculty [3]	41	32	41	33	33
Graduate Students	75	86	81	81	81
Undergraduate Students	40	84	66	123	137
REU Students	15	15	26	19	26
K-12 Teachers	11	32	15	21	17
K-12 Students (Young Scholars)	19	55	42	0	0
Faculty/Teachers That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	212	121	500	100	500
Students That Attended ERC Sponsored Educational Outreach Events for K-12 Students [4]	2,749	3,678	4,899	10,926	11,000
Faculty That Attended ERC Sponsored Educational Outreach Events for Community Colleges [4]	74	203	185	50	4
Students That Attended ERC Sponsored Educational Outreach Events for Community Colleges [4]	1,521	2,374	2,332	5,000	250
% Women [5]	30%	32%	30%	24%	22%
% Underrepresented Racial Minorities [6]	14%	14%	17%	34%	29%
% Hispanic [6]	10%	11%	10%	2%	4%

Publications	**Average**	**Average**	**Average**	**Total**	**Total**
In Peer-Reviewed Technical Journals	28	34	36	12	22
In Peer-Reviewed Conference Proceedings	18	14	26	52	32
Multiple Authors: Co-Authored With ERC Students	32	38	44	51	40
Multiple Authors: Co-Authored With Industry	3	2	4	2	2

Intellectual Property	**Average**	**Average**	**Average**	**Total**	**Total**
Invention Disclosures	6	12	12	12	3
Patent Applications (Provisional and Full)	3	5	4	4	6
Patents Awarded	1	1	1	2	1
Licenses (patents, software)	0	0	1	0	2

Metric	Average All Active ERC's FY 2012	Average Advanced Manufacturing Sector FY 2012	Average Class of 2006 FY 2012	Minnesota Twin Cities-CCEFP Total	Minnesota Twin Cities-CCEFP Total
	(17 ERC's)	(4 ERC's)	(5 ERC's)	FY 2012	FY 2013
Education and Outreach Outputs	**Average**	**Average**	**Average**	**Total**	**Total**
New Courses Developed	3	4	4	2	0
Currently Offered, Ongoing Courses With ERC Content	16	11	20	19	28
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.

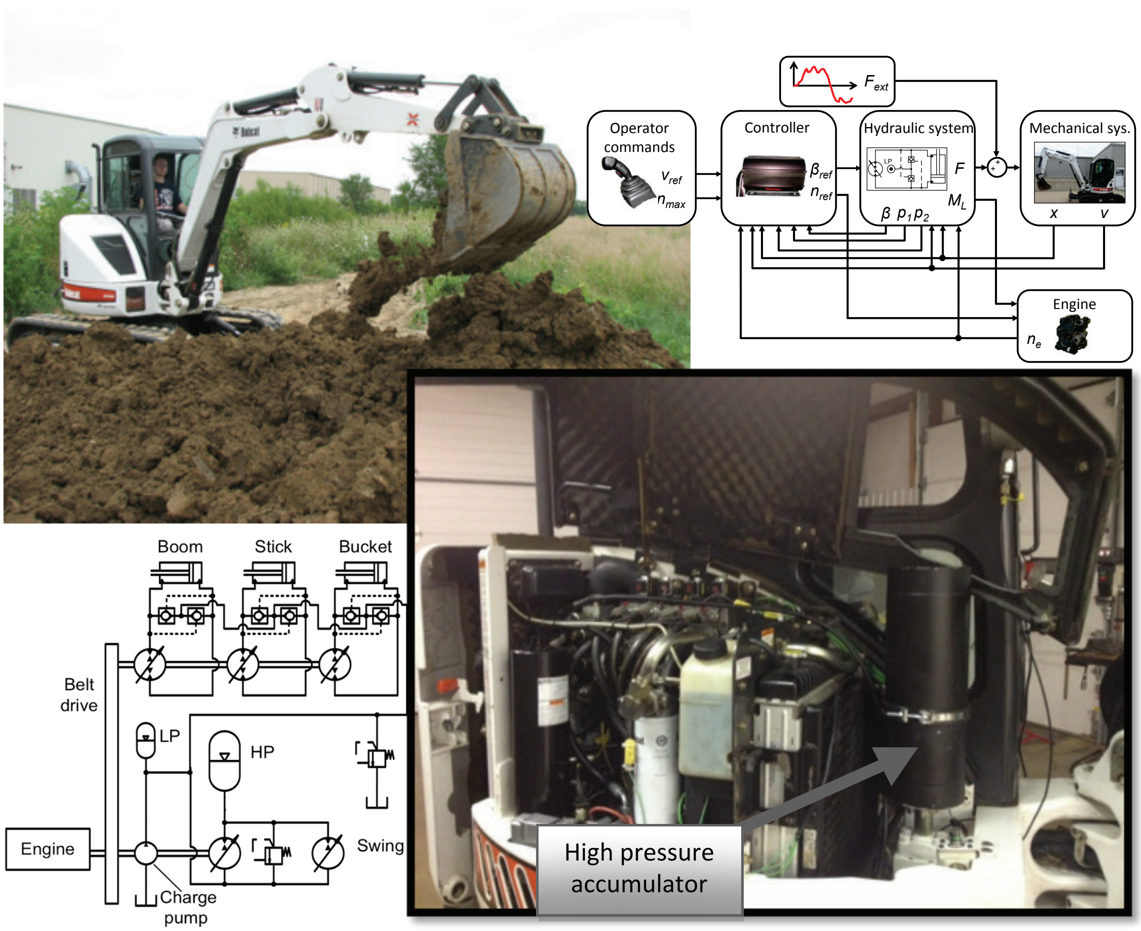
[5] - Calculated out of total number of personnel.

[6] - Calculated out of total number of U.S. Citizens or Permanent Residents.

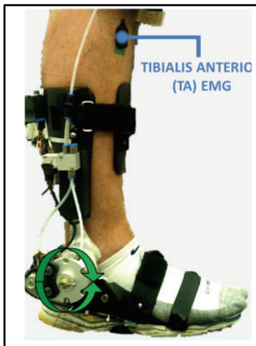
1.3 HIGHLIGHTS OF SIGNIFICANT ACHIEVEMENT AND IMPACT

RESEARCH / TECHNOLOGY ADVANCEMENT HIGHLIGHTS

World's First Energy Efficient Hydraulic Hybrid Excavator – CCEFP researchers built the first hydraulic hybrid excavator. The novel hydraulic hybrid system combines hydraulic hybrid technology with energy efficient displacement controlled actuation. Hydraulic accumulators are used to store and reuse brake energy, which helps to further reduce fuel consumption. Novel control and power management concepts allow effective power flows between actuators, engine and accumulator. System simulations have shown, that the combination of both novel technologies in one system architecture allows 50% engine downsizing and up to 20% additional fuel savings over the non-hybrid displacement controlled excavator. In 2010 measurements made by Caterpillar on the CCEFP developed non-hybrid displacement controlled excavator had demonstrated 40% fuel savings and 69% machine efficiency improvements in ton soil moved per kg fuel burned. The hybrid system has been implemented in the CCEFP excavator test bed, the 5-t displacement controlled mini-excavator. The machine is operational and ready for first machine performance measurements, which are planned for spring 2013.

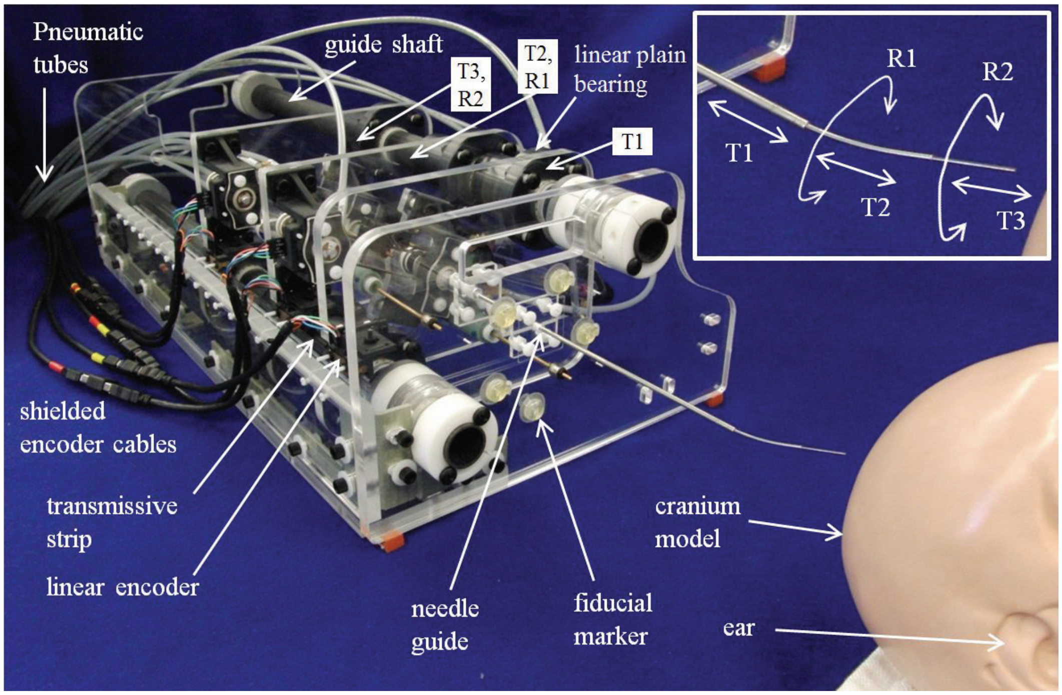


Orthosis to be tested on people with Parkinson's disease – The use of cues (audio, visual, touch) can improve the ability to start and/or continue walking in people with severe Parkinson's disease (PD). Yet, the success of cueing interventions is limited by low reliability and a reduced capacity of patients to produce the forces necessary to generate the anticipatory postural adjustments (APAs) for gait initiation. APAs involve a well-orchestrated sequence of shifts in body weight to prepare the swing limb for smooth forward progression. Recently studies have demonstrated that mild mechanical perturbations, which elicit postural responses, can significantly improve gait initiation in people with PD, but to date, no wearable device has been tested. We are exploring whether the pneumatic Portable Powered Ankle-Foot Orthosis (PPAFO) that is being developed in Testbed 6 at the University of Illinois can provide an appropriate sequence of joint torques to compensate for deficits in torque generation. The first study is assessing whether the presentation of a mechanical cue - modest torque at the ankle via the PPAFO - will significantly improve the generation of appropriate APAs required to initiate gait. This work is in collaboration with experts in gait initiation, cueing and locomotion training in PD – Dr. Colum MacKinnon, PhD, in the Department of Neurology at the University of Minnesota, and Dr. Mark Rogers, PT, PhD, FAPTA, in the Department of Physical Therapy at the University of Maryland.



Fluid Powered Surgery via Compact, Integrated Systems – One half to one percent of the population in North America and 50 million patients worldwide are affected by epilepsy with a 7 to 17 percent chance of sudden unexplained death if left untreated. In the majority of temporal lobe epilepsy cases, seizures are caused by the hippocampus, and 60 to 70 percent of patients who undergo surgical removal of the hippocampus become seizure free for at least two years. Mechanical engineers at Vanderbilt University have created the first fully pneumatic robot designed for neurosurgical interventions. The idea is that this robot could be used to position a needle at the hippocampus to deliver thermal energy (e.g. via a laser, acoustic ablator or other ablation technology) instead of surgical removal of the hippocampus. Thermal ablation in the brain is an experimental procedure, meaning that much testing will be required to verify that heat can accomplish the same goal as surgery. Nevertheless, there is a large potential benefit to patients of replacing open brain surgery with needle insertion since trauma and complication risk is greatly reduced.

Actuated by five non-magnetic pneumatic piston-cylinders, the steerable needle robot rests on the MRI scanner bed just above the patient's head. Long lines of tubing tether the cylinders to remotely located pressure sensors and valves, which position the pistons to sub-millimeter precision. A five degree-of-freedom needle has been designed to target the hippocampus, an anatomical structure about 1 cm across and 4 cm long, located deep within the temporal lobe. The needle comprises a stiff outer tube and two tubes of a super-elastic memory metal called nitinol. Telescoping and rotating the tubes with respect to each other, the pneumatic robot steers the needle along a desired path in the patient's brain. Before the procedure, the front end of one nitinol tube is set to a curved shape, and during the procedure the tube returns to this shape as it telescopes beyond the outer stiff, straight tube. At its tip the needle carries an MRI-compatible thermal ablator. The MRI scanner provides real-time feedback of the needle location as well as real-time thermal dose monitoring using MR thermometry. A robust, nonlinear, model-based controller precisely translates and rotates the robot joints, with mean steady-state errors of 0.032 mm and 0.447°. MRI-compatibility testing in a 3-Tesla closed-bore scanner has shown that the robot has no impact on the signal-to-noise ratio, and that geometric distortion remains within recommended calibration limits for the scanner. These results demonstrate that pneumatic actuation is a promising solution for neurosurgical interventions that either require or can benefit from sub-millimeter precision. U.S. and international patent applications have been filed for the robot.

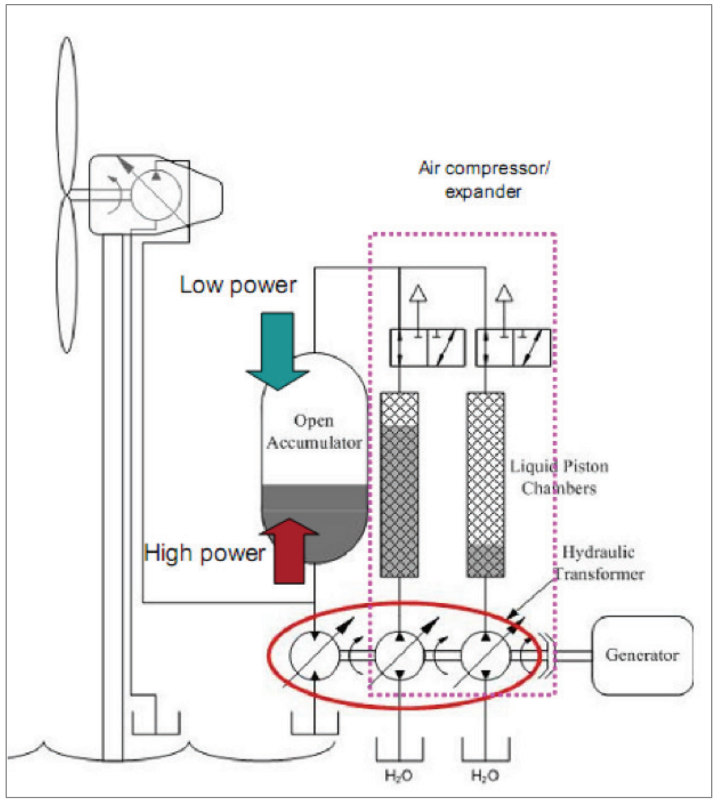


Hydrostatic Transmissions for Wind Power – In a conventional utility scale wind turbine, an 80-100X increase between the rotational speed (rpm) of the turbine blades and the speed at which the generator operates. This speed increase is done with a mechanical gearbox. The gearbox experiences high stress during wind gusts and the stress is transferred from the gearbox to the generator. As a result, two of the highest service items in a wind turbine are the gearbox and generator bearings. One aspect of the wind power research at CCEFP is replacing the mechanical gearbox with a hydrostatic transmission (HST). Since the power path in an HST is hydraulic, the inherent compliance in the fluid and fluid lines provides a damping effect resulting in a large stress reduction in the gearbox and generator during wind gusts. IThe continuously variable transmission functionality of an HST also allows a constant generator speed independent of the turbine blade rpm. This reduces the need for power electronics substantially, thus lowering cost and further improving reliability.

Center researchers have attracted considerable government and industry support for its research in wind power. An associated project with an industry partner investigating the use of HSTs in off-shore wind turbines was completed in the reporting period. High reliability and low maintenance are especially important in off-shore wind turbines due to logistic challenge

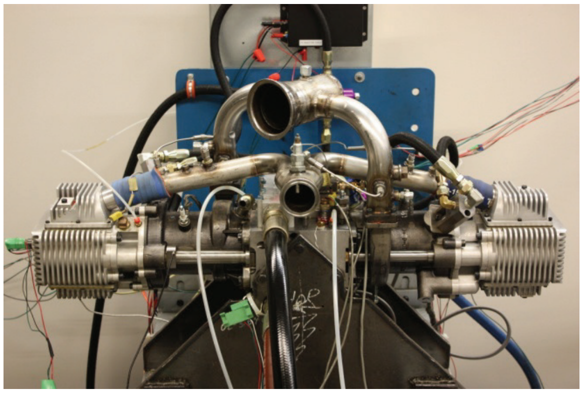
Open Accumulator Developed for Off-shore Wind Power Energy Storage – Because wind is intermittent and unpredictable, the ability to store wind power can significantly increase its usefulness. However, storing large amounts of energy (in the order of several MW-hrs) economically, efficiently and with the capability of high conversion rates (at several MWs) is a challenge. To answer this challenge, CCEFP researchers are developing a fluid power-based approach to wind energy storage with a four-year, $2 million research grant from the National Science Foundation (NSF) Engineering Frontiers for Research and Innovation (EFRI) program. The approach being pursued draws upon the open accumulator energy storage concept previously developed within the CCEFP.

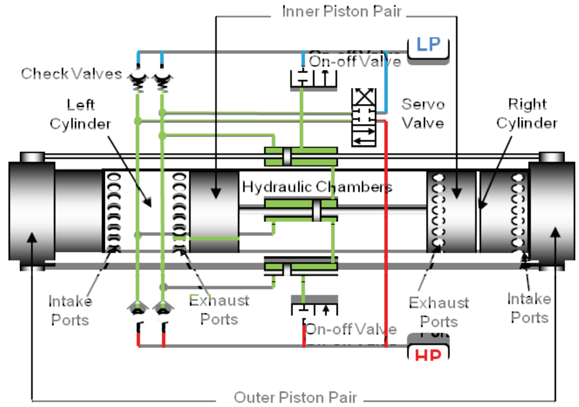
In the open accumulator, excess wind energy is stored as high-pressure compressed air. When power demand exceeds available wind power, compressed air is released to generate electricity. Power output from the wind turbine becomes more predictable, and energy that would otherwise be wasted is captured. Because energy storage occurs prior to generation of electricity, many electrical components can be downsized. By enhancing heat transfer inside the air compressor/expander, a near isothermal process is achieved thus attaining high efficiency. The open accumulator concept makes use of the high power capability of hydraulics (liquid fluid power) and the high energy density of pneumatics (gas fluid power) in a single architecture. This architecture allows the system to operate at nearly constant pressure, regardless of the energy content, so that efficiency and power capability can be maintained at all times.



Open accumulator energy storage concept enables energy storage at the turbine.

Free Piston Engine Pump – For mobile applications including both on-highway vehicles and mobile heavy equipment, fluid power is currently generated using a crankshaft-based internal combustion engine (ICE) coupled to a rotational hydraulic pump. The main drawbacks of this configuration are its relatively low efficiency and the complex design of both the ICE and the hydraulic pumping system due to the dynamic operating requirements. The free piston engine (FPE) is an alternative that offers the ultimate flexibility for variable compression ratio control by eliminating the crankshaft. The merit of this setup lies in its simple design with few moving parts, which results in a compact engine with low maintenance costs and reduced frictional losses. As shown in the photograph and schematic of the FPE hydraulic pump, linear hydraulic pumps are integrated into the engine block to produce hydraulic flow. This design eliminates the need for mechanical linkages between multiple engines and hence drastically increases the modularity of the system. The major technical barrier for the FPE is the large cycle-to-cycle variation, especially during transient operations. Therefore a robust and precise piston motion controller was designed to ensure stable engine operation. The controller acts as a virtual crankshaft that guides the piston to follow a reference trajectory via the hydraulic actuator (servo valve) by utilizing energy from the storage element. The advantage of the active motion controller lies in its ability to precisely track and shape the piston trajectory. Specifically, the reference trajectory of the virtual crankshaft can be altered digitally, in real-time, to achieve a wide range of piston motions, and thus obtain maximum engine efficiency with respect to various operating points. Experimental results have demonstrated the feasibility and promise of the technology. Engine power control will be combined with piston motion control in the future, to achieve a wider range of engine operation and higher engine efficiency.

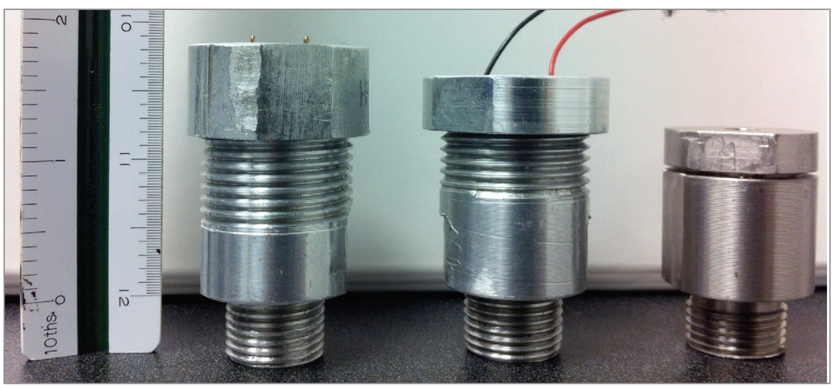




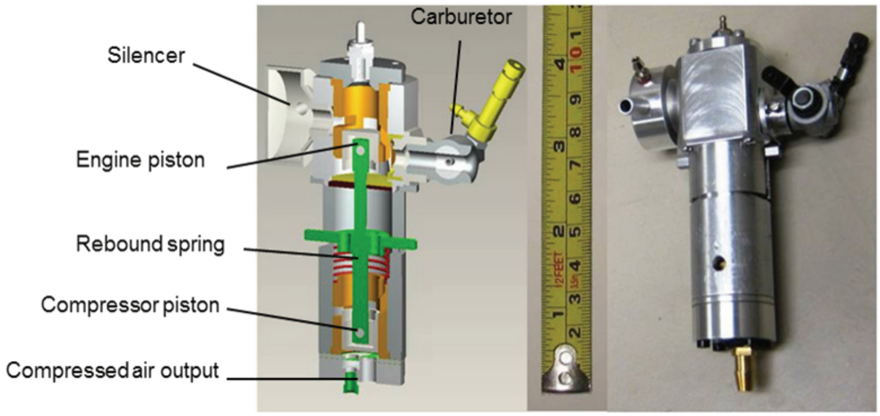
Free Piston Engine-Driven Hydraulic Pump.

Schematic of the Free Piston Engine Driven Hydraulic Pump.

Energy harvesting for self-powered sensors – The pressure ripple present within most hydraulic systems is commonly viewed as an annoyance or a detriment to system performance; however, the pressure ripple also represents a high-intensity power source for energy harvesting. In fact, the energy density is so high that material and system nonlinearities will come into play. In a hydraulic system, an energy harvesting technology might be integrated with health-monitoring sensors and eliminate the need for batteries or wires providing power to individual sensors; this would reduce maintenance contact and eliminate potential points of failure. This concept has been explored to develop models of energy harvesting devices exposed to hydraulic pressure ripple, accounting for the electrical-mechanical coupling between the hydraulic fluid and an electrical-conversion material within the device. Three generations of prototype devices, depicted in the photograph, have been developed and tested. The devices are being designed to withstand static pressures up to 5000 psi, and to generate 120 micro-watts power, or more; this is sufficient to power a typical wireless sensor node. The devices in the photograph have been designed to thread into a 3/4” port on a hydraulic system; future generations already under design will be much smaller and have the same power output.



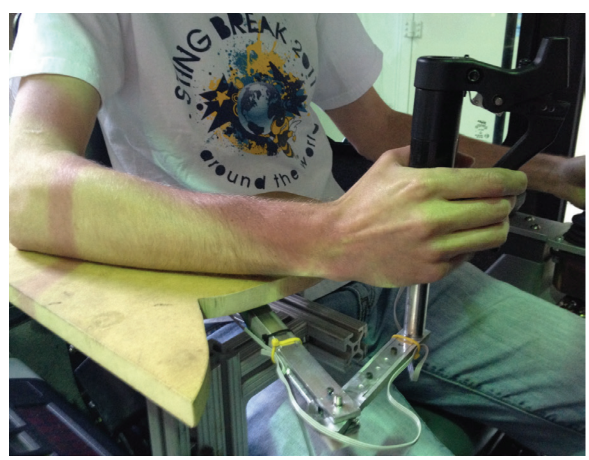
Miniature HCCI Free-Piston Engine Compressor – There is a need for untethered tiny power supplies that can power new portable tools and technologies that use pneumatic actuators. Because battery-powered electric air compressors are inefficient and the batteries are bulky, we have taken a different approach and have created the world’s smallest internal combustion engine air compressor that directly converts hydrocarbon fuel to compressed air. Our engine/compressor uses homogeneous charge compression ignition (HCCI) and a free-piston configuration to maximize efficiency and minimize space. A prototype engine, about 12 cm long, pressurized a 530 mL air tank to 6.7 bar (97 psi) in 38 seconds. The engine design was made possible by extensive mathematical modeling of its underlying physics.



Schematic and prototype of the Miniature HCCI Free-Piston Engine Compressor.

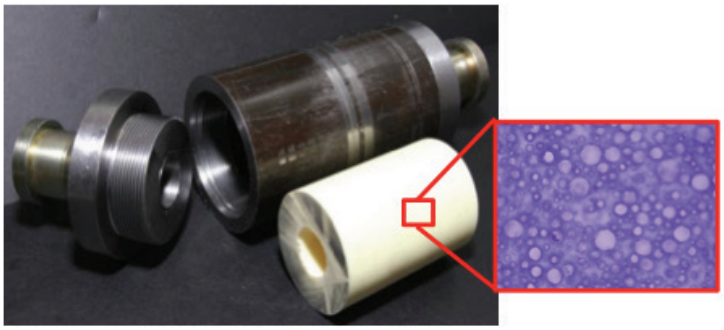
Improved User Interface for an Excavator – Excavators, backhoes and similar earthmoving equipment have been controlled for decades by joysticks with each joystick motion controlling one axis of motion. The current standard electronic joystick has two motions or degrees of freedom hence two functions are controlled with each joystick. However, the swing, arm, stick and bucket motions are not intuitively coupled to the joystick motions. "Natural" motions can be achieved with a single device that has been shown to remove 85% more soil than the two joystick interface when operated for short periods in tests on an excavator simulator. Unfortunately the arrangement tested initially was tiring to the operator because the weight of his arm did not have support during operation. Additionally, releasing the grip causes the device to drop under gravity. Consequently, a search for new configurations was launched with both natural correspondence and ergonomic arm support. A "kinematically similar" design as shown below, with motion in the vertical plane and with swing controlled by a separate joystick proved to move 50% more soil than two joysticks but failed to have ergonomic support. By changing the motion to a horizontal plane the learning time was not significantly affected and the operator's arm is now well supported. Tests concluded that on longer duration runs the operator did not fatigue and still moved 35% more soil than two joysticks.

A kinematically similar interface controls the vertical motion of an excavator arm. The cab swing rotation is still controlled by a joystick.



By changing the arm control to a horizontal motion the operator's arm is supported reducing fatigue. Minimal reduction of the "natural" correspondence of motions was observed.

Compact Hydraulic In-line Silencer – Hydraulic systems can be noisy, limiting their use in products where noise is a critical factor in consumer choice, such as passenger vehicles. Currently available noise control devices can be relatively bulky, and require more maintenance than is desirable. A novel hydraulic noise control device has been developed that employs an engineered compliant material lining. The device his fewer parts than current products, so it will be less costly to manufacture, and, its lining is maintenance-free. The device has been shown to have performance acceptable to industry in direct comparison to the available products. The material has uses beyond the silencer, and is being considered for compliance control in other devices.

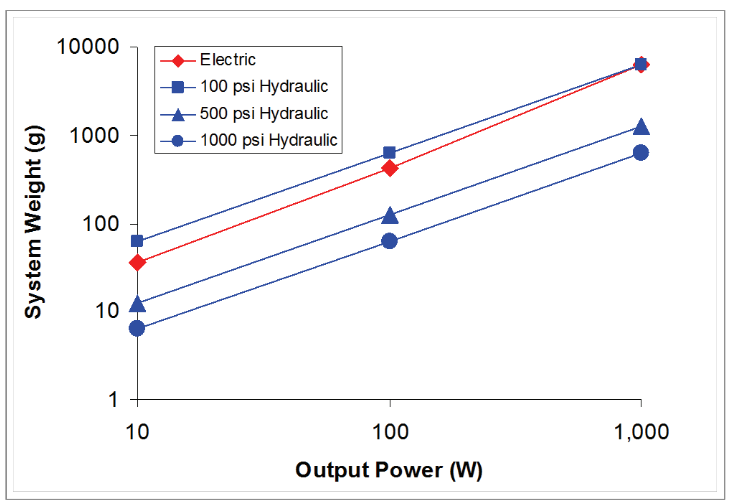


Advanced Strain Energy Accumulator – An accumulator is a hydraulic energy storage device found on most hydraulic equipment. It is typically a steel tank that can be filled with high pressure hydraulic fluid. Inside the tank is a sealed bag of gas, usually nitrogen. These accumulators can be used to store the energy usually wasted during vehicle braking in a regenerative braking (RB) equipped hydraulic hybrid vehicle. They can also be used to accumulate the energy output of the car's engine such that the engine can operate at its most fuel efficient point irrespective of what the driver is doing. The challenge in doing these energy savvy schemes is the high weight and maintenance requirements of the conventional gas-charged accumulator. By switching to a fundamentally different energy storage mechanism by using a highly deformable material, researchers are designing an advanced hydraulic accumulator device which will enable implementation of hydraulic RB and engine optimization on an average four-door sedan. This device will act similarly to a thick rubber balloon, slowing down the vehicle by forcing the wheels to pump a fluid inside of it and stretching it. When the vehicle needs to recover the energy, the fluid filled balloon will be allowed to deflate, channeling the high-pressure fluid to a hydraulic motor to propel the wheels. Materials testing data and device design have shown a potential increase in energy storage of at least two times that of conventional accumulators. This means the accumulator can be half the weight. Maintenance is expected to be less, and the non-exotic elastomeric material may offer lower costs. Should this mechanism prove effective, it has the potential to save billions of gallons of gasoline annually.

Fluid power surgery and rehabilitation via compact, integrated systems – The Milwaukee school of engineering developed and implemented an additively manufactured compliant pneumatically powered two-level Gough-Stewart platform for technological demonstration. The highlight of the demonstration is the proof of feasibility for manufacturing fluid power components and systems, simultaneously, where actuators, sensors, valves, and mechanisms are manufactured at the same time. Thus, requiring no-assembly after the additive manufacturing process is complete. The robot was recognized and awarded at the Additive Manufacturing User Group (AMUG) conference in the advanced concepts technical competition. Applications outside MRI guided robotic surgery were also recognized and being further pursued.

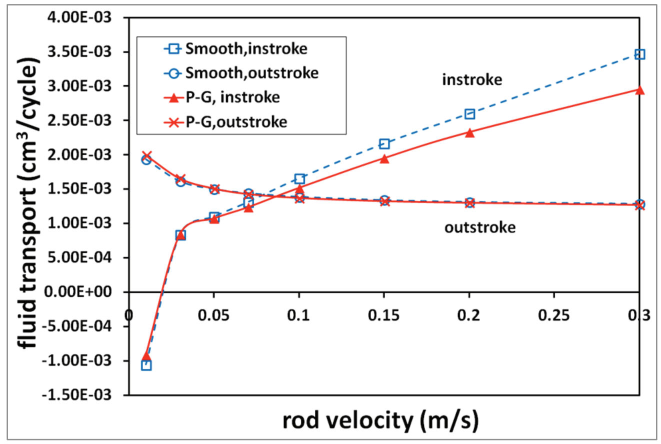
  

Publication of new ASTM Standards – CCEFP activities gave rise to the publication of two new ASTM Standard Practices; the "Standard Practice for Determining the Effect of Fluid Selection on Hydraulic System or Component Efficiency" and "The Standard Practice for Evaluating Compatibility of Mixtures of Hydraulic Fluids." The standard practice for fluid efficiency (ASTM D7721-11) was drafted by a working group that consisted of CCEFP members Afton Chemical, ExxonMobil, Evonik, MSOE, and Shell. The standard practice for evaluating the compatibility of fluid mixtures (ASTM D7752-11) was the product of five years of REU projects at MSOE. These standard methods facilitate evaluation of the fluids developed within the Center and provide a means of ensuring that energy efficient fluids are compatible with legacy lubricants.



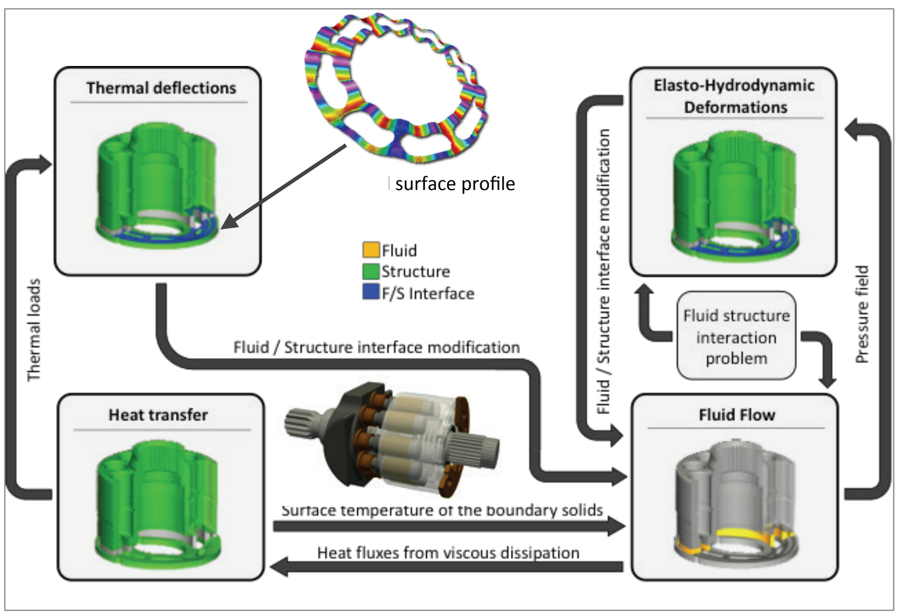
Principles of Miniature Hydraulics – For the same reason that large-scale hydraulics makes sense in mobile excavators, miniature hydraulics makes sense in wearable human assist machines, including powered orthotics. Hydraulic actuators at all scales have exceptional force to weight and power to weight ratios, so if you want to don a lightweight power suit, choose hydraulics. However, as hydraulic system become smaller, their efficiency drops because of the losses resulting from pushing oil at high speed through small passages. A goal of this CCEFP project was to use basic mathematical models to develop guidelines for engineers designing tiny hydraulic systems. One conclusion of a system level analysis is that to maximize the weight advantage of tiny hydraulics, one must use high pressure. This is shown in the plot below, which demonstrates that a 100 W hydraulic system running at 1,000 psi will be about 10 times lighter than the equivalent 100 W electric motor system. Another conclusion is that to maintain reasonable efficiency for systems in the range of 100 W, one should not use a cylinder bore size of less than 4 mm. A third conclusion is that for maximum efficiency in a tiny hydraulic cylinder, replace the traditional elastomer seal with a small gap seal. Application of these and other principles enables the development of novel technology using miniature hydraulics.

Effect of rod surface finish on seal behavior -- The elastomeric rod seal, which seals the gap between the protruding rod and the housing of a linear hydraulic actuator, is one of the most critical elements in a hydraulic system because it must prevent the leakage of hydraulic fluid directly into the environment. Numerical models of the rod seal have been developed by the CCEFP. They are capable of predicting the key seal performance characteristics; especially seal leakage and friction for a proposed design. These models simulate the physical processes governing the operation of the seal. They analyze the behavior of the hydraulic fluid in the interface between the seal and the rod, the contact between asperities on the seal and the rod, and deformation of the seal. The most recent model has shown how a plunge-ground (P-G) rod surface finish, the most common finish, degrades the seal performance by reducing the amount of fluid transported back into the hydraulic cylinder during the instroke and increasing the friction force on the rod, compared to a perfectly smooth rod.

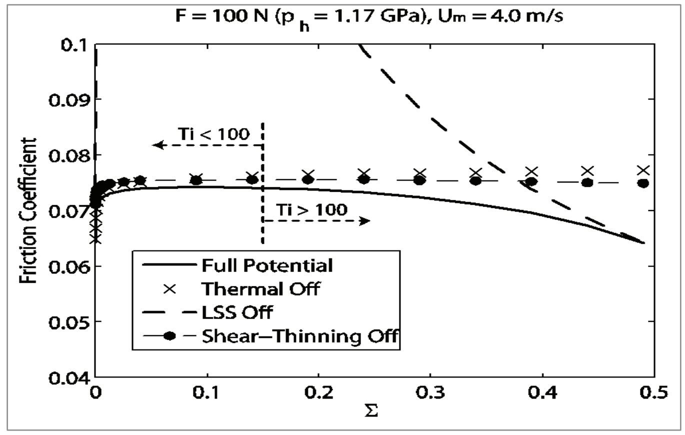


Pump research discloses the secret of the fluid film – Pump and motors form the heart of each fluid power system. Thin fluid films separate highly loaded movable pump and motor surfaces from each other and prevent wear and fatal machine failures. Despite many decades of worldwide intensive research experts and pump designers still lack a complete understanding of the complex physical behavior of these thin critical fluid films.

CCEFP researchers have combined experimental research with advanced multi-domain modeling to discover the secrets of the fluid film in those important pump and motor interfaces. A major breakthrough was the discovery of the fundamental importance of elasto-hydrodynamic and thermal effects on film generation and film stability. Recent research results have proven that these phenomena are responsible for substantial modification of the fluid film thickness and need to be considered in addition to micro and macro motion effects to correctly predict fluid film behavior. Researchers discovered that thermal expansion due to energy dissipation in the fluid film could introduce a wavy surface shape that helps to improve the load carrying ability of the fluid film. The inclusion of these additional effects however, increases enormously the complexity of the simulation model and has required tailoring numerical techniques and the modeling approach to the specific needs of each interface. The researchers created the world's first fully coupled fluid-structure interaction and multi-body dynamics simulation model that also considers thermal deformation of main interfaces and their influence on fluid film behavior. The model will be used to investigate the potential of novel material combinations and specially shaped surfaces to increase load-carrying ability of the film while simultaneously reducing energy dissipation.



Rheology of High Pressure Films – This project has been providing discoveries at an astonishing rate. As a result of these discoveries the field of elastohydrodynamic lubrication (EHL) has been transformed from one for which many explanations existed for the same phenomena to one in which precise predictions may be made from measurable properties of the liquid. The most challenging problem for EHL has been prediction of friction in full-film lubrication. For the first time, full-film friction has been accurately predicted from the properties of the liquid before the friction has been measured. A major step has been taken by characterizing the individual friction regimes in terms of dimensionless numbers, the Weissenberg number, Wi, the Nahme-Griffith number, Na, the limiting stress number, Li, and a new number that is a combination of the first three. In the figure, the decreasing friction with increased sliding begins when Ti=Na×Wi/Li>100.



EDUCATION HIGHLIGHTS

Innovative Research/Educational Outreach Program Leads to Breakthroughs in the Application of Hydraulic Hybrid Technology – A project to develop a hydraulic hybrid retrofit of a school bus, led by Dr. Michael Leamy at the Georgia Institute of Technology and his team of undergraduate and graduate engineering students, is yielding impressive results. Not only is their work realizing the potential of new fuel efficiencies for school buses everywhere, but it also provides a model for effectively engaging college and pre-college students in hands-on learning about eco-friendly fluid power.

Over the last two years, Dr. Leamy and his students have designed, built and have begun testing a hydraulic hybrid propulsion system retrofit and biofuel conversion of a public school bus donated by the Atlanta (GA) Public Schools. Much of the design and fabrication work to date has been carried out by undergraduates in Georgia Tech's mechanical engineering program; mechanical engineering graduate students have taken on leadership roles in the project. Their work, originally funded by grant from the Ford Motor Company Fund, has been supported by donations of components and guidance from engineers at Eaton Corporation, Evonik RohMax, Linde Corporation and Poclain Hydraulics, all industry affiliate members of the CCEFP. School buses are ideal for hydraulic hybrid power due to their large mass and typically stop-and-go drive cycles. The hydraulic retrofit captures braking energy using a pump-motor which first pumps hydraulic fluid into a high pressure accumulator (thereby storing energy), and then releases this energy to the drivetrain through the motoring capability of the pump-motor. A microcontroller-based system developed at Georgia Tech controls the mode of operation of the pump-motor, its displacement and associated valve components. Next steps involve incorporating complementary technologies including a clean start technology in which the diesel engine is shut down at bus stops and restarted using a hydraulic motor, saving children's lungs from harmful emissions. The hybrid retrofit has moved from the lab to the street, and tests are underway to verifying predicted gains of over 20% in fuel economy. Considering that more than 700,000 gallons of diesel fuel are used by school buses each year in Atlanta alone, a 20% gain in efficiency could significantly lower both fuel costs and emissions through widespread adoption.

The impact of the project's education and outreach efforts grows, too, as more undergraduates and graduate students get involved, some even taking on the role of teacher as they use the bus to show pre-college students not only how hydraulic systems operate but also why the work of engineers is so important.

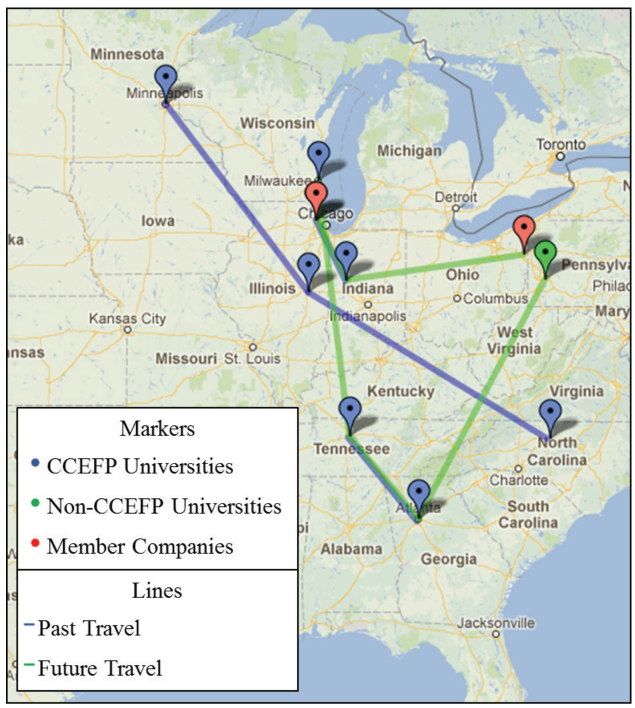
First graders at Mary Lin Elementary School (Atlanta, GA) paint the school bus, which is being converted by Georgia Tech researchers and students, into a hydraulic hybrid that runs on biofuel.

Innovative Engineers Identified as Top 100 Sustainable Ideas in the World – The CCEFP supported student organization Innovative Engineers has received international recognition for their wind energy project in Nicaragua. The group's work is included in Sustainia100, a guide to the 100 top global solutions in sustainability, unveiled in June 2012 at the Rio+20 United Nations Conference on Sustainable Development in Rio de Janeiro, Brazil.

For more than three years, Innovative Engineers have been using their technical education to power developing communities with wind energy. The engineering students designed, constructed and installed a wind turbine for the village of La Hermita, a half-hour ride up a dirt road from the city of Jinotega, Nicaragua. The turbine generates one kilowatt of electricity, enough to recharge the batteries used by La Hermita residents to power their lights at night and to operate their radios. Before the power from the turbine, villagers would travel to the nearest town by horseback to recharge batteries.

Innovative Engineers continues to teach the villagers about how the turbines work and how to repair them. An important component in the group's construction of the turbine was that the materials used could be easily obtainable in Nicaragua if the turbine needs repairs. Future plans include turbines for hydropower, refinement of turbine blade designs, design of robust wind-speed meters, and harnessing wave power.

CCEFP Student Leadership Council sponsors travel grants to promote a culture of collaboration -- The SLC Travel Grant Program aims to provide travel funds that allow students to travel to another project or industry location, making collaboration more accessible. This grant is managed by a student-organized call for proposals in which Center students can submit written proposals and the SLC is responsible for approving grants. This program has proven to be very popular with students and faculty. During Year 6 the SLC held two calls for proposals and funded travel for 7 students to other universities and industry partners. For Year 7 there are currently 5 approved student travel grants. There are plans to hold another call for proposals later in spring semester. Upon completion of the Year 7 travel, students from all member universities will have benefited from this program. The travel grant program has been a valuable tool for empowering students to pursue their own collaborations and strengthening communication within the CCEFP. Here is a quote from one participant in the travel grant program.



"Overall I believe the trip was very useful, I was better able to understand their work and its impact on my research. I also believe it fostered a closer relationship between the two research groups which will benefit these projects in the future." – Kathy Houle

In addition to providing an outstanding collaborative opportunity for CCEFP graduate students, this program has also been a good opportunity for SLC members to gain experience reviewing proposals and organizing a grant program.

Robotics Outreach Program to Underrepresented Students Now in Core School Curriculum – The purpose of the CCEFP gidakiimanaaniwigamig (Our Earth Lodge) odaangiina anaangoog (Shooting for the Stars) Robotics Program is to interest and prepare Native American youths for STEM careers. This effort supports the Center's goal of developing interest in science, technology, engineering and mathematics for students of all ages. As the successful FIRST Robotics program attests, robotics is an effective channel for introducing children to basic principles of engineering and related disciplines. The gidaa Robotics Program enables Native American students in and around Culver, Minnesota 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 through hands-on construction engineering. Gidaa Robotics teachers have drawn on lessons learned through FIRST and introduced K-12 robotics day and after-school curricula, into their local schools, using Lego Wedo-Webots and Lego Mindstorms robots and curriculum. In addition to the day and after-school program, the program's host school, South Ridge School, on the Fond du Lac Indian Reservation in Northern Minnesota, also participates in the Lawrence Technical University Robofest International Competition. This program engages students at the elementary, middle and high school levels. Due to the CCEFP initiative, this program has been growing for several years with new building infrastructure being designed around the robotics curriculum and robotics integrated into the core set of regularly offered courses. Over 60 students per year participate in the day and after-school program. The teachers responsible for promoting this effort held a local Teacher Training Robotics Workshop where several local interested teachers received training in Lego Mindstorms and were invited to participate in the local and regional Robofest Competition. In 2012, with CCEFP sponsorship, a secondary robotics program was launched at a neighboring facility, Cloquet Middle School.

CCEFP Hosts the Fluid Power Challenge; An 8th Grade Engineering Design Competition – 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 design concepts, physics concepts, develop mathematical thinking, problem solving; and participate in team-building through hands-on construction engineering.

The event comprises of two days. On the first day - Workshop Day - students are introduced to the basics of fluid power, get hands-on experience by building kits that use fluid power, and are introduced to the challenge they must solve. The students return to their schools to work in teams to design and build their fluid power device, along with keeping a portfolio to document their work. About a month later, the students return for the second day of the event - Challenge Day - to build their device and compete against the other teams in a timed competition. The goals of the Fluid Power Challenge are to: 1) actively engage students in learning the basics about fluid power; 2) give support and resources to teachers for science and technology curriculum; 3) create a fun learning environment for math and science; 4) encourage students to acquire a diversity of teamwork, communication, engineering, and problem-solving skills; 5) introduce eighth grade students to the fluid power industry; 6) help build a strong workforce for tomorrow.

Fluid Power Challenge corporate sponsors include Eaton Corporation, AirLogic, MICO, Inc., Tolomatic, Precision Associates, National Fluid Power Association (NFPA), University of Minnesota's College of Science and Engineering and the Center for Compact and Efficient Fluid Power (CCEFP). This program supports industry's desire for the preparation of a talented and diverse pool of future fluid power leaders in academia and industry.

Fluid Power Exhibits – The CCEFP exhibit program educates adults and families about the basics of fluid power and introduces them to some of the research carried out in the Center's programs. Prototypes and exhibits are developed and extensively field-tested at the Science Museum of Minnesota, an organization affiliated with the CCEFP. These will serve as models for dissemination to other science museums around the world. Two exhibits are shown here. The upper photo is a detail from Hydraulics Lab, which challenges visitors to create hydraulic circuits to ring a large bell and operate a carousel powered by a Pelton wheel. The lower photo shows a detail from an exhibit created in collaboration with a team of senior mechanical engineering students at the University of Minnesota. The exhibit shows how wind energy can be stored through compressing air into an open accumulator.

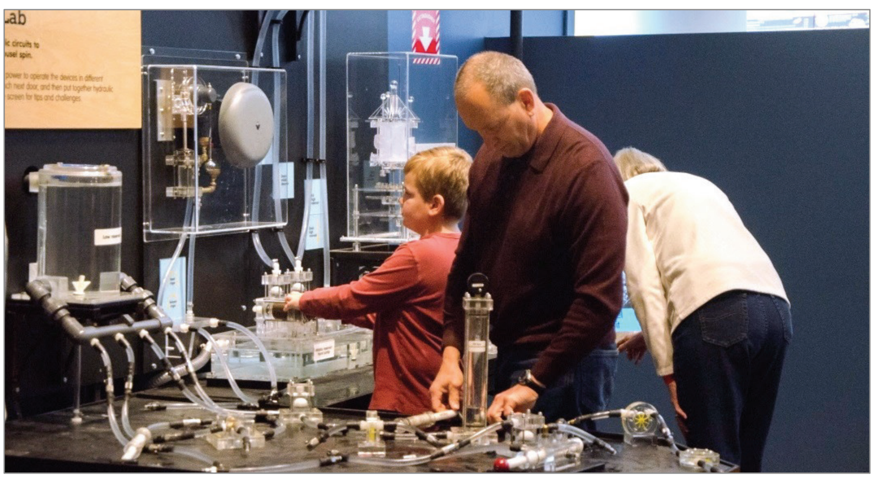


Photo credits: Science Museum of Minnesota

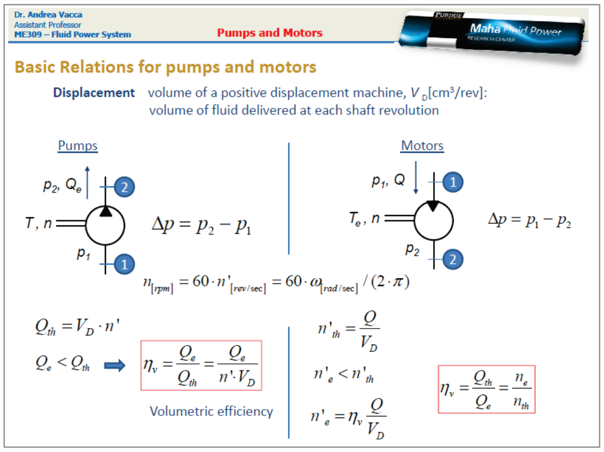
Parker Hannifin Chainless Challenge – The Chainless Challenge is a design competition for undergraduate university students. The focus is creating a human powered vehicle (typically bicycles or recumbent bikes) in which the mechanical chain drive is replaced with a hydraulic transmission. Elements of the competition include the design (creativity, functionality, presence of renewable energy systems), fabrication (quality, aesthetics), design process (design report, cost analysis) and a 3 event competition (efficiency, acceleration and distance events).

The Chainless Challenge is targeted at mechanical engineering capstone design project courses. It provides undergraduate students with a hands-on experience in fluid power design and development. Teams of 5 undergraduate students learn about fluid power, develop design specifications for the modifications to their bike, complete the design and install the modifications on the bike. The students then test and optimize the bike's performance in preparation for the national competition in April.

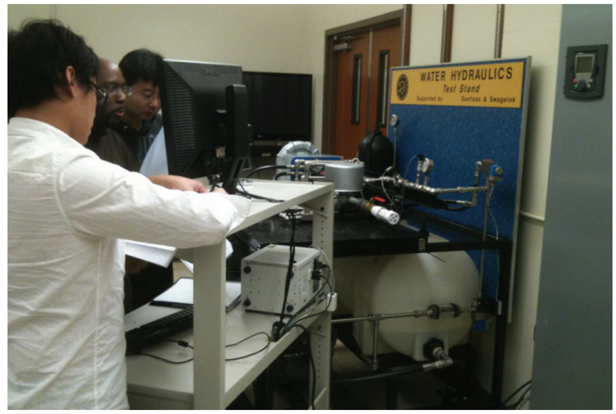
There were teams from 12 universities in the 2011-12 Chainless Challenge competition. CCEFP was represented by Illinois, Minnesota, Purdue and Illinois Tech (advised by Prof. Jose Garcia, a recent CCEFP PhD from Purdue). Minnesota took second place overall in the competition. In the 2012-2013 competition, CCEFP will be represented by teams from Illinois, MSOE, Minnesota and Purdue.

Power Mini-Books and Curriculum Modules – The CCEFP is leading the effort to develop new courses or make modifications to courses in CCEFP universities. This will help create a cadre of highly skilled students who will become future fluid power industry professionals and future engineering faculty. Advanced graduate courses with content based on CCEFP research provide a means for knowledge transfer of research results. New courses require significant faculty effort and must be consistent with teaching loads and departments' policies for new course adoption, which are outside the control of the Center. The CCEFP has successfully published one mini-book, titled "Fluid Power System Dynamics" by William Durfee and Zongxuan Sun. Recently, a set of mini-book homework problems were developed by CCEFP students. The homework problems will be integrated into the next edition of the mini-book, making it easier for instructors to use the book in existing courses. The CCEFP has plans for additional mini-books with homework problems in the future. The writing of "Fluid Mechanics" and "Hydraulic Fluids" is currently underway. The CCEFP has plans to continue to encourage the incorporation of fluid power content into existing courses and to develop new lecture and lab courses in fluid power. The Fluid Power OpenCourseWare -- an open source repository of fluid power lecture notes and materials -- makes it easier for instructors to include college-level fluid power material in their courses.

Integrating Fluid Power into Fluid Mechanics Courses – A method for integrating fluid power in the basic mechanical engineering curriculum has been successfully developed at Purdue University. This educational project, titled "Fluid Power in Fluid Mechanics" is now applied in the ME309 "Fluid Mechanics" class at Purdue. The course uses fluid power examples to illustrate the use of basic concepts such as the Bernoulli equation, the momentum equation, and many others. Students also learn about fluid power applications, such as the method and symbols used to represent circuits, the functionality of a hydrostatic transmission, and many others. The basic structure of the traditional fluid mechanics class is maintained without sacrificing other fundamental concepts of this discipline. The students are provided with accompanying material (figure below) and they have to perform a fluid power lab experience utilizing the Water Hydraulic Test Rig developed with the support of CCEFP and NFPA.

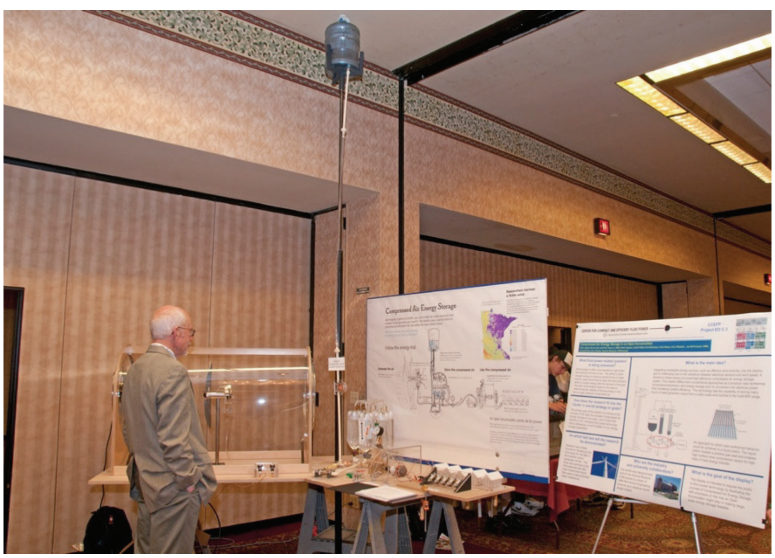


One of the 57 page document on Fluid Power basics prepared by Dr. Vacca as lecture notes.



Students performing data acquisition for the "pump characterization" lab experiment

Science Museum of Minnesota Sponsors Fluid Power Capstone Design Project – With support from CCEFP's Education and Outreach program, the Science Museum of Minnesota (SMM) has developed a set of interactive exhibits on fluid power fundamentals and applications. Through 2011, SMM had developed a cutaway (but functioning) axial piston pump, a hybrid hydraulic braking system (developed by capstone design students), a variable hydraulic transmission, a hydraulic experiment lab and a hydraulic assist device. SMM expanded its exhibits of fluid power technologies by sponsoring a mechanical engineering capstone design project at the University of Minnesota to design and build a working model of the open accumulator compressed air energy storage system.



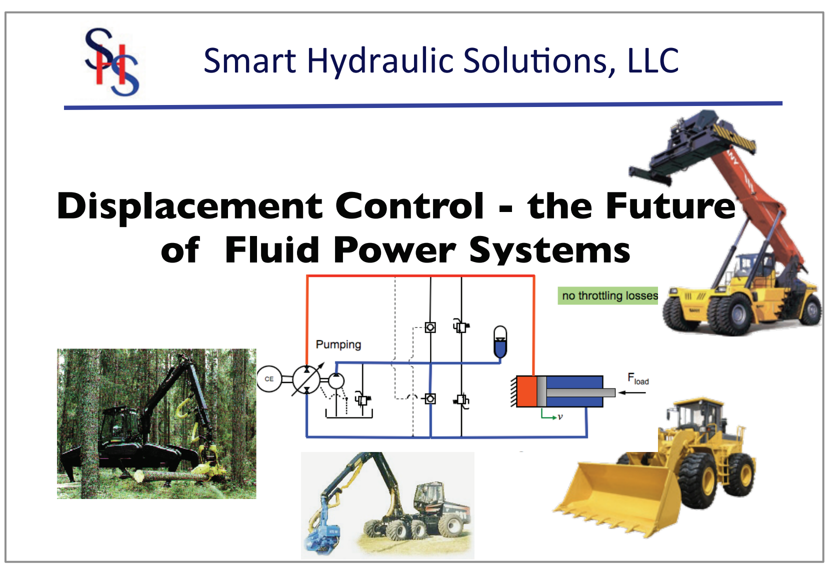
Capstone Design Project of the open accumulator compressed air energy storage system.

TECHNOLOGY TRANSFER HIGHLIGHTS

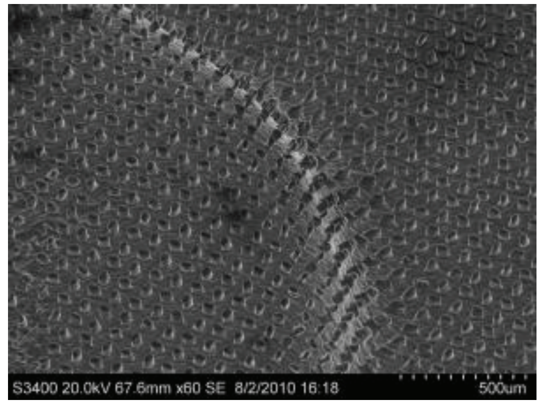
Parker Hannifin creates new division to commercialize hydraulic hybrid technologies – Researchers with the National Science Foundation Engineering Research Center for Compact and Efficient Fluid Power (CCEFP), led by Prof. Monika Ivantysynova of Purdue University, recently developed a novel and efficient hybrid system for commercial vehicles. Parker Hannifin Corporation funded the research and has commercialized the new hybrid system. While most hybrid systems today are hybrid electric, the research developed a hybrid *hydraulic* system featuring a hydromechanical transmission (HMT). The system is initially being targeted at medium duty package delivery vehicles, such as those used by UPS. In this type of vehicle, the hybrid HMT provides more than 50% percent better fuel economy than current package delivery vehicles.

The hybrid HMT holds the promise of reducing the payback period to one that is broadly acceptable to commercial vehicle end users, thus adding to their bottom line. Parker Hannifin created a new division, Hybrid Drive Systems (HDS), located in Columbus, Ohio to design and manufacture hydraulic hybrid systems. Thus, the technology was created in the US, is being built in the US and creates a new market segment for hydraulics all of which lead to good paying jobs in the US. In fact, HDS currently employs about 80 people including more than a dozen former CCEFP students. Finally, the significant fuel consumption savings from the hybrid HMT coupled with broad market acceptance will reduce greenhouse gas emissions and help lower US dependence on foreign oil.

Purdue researchers founded first CCEFP technology transfer company – The successful implementation and demonstration of energy saving displacement controlled (DC) actuation technology in the CCEFP mini-excavator test bed has led to an increased interest of fluid power industry and machine manufacturers in this technology world wide. To help companies to introduce this revolutionizing technology to the market, Purdue CCEFP researchers established Smart Hydraulic Solution LLC as a technology transfer company. One of the CCEFP young researchers became chief engineer at Smart Hydraulic Solutions after completion of his PhD study.

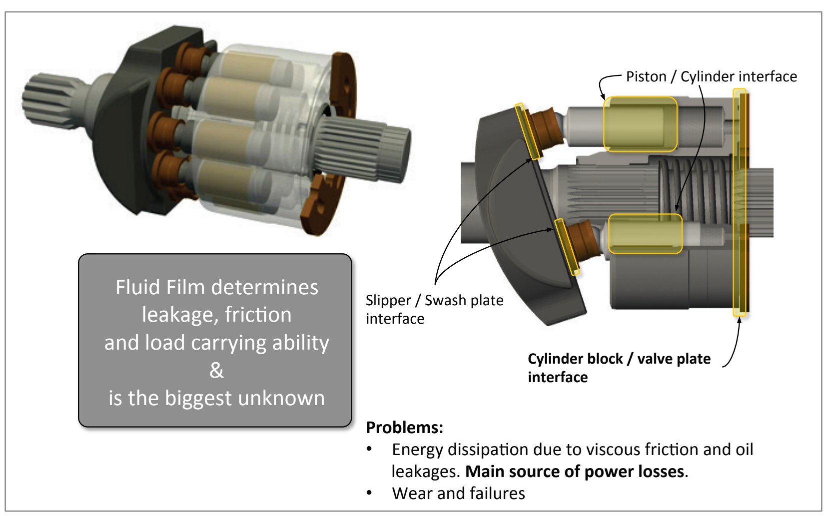


Friction Reducing Technology Commercialized by Hoowaki LLC – Researchers at the University of Illinois have developed a new technology for reducing friction on sliding surfaces. The CCEFP-sponsored research involves the design and fabrication of complex microstructures that can be integrated into shafts, rods, and other bearing surfaces. The microstructures cause friction reduction during the sliding or rotating of these surfaces, and this friction reduction in turn leads to improved fuel efficiency. In some applications, the microstructures also reduce the leakage of lubricant oil. The research was reported in an article titled, "Friction characteristics of microtextured surfaces under mixed and hydrodynamic lubrication," which was published in the journal *Tribology International* in 2012. The research project is led by Professors William King and Randy Ewoldt in the Department of Mechanical Science and Engineering at the University of Illinois. Collaborators include Professor Andreas Polycarpou, and graduate students Michael Johnston and Ashwin Ramesh.

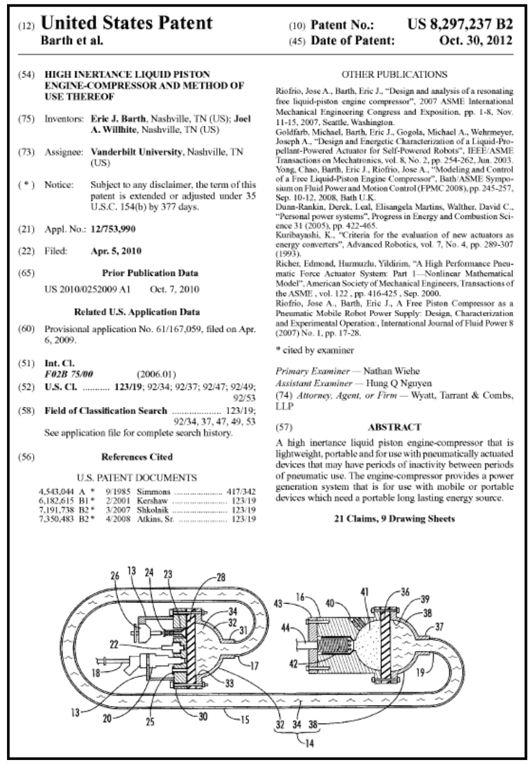


A South Carolina company, Hoowaki LLC, had adopted the University of Illinois microstructures technology, to reduce friction in applications such as biomedical devices. Friction reduction provides important benefits for biomedical products such as increased productivity of surgeons and increased patient comfort and safety. In the Hoowaki applications, the micro-machining is used to fabricate complex microstructures onto the surface of metal molding tools, the metal templates used to form plastic, glass, or metal parts in a manufacturing process. The microstructures on the molding tools are transferred onto the final part during injection molding, embossing, or rolling.

CCEFP industry members utilize advanced pump models – CCEFP researchers have achieved major breakthroughs in developing a better understanding of the fundamental physical behavior in critical tribological pump and motor interfaces. Recently researchers successfully extended the non-isothermal fluid structure interaction model previously developed for the piston/cylinder interface to the other two important interfaces of piston machines. The novel fully coupled fluid structure interaction model allows the prediction of fluid film behavior in all main pump interfaces. This information is crucial for the design of positive displacement machines, because the correct working process, the main achievable operating parameters, the energy dissipation and power loss are directly linked to the fluid film behavior. Recent discoveries together with the developed multi-physics model form the starting point for a new computational based design approach. These achievements have created major interest for pump and motor manufacturers. CCEFP research results have been used to develop a custom-made code to study and optimize current pumps and motors of CCEFP member companies and to utilize digital prototyping methods in future pump design.



High-Inertance Liquid-Piston Engine-Compressor Patent Issues – U.S. Patent # 8,297,237 was issued October 30, 2012 for the high-inertance liquid-piston engine-compressor – a project funded by the NSF Center for Compact and Efficient Fluid Power. The high inheritance free piston compressor represents a significant advancement in the field of compact pneumatic power. The system has an energy density that is up to four times higher than a battery-powered motor actuated system. This means that an untethered device such as a rescue crawler robot can be lighter and operate for longer periods of time. Replacing batteries with the engine/compressor and replacing motors with high power density pneumatic actuators results in a robot that is more powerful, runs longer and is ultimately more useful. This is achieved by using a novel “liquid piston” trapped between elastic diaphragms. The device exploits the fluid hammer effect of liquid in a long pipe – the same effect that bangs your water pipes inside your walls when you suddenly turn the faucet on or off.



(12) **United States Patent**
Barth et al.

(10) **Patent No.: US 8,297,237 B2**
(45) **Date of Patent: Oct. 30, 2012**

(54) **HIGH INERTANCE LIQUID PISTON ENGINE-COMPRESSOR AND METHOD OF USE THEREOF**

(75) Inventors: **Eric J. Barth**, Nashville, TN (US); **Joel A. Willhite**, Nashville, TN (US)

(73) Assignee: **Vanderbilt University**, Nashville, TN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 377 days.

(21) Appl. No.: **12/753,990**

(22) Filed: **Apr. 5, 2010**

(65) **Prior Publication Data**

US 2010/0252009 A1 Oct. 7, 2010

Related U.S. Application Data

(60) Provisional application No. 61/167,059, filed on Apr. 6, 2009.

(51) **Int. Cl.**
F02B 75/00 (2006.01)

(52) **U.S. Cl.** **123/19**; 92/34; 92/37; 92/47; 92/49; 92/53

(58) **Field of Classification Search** 123/19; 92/34, 37, 47, 49, 53
See application file for complete search history.

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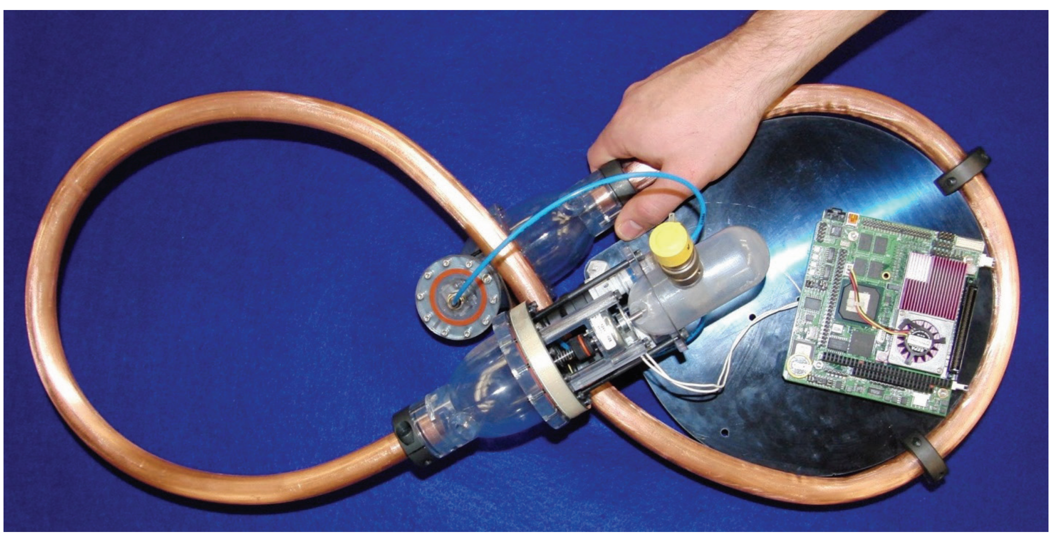
Primary Examiner — Nathan Wiehe
Assistant Examiner — Hung Q Nguyen
(74) *Attorney, Agent, or Firm* — Wyatt, Tarrant & Combs, LLP

(57) **ABSTRACT**

A high inertance liquid piston engine-compressor that is lightweight, portable and for use with pneumatically actuated devices that may have periods of inactivity between periods of pneumatic use. The engine-compressor provides a power generation system that is for use with mobile or portable devices which need a portable long lasting energy source.

21 Claims, 9 Drawing Sheets

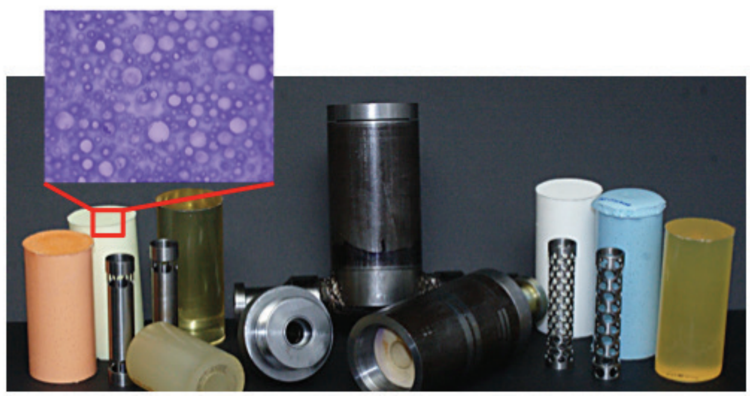
Because of its unique configuration and operation, the engine-compressor can turn on instantly to produce power when needed or stay idle indefinitely without wasting fuel. The unique figure-eight arrangement of the liquid piston self-balances the device to reduce vibrations and eliminate the need of opposing cylinders. The device features on-board electronics and seamless tubing to lower hydraulic friction and improve efficiency.



High Inertance Free Piston Engine-Compressor with Self Balancing Figure-8 Design

Open Accumulator Patent – A US patent the concerns a compressed air energy storage concept that combines the power density advantage of hydraulics, and energy density of pneumatics has recently been granted. The concept, called "open accumulator", was conceived within CCEFP that can increase the energy density of conventional hydraulic accumulator by an order of magnitude. This concept is finding use in methods to store large amount (MW-hrs) economically. Two companies that are developing utility scale compressed air energy storage systems have licensed the patent.

Eleven Invention Disclosures Generated by Project on Compact In-line Silencers – CCEFP researchers have created compact noise control devices for fluid hydraulic systems. The primary focus of the work was on an in-line silencer device, where a unique engineered compliant lining was a key component. Extensions of the underlying concepts and the engineered material ultimately generated eleven invention disclosures revolving around using the liner material for a variety of noise control devices, including the silencer. Beyond the silencer, the invention disclosures included the use of the material to generate micro-textured surfaces, noise filtering networks, and seven additional noise control devices including a water hammer arrester, low-noise hydraulic hose, and tuned resonator. Technology transfer and commercialization discussions are in progress with several of the industrial members of the CCEFP.

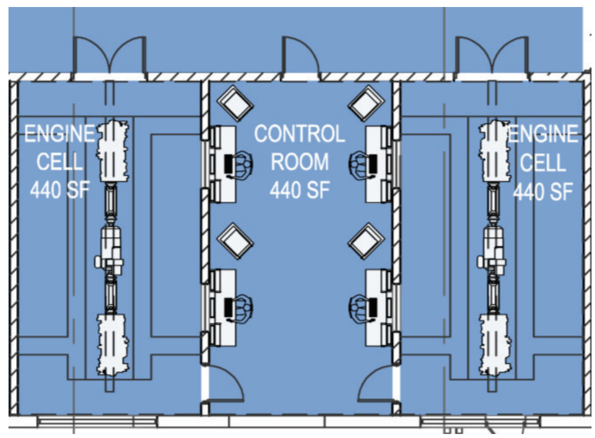


Orthosis patent applied for – A team of researchers that have been working on the pneumatic Portable Powered Ankle-Foot Orthosis (PPAFO) have applied for a US patent. The PPAFO is being developed in Testbed 6 as a platform for highlighting new opportunities for miniaturized fluid power systems used in untethered assistive devices that can work closely with or attached to humans. The PPAFO provides torque at the ankle to assist with dorsiflexion (toes-up) and plantarflexion (toes-down) of the foot. This small exoskeleton uses a series of sensors, valves and regulators to control the movement of a pneumatically-powered actuator at the ankle. The user can wear a portable power source (e.g., a small canister of compressed gas) to allow for unconstrained operation without the restriction of tethered power lines. The patent also includes a novel design for a compact rotary actuator that can be constructed using new additive manufacturing technology (i.e., rapid prototyping). The inventors include CCEFP students and faculty from the University of Illinois, University of Minnesota, Georgia Tech, and Milwaukee School of Engineering.

INFRASTRUCTURE HIGHLIGHTS

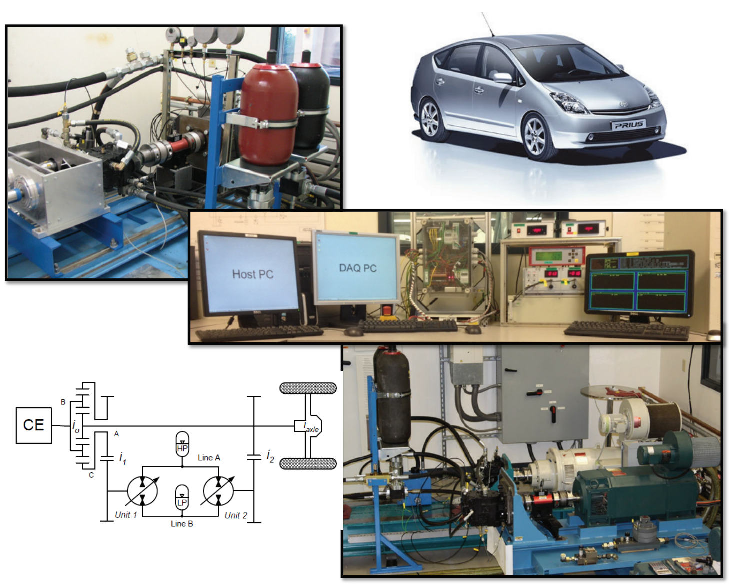
University of Minnesota Constructing $5M Powertrain Research Lab – Powertrain research activities at University of Minnesota will be relocating to a new laboratory in 2013. The University is investing $5M to build a state of the art 6,500 square foot facility that will have test cells that significantly increase the lab's research capabilities. The new lab will allow researchers to perform relevant experimental work to meet critical challenges in improving engine efficiency and emissions. It will allow for significant expansion in the research areas of alternative fuels for spark-ignited and compression ignition engines, combustion-generated particulate matter characterization, gaseous emissions, engine controls, sensor development and fundamental combustion studies. Some of the projects to be completed in the new laboratory in the short term include an experimental study of hydrous ethanol use in diesel engines, characterization of organic particulate emissions from diesel low temperature combustion and quantification of ash exhaust emissions originating from lubricating oils. CCEFP Sponsored studies of hydraulic powertrain and hydraulic hybrid vehicles will be a major activity of the lab. A future, second phase of the lab project has also been proposed to add an additional 6,000 square feet of laboratory space containing a chassis dynamometer along with two additional engine dynamometer test cells.

Elevation of lab exterior Figure



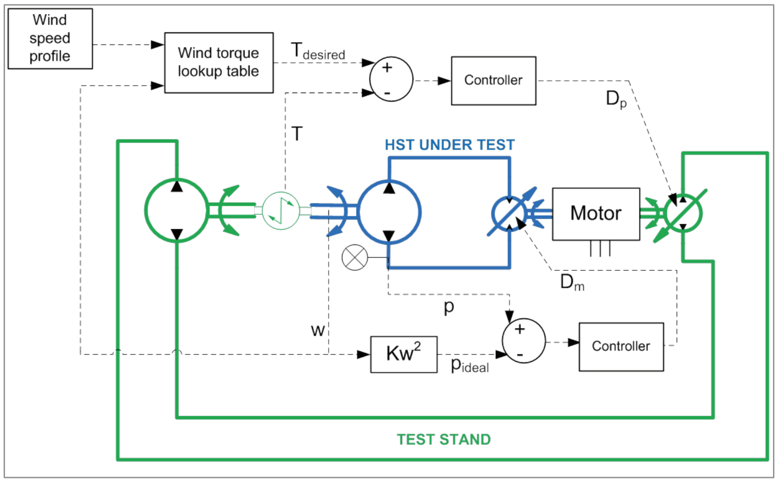
Floor plan of two dynamometer test cells

Powertrain research additions to Purdue's Maha lab – Research of Purdue's Maha team centers on investigating the feasibility and performance of alternative drive line technologies for different types of vehicles. The aim is to develop system concepts for minimizing fuel consumption and exhaust emissions without limiting the vehicle's driving power. A special software tool called PSDD (Power Split Drive Design) has been developed to support virtual prototyping of power split drives, multi-motor hydrostatic transmissions and hydraulic hybrid power train configurations. The research activities are supported by performance measurements using pump and motor test rigs and two hardware-in-the-loop power train test rigs. A 180 kW power train test rig uses hydrostatic dynamometers. A second powertrain test rig utilizing electric dynamometers has been built recently to enlarge the testing

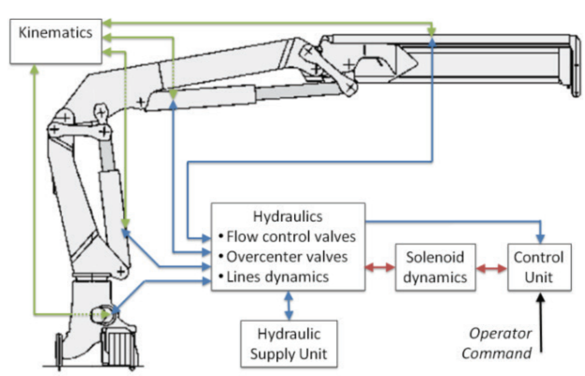


capacity of the Maha lab. In a recent study Maha researchers demonstrated that the optimally sized and controlled hydraulic hybrid powertrain for the Prius is able to obtain a fuel economy of 65.1 mpg, up from the EPA's published value of 48 mpg for the 2004 electric Prius on which the study was based. The power split based hydraulic hybrid system for the Prius has been implemented and tested on one of the Maha powertrain test rigs. The other power train test rig is currently used to study advanced powertrain control concepts and the behavior of novel energy efficient fluids under realistic drive cycles.

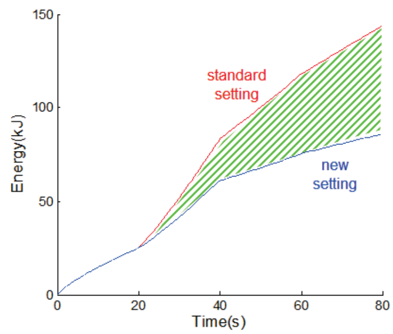
Hydrostatic Transmission Test Stand for Wind Energy Research – The University of Minnesota is constructing a 55 kW laboratory scale test stand for research on wind energy. The test stand will be regenerative so its energy consumption will be reduced by roughly 80%. The primary objective of the research will be to identify and overcome the challenges of replacing the fixed ratio gear boxes currently used in utility scale wind turbines with a hydrostatic transmission (HST). The gearbox is among the least reliable components in a wind turbine. The HST is a proven, robust system that functions as a continuously variable transmission (CVT). The CVT functionality allows the use of an inexpensive generator with minimal power electronics because the HST can provide a constant rotational speed to the generator regardless of the rotating speed of the turbine blades. Much of the initial research will be to investigate novel control schemes to leverage the unique attributes of an HST to minimize the cost of electricity. The test stand is anticipated to be operational in the summer of 2013.



Hydraulic Crane Test Stand for Research on Valve Controlled Systems -- In summer 2011, a mid-size (max elevation 22 m) hydraulic crane for truck applications was installed at the Maha Fluid Power Research Center of Purdue University. Installed with the contribution of Parker Hannifin (Mobile System Group) and of National Fluid Power Association, the crane will serve studies on valve controlled hydraulic circuits. The focus of the research activities for 2012 will be the study of novel control methods to reduce system oscillations and improve energy efficiency. Mobile applications such as hydraulic cranes are subject to high energy dissipations purposely introduced by valves to stabilize the system and obtain satisfactory controllability. In some applications, up to 60% of the total energy consumed by the machine



is dissipated to achieve satisfactory operation of the unit. The efficacy of novel adaptive control strategies generally applicable to any mobile machine based on flow control valves will be experimentally proved on the new experimental test stand installed at Purdue University. The test stand will also serve educational purposes, permitting the analysis of the features of operation of several hydraulic valves (including flow control and counterbalance valves), programmable electronic control unit, and data acquisition systems.

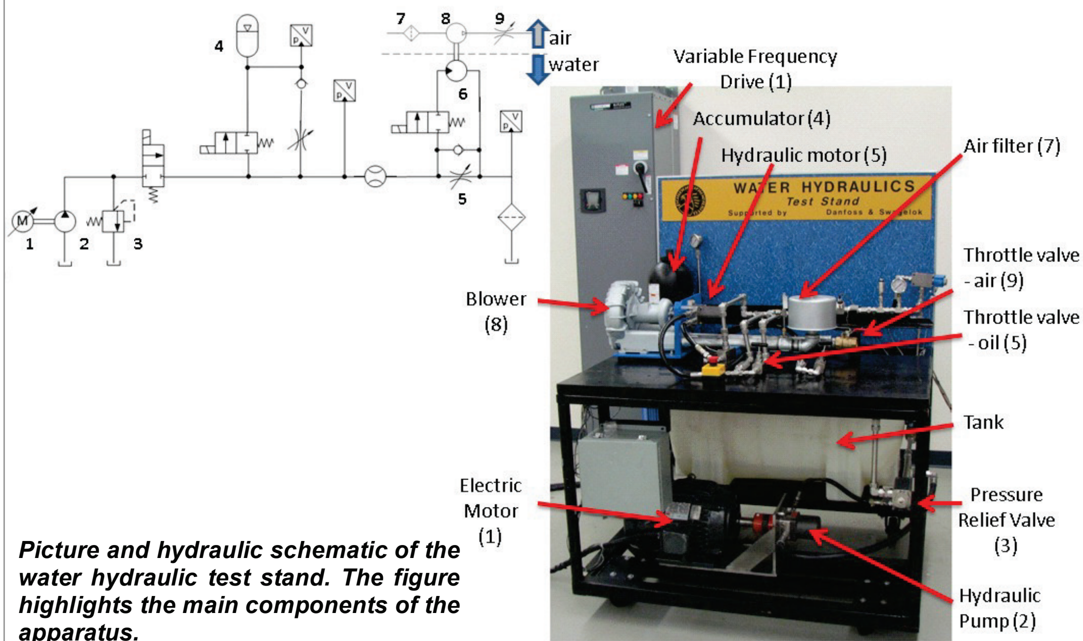


The hydraulic crane installed at Maha to test novel control strategies in valve controlled hydraulic mobile applications (top left); simplified diagram of the multi-domain, non linear, simulation model for the system and the controller (top right); measured energy consumption over a lifting/lowering cycle for different configurations of the counterbalance valves (left).

New Water Hydraulics Lab at Purdue – A high pressure (p_{max}=140 bar) test stand, using tap water as the working fluid, has been developed within the *Fluid Power in Fluid Mechanics* project supported by the CCEFP and the National Fluid Power Association (NFPA). Installed at the Fluid Mechanics Lab in Purdue's Mechanical Engineering Department, the test stand enables undergraduate students to better understand fluid power principles within the context of their fluid mechanics courses (see photo below). The stand is complemented by a mini-book containing basic examples of hydraulic systems. While the mini-book provides the theoretical understanding of the operation of fluid power components according to the basic principles of fluid mechanics, the rig offers:

- characterization of pumps and motors,
- study of the operation of pressure relief valves and variable throttle orifices,
- analysis of the operation of an open circuit hydrostatic transmission,
- study of a hydraulic air blower-drive system,
- energy storage in hydraulic accumulators and energy recovery in hydrostatic transmissions.

During fall 2011, 218 junior engineering students successfully operated the water hydraulic test stand, documenting their work in conventional lab report formats. Given the success of its first application, the teaching methodology developed within the *Fluid Power in Fluid Mechanics* project will become a standard for introducing fluid power concepts to Purdue's mechanical engineering students. Additional students will benefit from this project, too. Plans call for *Fluid Power in Fluid Mechanics* to be presented as a teaching model to CCEFP participating universities and to academic institutions outside CCEFP.



Picture and hydraulic schematic of the water hydraulic test stand. The figure highlights the main components of the apparatus.

Novel Interface between Engineering Research Centers, Industry and the National GEM Consortium – 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 specialized membership model includes cooperation between the ERC and the industry member, who are both academic and corporate members of the National GEM Consortium. The ERC provides the initial funds to recruit and sponsor a GEM Fellow; the research institution provides an additional supplement to sufficiently support the student in full, and the industry member provides the recommended summer graduate internships. The GEM Fellow receives over $150,000 in the form of academic student stipend, tuition remission and summer intern salary. Often, the industry member hires the student as an employee following the program. This rich collaboration offers nothing but benefits to the GEM Fellow, the ERC, the Industry member and the GEM Consortium.

CCEFP has just initiated it's first partnership in this program. Caterpillar, who is a corporate member of the National GEM Consortium, has agreed to co-sponsor a CCEFP-CAT GEM Fellow for the 2013-2014 academic year. A faculty member at Georgia Institute of Technology will be advising the GEM Fellow on CCEFP fluid power research.

CCEFP Provides Supplemental Funding to Support Underrepresented Undergraduate and Graduate Students in Engineering – The CCEFP is committed to promoting the increased participation, recruitment and retention of diverse undergraduate and undergraduate students in engineering. The CCEFP has launched two initiatives under the Education and Outreach Program that closely mimic the former NSF Graduate Research Diversity Supplement (GRDS) opportunity. Recognizing that funding and student support is often the lynchpin in identifying and recruiting a highly qualified student, the CCEFP earmarked funds to offer opportunities to underrepresented students in engineering. The CCEFP Undergraduate Research Diversity Supplement (URDS) and the CCEFP Graduate Research Diversity Supplement (CCEFP) have both short and long-term goals. They are: to provide CCEFP faculty with the means to involve additional undergraduate students on CCEFP research projects, 2) to identify an underrepresented undergraduate and 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 environment, 4) to further provide exposure to fluid power technology to a diverse audience, and 5) to answer the country's need for greater retention of underrepresented students in engineering.

The CCEFP has been "topping up" the NSF Graduate Research Diversity Supplement (GRDS) for the past several years. The supplement has provided opportunity for five women, four Caucasian and one African-American, to matriculate through the CCEFP and either earn their Masters Degree or continue pursuing their PhD in an area of fluid power. The CCEFP added $50,000 to the grant received from NSF, to ensure that the students would have sufficient funds. Four undergraduate students have also received supplements to support research laboratory experience during the academic year. Coincidently, as with the GRDS, each awardee has been female, two Caucasian, one Hispanic and one African-American student have had the opportunity to work in CCEFP research facilities. Their path through their undergraduate education continues, and it is the CCEFP's goal that each of these awardees would consider graduate study in fluid power.

Collaborations between GT and NCAT on the CCEFP Research – In the past seven years, researchers from North Carolina A&T State University (NCAT) and Georgia Institute of Technology (GT) have been collaborating on research in both excavator test bed(TB1) and rescue crawler test bed(TB4). Researchers from NCAT bring the human factors expertise while their counterparts from GT are experts in fluid power and system dynamics. With the proposed new fluid power technology, there come opportunities for more efficient and effective user interface for those fluid power systems. A user centered design approach which emphasis on user needs has been adopted in this process. Meanwhile, human performance modeling was used to study operator performance in those fluid power systems. Over the years, researchers from the two universities have collaborated on Project 3A1 and Project 3A3.

Over the years, faculty members and graduate students from both universities have visited each other's campus and collaborated on research. The following are some major collaboration activities between NCAT and GT:

- Faculty visit to each campus (Wayne Book from GT, and Steven Jiang, Eui Park, and Silvanus Udoka from NCAT) many times.
- Graduate students from NCA&T (Benjamin Osafo-Yeah, Antonio Lee, and Ritson Delpish) worked in the lab at GT to conduct task analysis for the excavator test bed an the rescue crawler test bed and developed collaboration plans. Especially, Antonio Lee spent 6 weeks in the lab at GT working with GT graduate students to develop future collaboration.
- Graduate student, Mark Elton from GT, worked on excavator simulator in the lab at NCAT.
- Research teams from both universities held teleconferences many times to discuss research progresses.
- NCAT Graduate student, Benjamin Osafo-Yeboah, along with GT graduate student, Mark Elton, conducted a usability study on haptic-controlled excavator in the lab at GT. The Institute Review Board (IRB) from both universities approved this research. This collaboration has resulted in a proceedings paper that was published in the 2010 Industrial Engineering Research Conference.
- Steven Jiang serves on the thesis committee for Heather Humphreys of GT.
- Wayne Book provided much assistance in Benjamin Osafo-Yeboah's dissertation research.

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2. STRATEGIC RESEARCH PLAN AND OVERALL RESEARCH PROGRAM

Fluid power is the use of fluids 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 and high power density that can be more widely exploited. 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 bar (3000 psi), such a hydraulic motor will have twelve times the torque of the same sized electric motor. If the shaft speeds are the same, the power ratio will also be twelve, which is why fluid power systems can have a much higher power density than 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 possible technology for high-power, high- force applications, fluid power is essential for large equipment. The use of fluid power is so prevalent that any improvement 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.

In spite of its advantages, fluid power has been confined to applications where the required power density precludes other solutions. This is because fluid power has several 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 their lives. Current fluid bearing technology has energy losses that limit efficiency of pumps, motors and actuators. Current fluid power control relies on the throttling action of metering valves, causing large amounts of energy to be wasted. Excessive weight and bulkiness also lead to increased energy consumption and prevent applications where smaller, untethered or portable devices are required. Despite the high power density of fluid power actuators, pneumatic and hydraulic power units are bulky. The needed compact energy sources and compact energy storages are not available. Noise and vibration are annoying and have adverse effects on human health and machine reliability, and awkward user interfaces require increased training and task completion time, prevent convenient use and compromise safety. Awkward machine interfaces that slow operations also result in increased energy consumption. The most common working fluids are toxic, and benign working fluids compromise performance and cause corrosion of components. For this reason, fluid power components must be leak-free to prevent environmental damage. Contamination is another barrier to reliable and trouble-free operation, and new approaches are needed to minimize its impact.

State of the Art for Fluid Power

The commercial success of a technology can be traced to 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 well each of the technologies fares.

Mobile Off-Road Equipment

Hydraulics is the dominant power transmission choice for mobile off-road equipment. 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 other 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 operating costs. This requirement can be met 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 provide a differentiation for equipment OEMs, but 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 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 industrial pneumatics

Factories using pneumatics require a supply of compressed air that is stored in a tank and supplied by an electrically powered compressor. 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 the scale of these devices is so small, 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 hydraulic 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. But 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 unique advantages over electric hybrids in 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 hydraulics usage 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.

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 desire shared by CCEFP and its industry members to leverage fluid power's strengths and overcome key weaknesses 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 ubiquity.

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

- Test Bed α - Wind Power Generation (mid-wind and utility scale wind turbine drivetrains, 100 kW - 10 MW)
- 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.

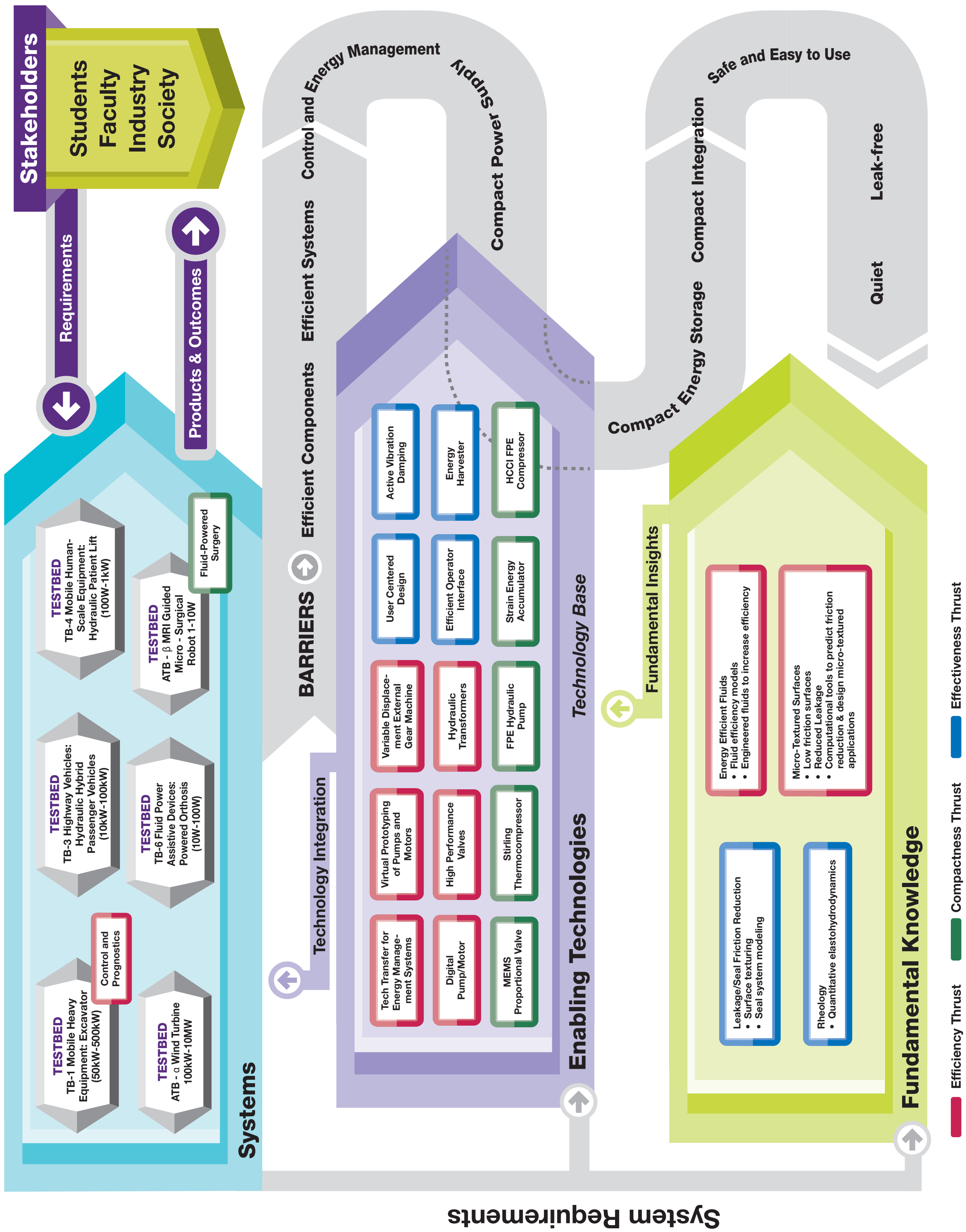
The CCEFP strategic research plan is designed to overcome the technical barriers to achieving the Center's vision. To overcome the barrier of inefficiency, the Center is developing new components and systems and novel control methods to improve system performance and reduce energy consumption. The approaches 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. CCEFP will integrate its insights and findings into its strategic research plan during 2013.

The 3-plane chart appears on the following page.


Stakeholders
Students
Faculty
Industry
Society
Requirements
Products & Outcomes
Systems
TESTBED TB-1 Mobile Heavy Equipment: Excavator (50kW-500kW)
TESTBED ATB - α Wind Turbine 100kW-10MW
Control and Prognostics
TESTBED TB-3 Highway Vehicles: Hydraulic Hybrid Passenger Vehicles (10kW-100kW)
TESTBED TB-6 Fluid Power Assistive Devices: Powered Orthosis (10W-100W)
TESTBED TB-4 Mobile Human-Scale Equipment: Hydraulic Patient Lift (100W-1kW)
TESTBED ATB - β MRI Guided Micro - Surgical Robot 1-10W
Fluid-Powered Surgery
BARRIERS
Efficient Components
Efficient Systems
Control and Energy Management
Compact Power Supply
Compact Energy Storage
Compact Integration
Safe and Easy to Use
Quiet
Leak-free
Technology Integration
Enabling Technologies
Technology Base
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
Efficient Operator Interface
Energy Harvester
MEMS Proportional Valve
Stirling Thermocompressor
FPE Hydraulic Pump
Strain Energy Accumulator
HCCI FPE Compressor
Fundamental Insights
Fundamental Knowledge
Leakage/Seal Friction Reduction
• Surface texturing
• Seal system modeling
Rheology
• Quantitative elastohydrodynamics
Energy Efficient Fluids
• Fluid efficiency models
• Engineered fluids to increase efficiency
Micro-Textured Surfaces
• Low friction surfaces
• Reduced Leakage
• Computational tools to predict friction reduction & design micro-textured applications
Efficiency Thrust
Compactness Thrust
Effectiveness Thrust
System Requirements

Translational Research

The CCEFP's membership agreement does not include a potential for a revenue stream from licenses issued for Center-funded inventions. Any licensing revenues flow to the inventing university. 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.

An overview of Center translational research projects that are judged to be at TRL 4 and above is provided below. Additional details on the projects funded in Year 6 and/or 7 can be found in Volume II of the CCEFP 7th annual report.

<u>Multi Actuator Hydraulic Hybrid Machine Systems (Project 1A.2)</u>

This project created displacement controlled hydraulic systems. It has been demonstrated on Test Bed 1 and is estimated to be at TRL 4. The inventors have formed a startup company to facilitate the transfer of the technology to industry.

<u>New material combinations/surface shapes for the main tribo-systems of piston machines (Project 1B.1)</u>

This project 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" also estimated to be at TRL 4-5. Technology has been demonstrated in a pump and has been licensed to a CCEFP industry member.

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

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 any CCEFP industry members. The technology has been demonstrated in a research lab environment and is estimated to be at TRL 4. One industry member that joined after the patent application was filed has expressed an interest in possibly licensing the technology.

<u>Free Piston Engine Compressor (Project 2B.1)</u>

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 has been demonstrated in a research lab environment and is estimated to be at TRL 4.

<u>Compact Energy Storage using Open Accumulator (Project 2C.1)</u>

This project is researching storing 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. 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.

<u>Advanced Strain Energy Accumulator (Project 2C.2)</u>

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 has been 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.

Pressure Ripple Energy Harvester (Project 3E.1)

This is a new project that started in June 2012. Its goal is to harvest energy from the flow ripple in a fluid power flow 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.

In addition to this hardware and control focused research, Center researchers have developed modeling and simulation tools for hydraulic hybrid energy management, seal design and fluid film properties that our industry members are leveraging to make their products and systems better.

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Table 2: Estimated Budgets by Research Thrust [1]

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	University and Department	Current Year Budget	Estimated Next Year Budget
1: Efficiency (Monika M. Ivantysynova)	1A.1: Technology Transfer Process for Energy Management Systems (Center Controlled Project)	NSF ERC Program	Andrew G. Alleyne	Kim A. Stelson	University of Minnesota-Mechanical Engineering	$69,003	$2,811,817
	1A.2: Control and Prognostics for Hybrid Displacement Control Systems (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova			$130,200	
	1B.1: Next Steps towards Virtual Prototyping of Pumps and Motors (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova			$130,200	
	1D: Microtextured Surfaces for Low Friction / Leakage (Center Controlled Project)	NSF ERC Program	William King	Randy H. Ewoldt	University of Illinois at Urbana-Champaign-Department of Mechanical Science and Engineering	$89,517	
	1E.3: Actively Controlled Digital Pump Motor (Center Controlled Project)	NSF ERC Program	John H. Lumkes	Monika M. Ivantysynova	Purdue University	$74,230	
	1E.5: System Configuration & Control Using Hydraulic Transformers (Center Controlled Project)	NSF ERC Program	Perry Y. Li			$94,615	
	1E.6:High Performance Valves Enabled by Kinetic Energy (Center Controlled Project)	NSF ERC Program	John H. Lumkes	Perry Y. Li	University of Minnesota	$65,483	
	1F.1: Variable Displacement External Gear Machine (Center Controlled Project)	NSF ERC Program	Andrea Vacca			$99,341	
	1G.1: Energy Efficient Fluids (Center Controlled Project)	NSF ERC Program	Paul W. Michael			$109,393	
	1J.1: Hydraulic transmissions for wind energy (Center Controlled Project)	NSF ERC Program	Kim A. Stelson	Brad Bohlmann	University of Minnesota-Mechanical Engineering	$37,000	
	Advanced Energy Saving Hydraulic System Architecture for a Wheel Loader (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$183,041	
	Advances in External Gear Machines Modeling (Associated Project)	Casappa S.p.A.	Andrea Vacca			$37,583	
	Advances in modeling external spur gear machines and development of innovative solutions (Associated Project)	Casappa S.p.A.	Andrea Vacca			$55,417	
	Design of low noise emission internal gear machines (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Andrea Vacca			$100,000	
	Design of positive displacement machines for SCR automotive applications (Associated Project)		Andrea Vacca			$87,000	
	Development of a Gasoline Engine Driven Ultra High Pressure Hydraulic Pump (Associated Project)		Andrea Vacca			$6,250	
	Effect Of Various Oils On The Efficiency Of A Series Hydraulic Hybrid Transmission (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$28,887	
	EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage (Associated Project - NSF)		Perry Y. Li	James D. Van de Ven	University of Minnesota	$333,500	
	Energy Efficienct Fluid Research (A) (Associated Project)		Paul W. Michael			$52,105	
	Energy Efficienct Fluid Research (B) (Associated Project)		Paul W. Michael			$126,316	
	Energy Saving Hydraulic System Architecture Utilizing Displacement Control (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$11,320	

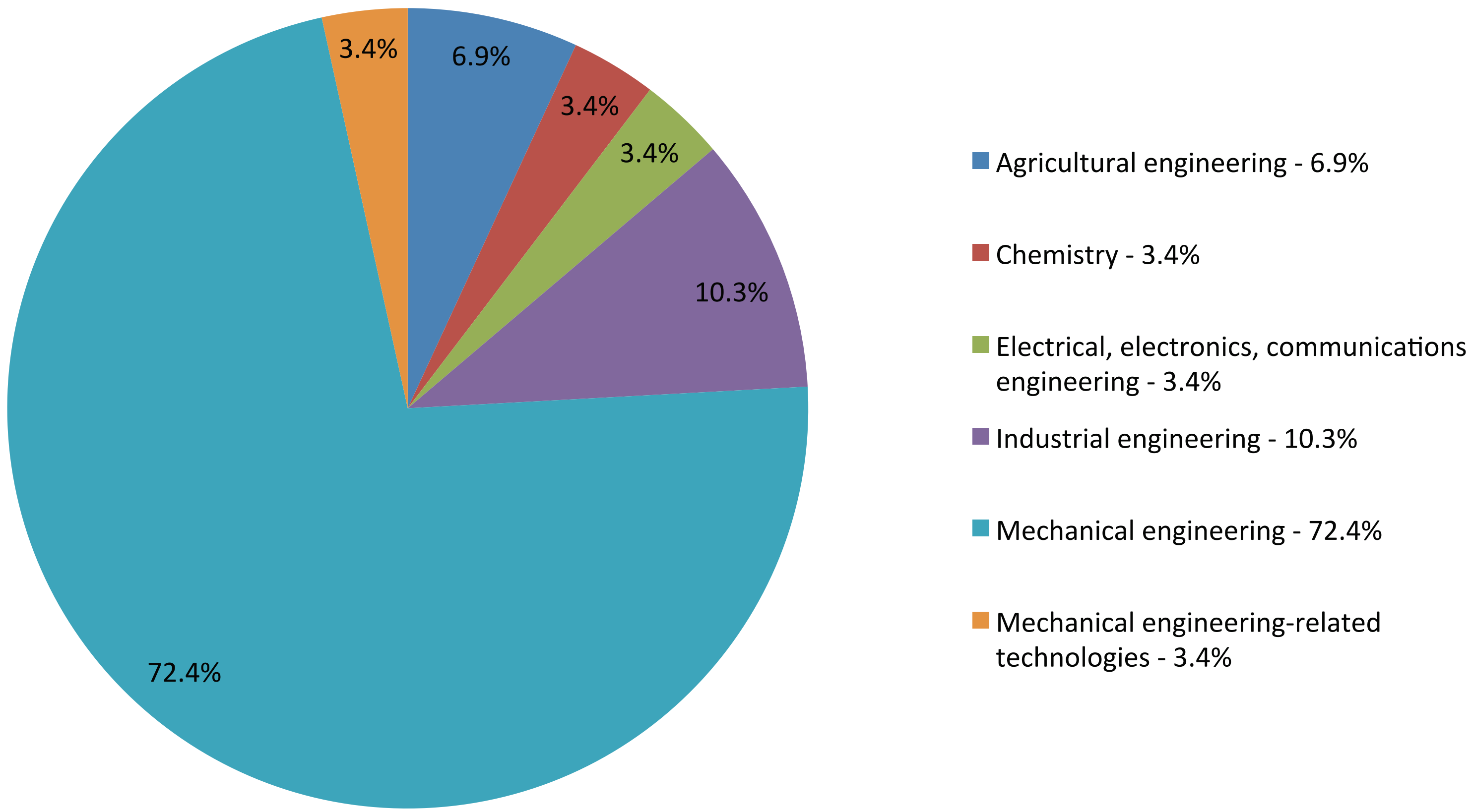
Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	University and Department	Current Year Budget	Estimated Next Year Budget
	Evaluation And Design Improvements For A Hydraulic Pump (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$47,009	
	Evaluation of a proprietary gear pump (Associated Project)		Andrea Vacca			$38,500	
	Fluid Efficiency (Associated Project)		Paul W. Michael			$134,526	
	Impact of De-aeration Technology and Hydraulic Reservoir Volume on Pump Efficiency (Associated Project)		Paul W. Michael			$2,842	
	MODELING AND ANALYSIS OF AXIAL PISTON PUMP (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$82,092	
	Modeling and Analysis of Swash Plate Type Axial Piston Pump (Interface) (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$61,678	
	Modeling Of Axial Piston Pumps And Motor (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$56,595	
	MODELING OF AXIAL PISTON PUMPS AND MOTORS (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$18,865	
	PCA Mule- System Implementation and Testing (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$187,643	
	Performance Prediction and System Control through Coupled Multi-domain Models: A Comparison Study (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$4,106	
	Pump Dynamic Model Development (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$230,275	
	Reliable Lightweight Transmission of Off-shore Utility Scale Wind Turbines (Associated Project)	Eaton Corporation, University of MN, IonE and IREE	Kim A. Stelson	Brad Bohlmann	University of Minnesota-Mechanical Engineering	$27,285	
Translational Research Projects Within Thrust						$0	
Subtotal (all projects) for Thrust						$2,811,817	$2,811,817
Total Number of Undergraduate Students in Thrust						2	
Total Number of Graduate Students (M.S. and Ph.D.) in Thrust						16	
Total Number of Postdocs in Thrust						1	
Total Number of Personnel in Thrust						34	
2: Compactness (Andrew G. Alleyne)	2B.2: Miniature HCCI Free Piston Engine Compressor (Center Controlled Project)	NSF ERC Program	William K. Durfee	David B. Kittelson	University of Minnesota-Mechanical Engineering	$84,926	$806,039
	2B.3: Free Piston Engine Hydraulic Pump (Center Controlled Project)	NSF ERC Program	Zongxuan Sun			$80,278	
	2B.4: Controlled Stirling Thermocompressors (Center Controlled Project)	NSF ERC Program	Eric J. Barth			$74,514	
	2C.2: Advanced Strain Energy Accumulator (Center Controlled Project)	NSF ERC Program	Eric J. Barth			$78,945	
	2C.3: Flywheel Accumulator for Compact Energy Storage (Center Controlled Project)	NSF ERC Program	James D. Van de Ven			$46,000	
	2F: MEMS Proportional Pneumatic Valve (Center Controlled Project)	NSF ERC Program	Thomas R. Chase			$86,522	
	2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems (Center Controlled Project)	NSF ERC Program	Robert J. Webster	Eric J. Barth Vito R. Gervasi Jun Ueda	Vanderbilt University Milwaukee School of Engineering Georgia Institute of Technology	$127,684	
	CPS: Synergy: Integrated Modeling, Analysis and Synthesis of Miniature Medical Devices (Associated Project - NSF)		Pietro Valdastri	Robert J. Webster	Vanderbilt University	$41,667	
	Functionally Graded Metallic Lattice Components for Advanced Propulsion Components (Associated Project)	DARPA	Vito R. Gervasi			$60,667	

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	University and Department	Current Year Budget	Estimated Next Year Budget
	Open Accumulator Compressed Air Storage Concept for Wind Power (Associated Project)	University of MN, IonE and IREE	Perry Y. Li			$5,826	
					Translational Research Projects Within Thrust	$0	
					Subtotal (all projects) for Thrust	$687,029	$806,039
					Total Number of Undergraduate Students in Thrust	5	
					Total Number of Graduate Students (M.S. and Ph.D.) in Thrust	9	
					Total Number of Postdocs in Thrust	0	
					Total Number of Personnel in Thrust	27	
3: Effectiveness (Wayne J. Book)	3A.1: Teleoperation Efficiency Improvements by Operator Interface (Center Controlled Project)	NSF ERC Program	Wayne J. Book	Steven X. Jiang Eui H. Park	North Carolina Agriculture and Technical State University-Industrial and Systems Engineering North Carolina Agriculture and Technical State University	$82,262	$888,065
	3A.3: Human Performance Modeling and User Centered Design (Center Controlled Project)	NSF ERC Program	Steven X. Jiang	Zongliang Jiang Eui H. Park	North Carolina Agriculture and Technical State University North Carolina Agriculture and Technical State University	$111,202	
	3B.3: Active Vibration Damping of Mobile Hydraulic Machines (Center Controlled Project)	NSF ERC Program	Andrea Vacca			$75,500	
	3D.1: Leakage/Seal Friction Reduction in Fluid Power Systems (Center Controlled Project)	NSF ERC Program	Richard F. Salant			$71,819	
	3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems (Center Controlled Project)	NSF ERC Program	Scott S. Bair			$71,866	
	3E.1: Pressure Ripple Energy Harvester (Center Controlled Project)	NSF ERC Program	Kenneth A. Cunefare			$69,277	
	Adaptive Control for Oscillation Damping (Associated Project)	CNH America, Inc.	Andrea Vacca			$56,000	
	Analysis of transmission noise sources (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$8,515	
	Development of an Experimental Pressurized Thin-film Couette Viscometer and Consultation (Associated Project)	Total Oil Company	Scott S. Bair			$15,000	
	EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership (Associated Project - NSF)		Paul Imbertson			$133,333	
	Evaluation of the High Pressure, High Shear Stress Capability at Georgia Tech (Associated Project)	The Lubrizol Corporation	Scott S. Bair			$1,974	
	Model Predictive Control of Pneumatic Actuators (Associated Project - translational research)	National Defense Science and Engineering Fellowship Grant (NDSEG)	Wayne J. Book			$31,000	
	Multimodal Human-Machine Interface Design with Augmented Reality and Ergonomics (Associated Project - NSF)	Confidential Organization (optional use for associated or sponsored projects only)	Wayne J. Book	Steven X. Jiang Zongliang Jiang	North Carolina Agriculture and Technical State University-Industrial and Systems Engineering North Carolina Agriculture and Technical State University	$25,667	
	OPTIMIZATION OF VALVE PLATE TO REDUCE NOISE AND CONTROL EFFORT FOR AXIAL PISTON PUMP (Associated Project)	Confidential Organization (optional use for associated or sponsored projects only)	Monika M. Ivantysynova			$43,789	
	Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals (Associated Project)	University of Stuttgart/German Research Foundation	Richard F. Salant			$3,077	
	Static Charge Generation in Tank-Mounted Return-Line Filters (Associated Project)		Paul W. Michael			$1,579	
	Suppressor System Development (Associated Project)	Eaton Corporation	Kenneth A. Cunefare			$49,077	
	Understanding and Reducing the Adverse Effects of Biodynamic Feedthrough (Associated Project)	National Defense Science and Engineering Fellowship Grant (NDSEG)	Wayne J. Book			$38,707	
					Translational Research Projects Within Thrust	$31,000	
					Subtotal (all projects) for Thrust	$889,644	$888,065
					Total Number of Undergraduate Students in Thrust	7	
					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	31	

Thrust	Project Name	Organizational Sponsor	Project Leader	Investigators	University and Department	Current Year Budget	Estimated Next Year Budget
Test beds (Kim A. Stelson)	Testbed 1: Heavy Mobile Equipment - High Efficiency Excavator (Center Controlled Project)	NSF ERC Program	Monika M. Ivantysynova			$119,500	$498,217
	Testbed 3: Highway Vehicles - Hydraulic Hybrid Passenger Vehicle (Center Controlled Project)	NSF ERC Program	Perry Y. Li	Thomas R. Chase	University of Minnesota	$135,192	
	Testbed 4: Patient Transfer Device (Center Controlled Project)	NSF ERC Program	Wayne J. Book			$104,715	
	Testbed 6: Human Assist Devices -- Fluid Power Ankle-Foot Orthosis (Center Controlled Project)	NSF ERC Program	Elizabeth T. Hsiao-Wecksler	William K. Durfee	University of Minnesota-Mechanical Engineering	$138,810	
				Steven X. Jiang	North Carolina Agriculture and Technical State University-Industrial and Systems Engineering		
					Translational Research Projects Within Thrust	$0	
					Subtotal (all projects) for Thrust	$498,217	$498,217
					Total Number of Undergraduate Students in Thrust	0	
					Total Number of Graduate Students (M.S. and Ph.D.) in Thrust	0	
					Total Number of Postdocs in Thrust	0	
					Total Number of Personnel in Thrust	8	

[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



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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.

The project numbering system does not capture all of the aspects of a given project. In actuality, nearly all of the research projects have substantial elements of more than one thrust. 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 lead to smaller displacement motors 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 and information about test bed integration.

EFFICIENCY

Efficiency projects are primarily focused on three technical barriers: creating more efficient components, creating more efficient systems and improving control and energy management. Creating efficient components is a transformational barrier for fluid power. The thrust also supports two of the Center's major goals: doubling fluid power efficiency in current applications and expanding fluid power use in transportation.

The table below lists the efficiency thrust projects funded during the reporting period and the barriers that they address. Further project details can be found in the following pages and in Volume II.

Thrust 1: EFFICIENCY	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	Supported projects and Test Beds
1A.1: Technology Transfer Process for Energy Management Systems	•	•	•							TB3
1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems	•	•	•			•				TB1
1B.1: New Material Combinations & Surface Shapes for the Tribo-systems of Piston Machines	•									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

This project focuses on creating and implementing a process for moving the energy management strategies (EMS) developed under Project 1A.1 to industry. The energy management research previously conducted by the CCEFP resulted in the development of a suite of EMS design methods, each with its own strength and weaknesses. The design methods are rule-based, stochastic dynamic programming and model predictive control. Each of these methods presents a different trade-off between the assumed knowledge of the duty cycle and online computational complexity. Therefore, the optimum choice of EMS design method is dependent on the application. In this project, a formal process is being developed for transitioning the algorithms developed to practitioners as well as developing a software framework for interfacing to the available tools. In this way, the project supports the development of more efficient hydraulic systems by enabling industrial partners to readily capitalize on research previously conducted within the Center. The software framework will allow practitioners to specify system dynamics, duty cycles, optimization objectives, and constraints. The toolbox will then use the built in methods for optimizing energy use to derive implementable control strategies. The user will then be able to compare different energy management strategies across a wide variety of platforms and duty cycles. It is envisioned that the software framework will allow for automated controller development from the user specified system description and aid the user in selecting the EMS design method which is best suited for their application. In addition, this project will provide a set of 'best practices' for transitioning of tools from the academic setting to the industrial setting which can be used by other projects throughout the Center that generate design tools or system models. The project is being done in collaboration with two CCEFP industry partners, Eaton Hydraulics and Sauer-Danfoss.

The project addresses all three of the efficiency barriers of efficient components and systems, efficient control and efficient energy management by providing a pathway for efficient operation algorithms developed within the Center to be readily adopted up by industrial partners. It will provide an easy interface for the choice of appropriate energy management strategies and will provide results in a format readily usable by practitioners.

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

In the past, this project has focused on the development of system architectures and control methods for optimal power management in multi-actuator mobile hydraulic machines using displacement-controlled (D-C) linear and rotary actuators. Conventional hydraulic systems typically have a single pump providing flow to multiple. In such a system, the system pressure is determined by the actuator requiring the highest pressure and the flow to the other actuators is throttled to reduce the pressure. The D-C technology focuses on the reducing throttling losses by increasing the number of pumps and providing the required flow and pressure to a given actuator. The project, has demonstrated fuel consumption reductions of up to 50% for typical working cycles. It has also been demonstrated that 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 introducing effective machine prognostics. It has been demonstrated that up to 39% of the system energy is lost through pump losses. To achieve lower production costs and higher system efficiencies, pump switching between actuators during machine operation will be analyzed, thus reducing the number of pumps installed in the hydraulic system and their sizes 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 addresses the three efficiency barriers of efficient components and systems, efficient control and efficient energy management by developing new system concepts and control strategies for multi-actuator mobile machines. The project also addresses the compact integration barrier since displacement-controlled systems allow higher operating pressures and a reduction in the number of interfaces and components. D-C systems with pump switching will further address the efficiency and compactness barrier 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 acceptance of the technology.

Project 1B.1: New Material Combinations and Surface Shapes for Tribo-systems of Piston Machines

The project's goal is to help transform the design of hydraulic pumps and motors from a cumbersome task, requiring "tribal knowledge" and 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. The research in this project addresses three key areas which must be investigated before the pump design models can be used in industrial practice. The areas are:

1. Two of the three lubricating interface models have been directly validated with empirical data to date. A test rig will be constructed to measure the third lubricating interface model, the fluid film thickness between the slipper-swashplate and compare measured values to simulation results.
2. Estimates for 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. State of the art 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.

Digital prototyping represents a practical design method to create more efficient designs which utilize new technologies for surface shaping, material coatings and other advanced manufacturing technologies.

The project primarily addresses the transformational technical barrier of efficient components and systems. The improvements in component efficiency also lead to system efficiency improvements. Piston pumps are a critical part of energy saving displacement controlled hydraulic systems and hydraulic hybrids, both of which are new concepts that have been proposed and developed in the CCEFP. By improving the efficiency of piston pumps and motors over a wide range of operating conditions, these new energy saving hydraulic system designs are better able to successfully compete with alternative technologies.

Project 1D: Microtextured Surfaces for Low Friction / Leakage

The goal of the project is to enhance the performance of fluid power components using microtextured surfaces that significantly reduce friction and leakage relative to state of the art. Surface microtexturing has shown significant promise over the past decade as a surface engineering method to modify friction performance. This project focuses on two important problems associated with surface texturing – developing a low cost scalable manufacturing technique and engineering design rules for fluid power applications. Microtextures have been fabricated on 17-4PH stainless steel disks as large as 75 mm in diameter using micro-casting. Unlike existing techniques, such as laser texturing, micro-casting does not produce material pile-up around the dimple. The effects of surface texture geometries like width, depth, density and aspect ratio on the friction characteristics under hydrodynamic lubrication were numerically and experimentally investigated. Friction reductions up to 80% were found for textured surfaces compared to untextured surfaces under these conditions. The trends obtained in the experiments match well with simulations, allowing optimum texture geometry prediction for various fluid power applications. 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 project addresses the technical barrier of leak-free components. These components will also have friction lower than state of the art thus helping to overcome the transformational barrier of efficient components. Finally, by lowering the starting friction of hydraulic motors and enabling smaller displacement motors to be used, the research addresses the compact integration barrier. The technology will be validated through collaboration with industry and through application to the excavator and orthosis test beds. The work will also improve fundamental understanding in areas critical to improving the design of fluid power components.

Project 1E.1: Helical Ring On/Off Valve Based 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 manner that substantially eliminates throttling. This goal will be met through the development of critical enabling technologies such as novel high speed rotary on/off valves. The high speed on/off valves (effectively hydraulic transistors) will enable effective switched-mode control of hydraulic components and systems. Switched-mode control concepts such as pulse width modulation enable non-throttling forms of valve control while maintaining the traditional attributes of low cost and high performance while increasing efficiency. Conventional on/off valves rely on oscillating linear motion to switch position, resulting in inertial forces that require actuation power that is proportional to the switching frequency cubed. This creates a tradeoff between valve flow area, switching speed and power consumption that is a barrier to switched-mode hydraulics. Using continuous rotary motion to achieve the desired high speed switching action, the rotary valves developed in this project reduce actuation requirements to the switching frequency squared.

This project addresses all three of the efficiency thrust barriers - efficient components and systems, efficient control and efficient energy management - by developing efficient pulse width modulated alternatives to eliminate the losses inherent in throttling valves. It also addresses the compact integration barrier by enabling variable displacement functionality using compact, inexpensive fixed displacement components. Finally, the project has the potential to address the quiet components and systems barrier by removing the throttling valves from a hydraulic system. The function of these valves – reducing the pressure of the fluid flow – can generate significant noise which would be eliminated with the implementation of the technology.

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

Hydraulic pumps and motors have reduced efficiency at certain speeds, pressures and displacements. The goal of this research is to extend the range of high efficiency operation by developing a hydraulic pump/motor actively controlled by high speed on/off valves. The valves are connected to each piston cylinder, replacing the valve plate. Operating modes and effective displacement can be varied by actively controlling the valves. Pump/motors of this design can have higher efficiency due to reduction of friction, internal leakage and compressibility losses as well as increased displacement control bandwidth. Supporting tasks include using the model created in previous reporting periods to characterize and predict pump/motor efficiency, define the dynamic response and flow requirements of the on/off valves required, simulate different operating strategies to characterize the effects on pump/motor efficiency (valve timing effects, partial fill methods, etc.), and to experimentally validate the model, design, and operating strategies. A prototype pump/motor will be built and tested for experimental validation.

The project is primarily focused on the barrier of efficient components and systems. It could also address the compact integration barrier by enabling variable displacement with fixed displacement components. The research will be validated on test bed 1, the displacement-control excavator, and test bed 3, the hydraulic hybrid passenger vehicle.

Project 1E.4: Piston-by-Piston Control Using Mechanical Methods

In conventional variable displacement pumps and motors, many sources of loss do not decrease as the output power of the pump or motor is decreased. The goal of this project is to develop a new method for varying the displacement of a pump/motor that has a shallower drop in efficiency as the unit goes to lower displacements. The displacement will be controlled by enabling/disabling fluid flow into individual pistons with high-speed on/off valves. The project will focus on creating a variable displacement pump/motor that can meet or exceed existing designs in peak efficiency and maintains a higher efficiency as the displacement is decreased. By utilizing a 2 degree of freedom rotary valve, the expected efficiency benefits of piston-by-piston control will be achieved with a control mechanism that is simpler and more cost effective than competing alternatives.

The project's main focus addresses the transformational technical barrier of creating efficient components and systems. The project also addresses the efficient control barrier. The development of high efficiency variable displacement pump/motors is essential to overcoming this barrier. Increasing the efficiency of pumps and pump/motors will greatly improve the likelihood of commercial success of hydraulic hybrid powertrains in both on-highway and off-highway vehicles.

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

Metering valves in hydraulic systems create large throttling losses. In theory, hydraulic transformers powered by a single fluid source could replace metering valves and substantially reduce losses. This project will investigate how hydraulic transformers can best be used to achieve both efficiency and control performance in a hydraulic motion control system. Different transformer configurations and connections will be modeled, analyzed and evaluated. New configurations may be discovered as a consequence. The effects of dynamic and efficiency characteristics of the underlying devices and component sizing on system performance will be considered. Control approaches that take into account both efficiency and precision will be developed and demonstrated. These approaches will be conducted in case studies with scenarios taken from CCEFP test beds 1 and 4.

The project is primarily focused on the three technical barriers in the efficiency thrust: efficient components and systems, efficient control and efficient energy management. Hydraulic transformers may also facilitate compact integration with actuators and the system overall. Efficient and high performance control of actuators with appropriate form factors can expand the use of hydraulics for human scale robotic applications. Validation of the research in the new test bed 4 - patient mover - is targeted. However, hydraulic transformers will also provide benefits in hydraulic hybrid vehicles, excavators and other multi-actuator machinery, renewable energy and human-scale wearable devices.

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

This project focuses on developing high performance actuation mechanisms to enable a new class of high bandwidth valves to 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 leverages the past research results in projects 1E.1 and 1E.2 in which new coupled dynamic modeling tools were developed, studies of linear and rotary motion valves were completed, benchmarks were done with existing technologies, and prototypes were constructed and tested. The goal of the project is to couple kinetic energy storage mechanisms with translational positive sealing valve components to achieve high bandwidth, high flow, on/off and proportional valves. The deliverables for the project will be the design, simulation, and testing of the appropriate coupling mechanism.

The project addresses all three of the efficiency technical barriers. The improvement in the efficiency of the hydraulic system comes from energy management and this requires innovative control. The development of high bandwidth valves will create new efficient components and are an enabler for efficient systems. The project also addresses compact integration. Hydraulic valves are found on nearly every fluid power system in production. Compact, modular, high performance, scalable valves would be enablers or enhancers across a broad spectrum of hydraulic equipment.

Project 1F.1: Variable Displacement Gear Machine

The primary goal of this project is to develop 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 developing a general and innovative design methodology for EGMs that surpasses the current empirical design approach used to design such units. In particular, the project will investigate unconventional designs, such as non-involute or helical gear profiles.

The research directly addresses the efficiency technical barrier of efficient components and systems by introducing a new concept for a variable displacement hydraulic device. CCEFP is extensively researching new system concepts to minimize energy consumption in the fluid power applications, and many solutions are based on variable displacement piston units. However, variable displacement piston pumps and motors are expensive and their market penetration could be improved by lowering system cost. Therefore, research toward more cost effective solutions for variable displacement units is warranted.

Project 1G.1: Energy Efficient Fluids

The goal of this project is to model and investigate the effects of boundary friction, traction, compressibility, and high pressure shear-thinning on the efficiency of hydraulic components and systems. Studying the interactions of hydraulic fluid properties by performing high pressure rheometer, bench-top tribometer and hydraulic dynamometer testing will help to bridge the knowledge gap between the performance of fluid power components of complex geometry and the fundamental understanding of tribology. This knowledge will be used to develop models to predict hydraulic fluid efficiency and propose new fluid formulation strategies to improve system efficiency.

This project addresses the transformational technical barrier of efficient components and systems by providing a deeper understanding of hydraulic fluid behavior through an analysis of the impact of boundary friction, traction, fluid compressibility, and high pressure shear-thinning characteristics on system efficiency. Fluid-induced reductions in motor starting friction would also support the compact integration technical barrier. Fluid formulations will be developed using design of experiments for mixtures and evaluated in high pressure rheometer, bench-top tribometer, and hydraulic dynamometer testing. Models that predict hydraulic fluid efficiency will be developed. Improving fluid efficiency is of strategic importance for CCEFP and in the fluid power industry because hydraulic fluids interact with nearly every component in a hydraulic circuit. Increasing fluid efficiency makes it possible to use smaller pumps, motors, and prime movers. This investigation will be conducted in collaboration with the elastohydrodynamic research of Professor Bair at Georgia Tech (Project 3D.2). The research results will be validated in lab tests as well as on test bed 3, the hydraulic hybrid passenger vehicle.

Project 1J.1: Hydraulic Transmissions for Wind Energy

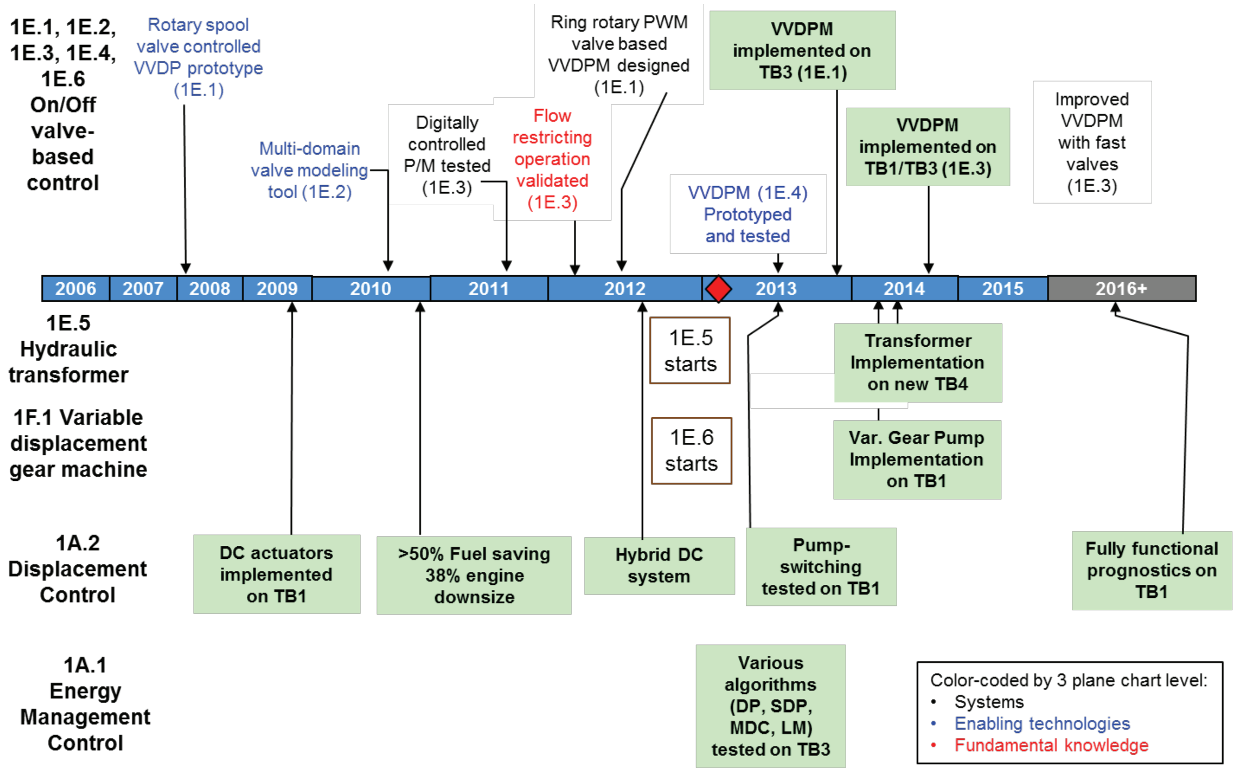
Wind is a plentiful, renewable source of energy. The US Department of Energy has a goal of having 20% of the nation's energy come from wind by 2030. Utility-scale wind turbines are generally located well away from areas of high energy demand. Therefore, the wind energy is transported on the electric grid. The grid is highly regulated and nearing its capacity in many areas of the country. An alternative to large utility scale wind farms tied to the grid is using small (up to 100 kW) to mid- (100 kW - 1 MW) wind turbines that use the wind generated electricity locally and don't require grid integration. This project is focuses on mid-wind turbines that could be used to provide power to a hospital, school, municipal building, company or a variety of other places. Mid-wind turbines, in general, use a gearbox to increase the rotational speed of the turbine rotor to lower generator costs. They also usually function as fixed speed machines to further reduce cost. With a fixed speed rotor, the turbine cannot maximize energy capture from the wind. A hydrostatic transmission (HST) functions as a continuously variable transmission thus allowing variable rotor speed operation. The ratio of the input (rotor) to output (generator) rotational speed in an HST is variable thus eliminating the need for a gearbox. 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 blade pitch systems. An HST has the potential to increase system efficiency, improve system reliability and decrease the cost of energy. The application of HST will initially be focused on mid-sized wind turbines since hydraulic components (pumps and motors) at higher power ratings are not commercially available.

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. The research seeks to demonstrate that although an HST has a lower efficiency than a gear drive, it allows the aerodynamic efficiency and electrical efficiency to increase resulting in a system efficiency that is as good or better than conventional wind turbines. An HST will reduce maintenance and repair costs (and, we believe, acquisition cost) thereby providing a better value than a conventional wind turbine.

The goals of the project are to investigate the application of an HST to mid-sized wind turbines, identify the technical barriers for the hydrostatic wind turbine, explore novel control methods to maximum energy capture and investigate the use of energy storage to minimize the cost of electricity. The approach will be to use numerical modeling followed by prototype fabrication and testing. To facilitate this research, a hydrostatic wind turbine test stand is being built at the University of Minnesota.

The project aligns with the Center's efficiency thrust and addresses all three of its technical barriers: efficient components and systems, efficient control and efficient energy management. The project also addresses the compact integration technical barrier by leveraging the inherent power density of hydraulics in a new application. Finally, the project supports the fourth major goal of the Center - ubiquity - by working to expand the applications and markets in which fluid power can provide its benefits.

Efficiency Thrust Technology Integration



Efficiency Thrust 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.

Gaps losses: At the fundamental level, detailed computational models have been developed in Project 2B.1 to predict losses in the lubricating interfaces of a piston machines, including deformation and thermal effects (2009-2012). 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. Currently materials effects are being modeled and investigated. The next milestone will be a digitally prototyped piston-cylinder combination which has been optimized based on these models, and its experimental validation (2014). 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 in the near future constant gap in 2013. In collaboration with Project 2B.2, this technique was experimentally demonstrated on geroter roller surfaces to reduce start-up friction by 25% in 2011. Use of this technique in seals to reduce friction and leakage will be attempted in the future (2014).

Fluid Properties: An unexpected effect of scale in generalized Newtonian elastohydrodynamic films was discovered in 2008. A thermodynamic scaling function for the accurate correlation of viscosity with temperature and pressure was developed in 2008 An unexpected effect of load in generalized Newtonian elastohydrodynamic films was discovered in 2009. The role of fragility in EHL entrapment was discovered 2010. A Newtonian elastohydrodynamic film thickness formula for linear piezoviscosity was found in 2010. The mechanical degradation of the liquid in an operating EHL contact was demonstrated in 2010. A molecule-based Ashurst-Hoover scaling for compressed liquids was found in 2011. Dimensionless groups which delimit friction regimes in EHL were derived in 2012. An elastohydrodynamic film thickness formula for double-Newtonian shear-thinning was found in 2012. The surprising effect of mechanical degradation on film thickness was demonstrated using measured shear-thinning response in 2012.

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

- Displacement control strategy to replace throttling valves (1A.2)
- On/off valve based control strategies (1E.1, 1E.2, 1E.3, 1E.4, 1E.6)
- Recently with the investigation of hydraulic transformer configurations (1E.5) and variable displacement gear machines (1F.1).

Displacement control: Closed circuit displacement control was demonstrated in TB1 (2009-2011), with 56% fuel-saving, 50% cooling power reduction. A series-parallel architecture has been proposed and analyzed with the possibility of further 25% fuel saving and 38% engine-downsize (2011). Major future milestones include demonstration of pump-switching in TB1 (2013), 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 (2008) and optimized VVDPM prototype currently under testing (2013). The VVDPM will then be installed and tested on TB3 (2013). A more efficient ring concept that reduces the loss by 50% and increases efficiency by 5% has been proposed and optimized (2012).

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 (2014). 1E.4's VVDPM's design is complete and will be prototyped and bench tested in (2013). 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. 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 targeted for TB3 are scheduled to be tested on TB3 in (2013).

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 lists the compactness thrust projects funded during the reporting period and the barriers that they address. Further project details can be found in the following pages and in Volume II.

Thrust 2: COMPACTNESS	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	Supported projects and Test Beds
2B.1: Free Piston Engine Compressor	•			•		•				TB4
2B.2: Miniature HCCI Free-Piston Engine-Compressor				•						TB4, TB6
2B.3: Free Piston Engine Hydraulic Pump	•	•	•	•	•	•				TB3
2B.4: Controlled Stirling Thermocompressors		•		•		•			•	TB6
2C.2: Advanced Strain Energy Accumulator		•	•		•	•	•			TB3, TB6
2C.3: Flywheel Accumulator for Compact Energy Storage		•	•		•	•	•			TB3
2D: Multi-Functional Fluid-Power Components Using Engineered Structures and Materials		•				•	•	•	•	TB6
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.1: Free Piston Engine Compressor

The project goal is to develop a dynamic model-based design framework for a novel compact high energy density pneumatic power supply applicable to untethered fluid-power applications. This is achieved by modeling, designing, building and testing a free-piston engine utilizing spark-ignited fuel that is specifically load matched to the task of compressing air. Target metrics for the device include 100W average continuous output power in the form of 80 to 150 psig compressed air, a dry weight of 1.5 kg, energy density greater than 1500 kJ/kg, and a small footprint. Fundamental research will result in a generalized design method for the exploitation of free-piston engine dynamics for optimizing the efficiency and power density of the energetic conversion and transduction processes between chemical stored energy, kinetic energy of the free-piston, compression and pumping work, and stored pneumatic potential energy. This model-based design methodology takes a combined system dynamic and thermodynamic perspective that uniquely addresses the role of dynamic elements and effects seen to have a larger role in free-piston engines than more standard kinematic engines. Correspondingly, a generalized control methodology for free-piston engines will be formulated and applied.

This project contributes mainly to the compactness thrust. The compactness is achieved both due to the high gravimetric energy density of the driving fuel and the compact configuration of the engine which favors dynamic “linkages” over larger kinematic ones. This project will contribute to the Center’s goal of breaking the barrier of low energy density power sources for untethered devices. Additionally, given that an adequate level of overall efficiency is required to break the energy barrier and provide an order of magnitude increase in energy density over conventional technology, this project also addresses the efficiency systems technical barrier.

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

The project is aimed at developing a miniature free piston internal combustion engine-driven air compressor to provide an on-board pneumatic power source for human scale mobile applications such as orthosis, power tools and robots. Utilizing hydrocarbon fuel as energy storage, the compressor will provide much longer run time than a battery - motor package.

The project has two primary goals. The first is to generate new knowledge about the science and engineering of homogeneous charge compression ignition (HCCI) free piston engine-compressors suitable for tiny power supplies in small scale fluid power systems. This goal builds on previous work which investigated novel small free-piston engine-compressors operating in glow-plug combustion mode. The second goal is to design, build, evaluate and deliver a high-efficiency air compressor that delivers approximately 10W of cold compressed air. The engine-compressor will be suitable for validation in test bed 6, the Ankle Foot Orthosis, and other small scale pneumatic fluid power devices including hand tools and robots.

This project addresses the technical barrier of developing compact fluid power supplies that are one to two orders of magnitude smaller than anything currently available (10 W-1 kW). Overcoming this barrier supports the achievement of CCEFP’s main goal #3, creating portable human-scale fluid power applications.

Project 2B.3: Free Piston Engine Hydraulic Pump

For mobile applications including both highway vehicles and mobile heavy equipment, fluid power is currently generated onboard using a crankshaft based internal combustion engine (ICE) coupled to a rotational hydraulic pump. The main drawbacks of this configuration are the relatively low efficiency and complex design of both the ICE and the hydraulic pumping system. An alternative approach is to supply fluid power using a free piston engine (FPE) with an integrated linear hydraulic pump. This configuration has the potential to significantly increase the ICE and pump efficiency while reducing system size and increasing system modularity. The major technical barrier of this technology is the large cycle-to-cycle variation in engine power and piston motion, especially during transient operation. This imposes a huge challenge on the engine operation and calls for systematic active controls that can precisely regulate the piston motion. Thus, we have developed an active controller which acts as a "virtual crankshaft" by balancing the in-cylinder gas pressure and the hydraulic loading pressure in real-time using the energy from the storage element to force the piston to follow the desired trajectory.

The research goal is to provide a compact and efficient fluid power source (10 kW-500 kW) for mobile applications such as on-highway and non-road vehicles. Specifically, this project will investigate the design, modeling and control of a free piston engine driven hydraulic pump. To support the research, our industrial partner Ford Motor Company, has donated a free piston engine driven hydraulic pump to the University of Minnesota. Subsystems have been designed and assembled for conducting experiments. System models and controllers have been developed and successfully implemented on a rapid prototype control system. Experimental data demonstrates the effectiveness of the active control during engine motoring and combustion tests.

The project addresses all three of the transformational technical barriers outlined in the CCEFP strategic research plan: efficient components and systems, compact power supply and compact energy storage. The free-piston engine hydraulic pump provides a solution for the compact power supply barrier because it is an integrated system (compact integration) with the inherent power density of hydraulics and the high energy density of an ICE. Storing energy in the form of hydrocarbon fuel and converting it to fluid power in real time in response to the power demand provides an energy density that is an order of magnitude greater than electrical systems. The light reciprocating mass and other engine features allow the engine to transition from off to full power quickly (estimated to be on the order of 100 msec), thus the device addresses the transformational barrier of compact energy storage.

Project 2B.4: Controlled Stirling Thermocompressors

The focus of this research is to create a sub-human scale free-piston Stirling-based thermocompressor as a pneumatic power supply. Utilizing a slight modification of the Stirling cycle, gains are hoped to be made in efficiency, noise reduction, and compactness compared to similarly sized engines.

The research goals of this project are to:

1) employ a physical feedback control design approach to purposefully design an unstable Stirling-based thermocompressor that generates power, and assess its merits, and
2) study the scalability of the Stirling thermocompressor from miniature pneumatic power supplies up to industrial pneumatic compressors.

By the end of the second year (May 2014), this research will be demonstrated as a silent, low vibration, 20W, 80 psig high energy-density pneumatic power supply on test bed 6, the ankle-foot orthosis. Based on the success of this goal, and based on the findings regarding scaling, research beyond the second year will focus on applying the fundamental research results to an efficient industrial-scale compressor. Fundamental research will result in a dynamic, as opposed to thermodynamic, understanding of Stirling thermocompressors. Dynamic models will be developed. Furthermore, Stirling thermocompressors will be recast and reinterpreted from a dynamic systems and controls perspective. This view will afford a feedback control design that assigns groups of physical parameters to feedback gains. In this manner, the complex dynamic interactions can be made to cooperate to produce a self-running compressor upon the addition of external heat (no combustion pulses).

This project addresses all three of the Center's thrusts. Enhanced compactness is particularly needed at the scale of test bed 6 (10-100W). A compact power supply will be created due to the simplicity of the proposed device, the high gravimetric energy density of the driving fuel and the characteristically high efficiency of the Stirling cycle. The latter two benefits address the efficient components and systems technical barrier. Such a power supply will facilitate compact integration. Also, the power supply should be nearly silent, thus addressing the quiet technical barrier. In addition, this project will contribute to the Center's goal of creating portable human-scale fluid power applications. This project also has the appeal of alternative energy since the source of heat utilized can encompass geothermal to solar (concentrator). Finally, as a larger goal, this project contributes toward future sustainability of the Center by continuing the line of research begun by the free-piston engine compressor as a foundational element of a Pneumatic Center of Excellence based at Vanderbilt.

Project 2C.2: Advanced Strain Energy Accumulator

By using multiple energy domains, hybrid vehicles seek to harness the strengths of each in order to make up for the weaknesses of the other. Hydraulic hybrids, in particular, offer high power density, transmission flexibility, and rugged efficiency that have benefited countless other mobile and industrial applications. Hydraulic regeneration is not hampered by the relatively low power density of electric batteries and offers greater opportunity for safer, more distributed storage than strictly mechanical regeneration techniques. The development of hydraulic hybrid vehicles has created a growing demand for the development of efficient, compact, high performance accumulators that are capable of fully utilizing the benefits of fluid power.

The objective of this work is to extend the state of knowledge in the use of strain energy storing materials for the engineering design of compact energy storage devices. The project focuses on increasing the energy storing capabilities of accumulators for the specific purpose of storing large amounts of hydraulic energy with an energy density appropriate for applications such as regenerative braking in passenger vehicles.

The metric for success of the project 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. Additional significant benefits could potentially include solutions to traditional accumulator problems including cost, pre-charge issues and fluid contamination from gas diffusion through the bladder.

The project addresses two of the Center's transformational technical barriers: compact energy storage and efficient components and systems. It also reduces control challenges in systems (efficient control). The task of designing new compact energy storage devices is central to two of the Center's main goals: increasing efficiency in existing fluid power applications and expanding fluid power use in transportation. Compact, high energy density storage solutions are critical to achieving these goals. This project will be demonstrated on test bed 3, the hydraulic hybrid passenger vehicle.

A new aspect of the project is applying this concept to energy storage in pneumatic systems. There is a great potential for energy savings, and hence increased efficiency, in industrial pneumatics and pneumatic systems more generally. A prototype accumulator for the Ankle-Foot Orthosis (TB6) was designed, constructed and tested at Vanderbilt, then implemented in the test bed at UIUC. This very early prototype was experimentally demonstrated on the test bed to have an energy savings of 17.5% relative to operating with no accumulator.

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

Hydraulic energy storage is important in numerous applications including the emerging areas of hydraulic hybrid vehicles and wind turbines with hydraulic drive trains. There are two primary limitations of conventional hydraulic accumulators. First, the energy storage density of hydraulic accumulators is significantly lower than other energy storage mediums. For example, the specific energy of lithium-ion batteries is 432 kJ/kg and that of a composite hydraulic accumulator is 6 kJ/kg. The second limitation is that the system pressure in conventional accumulators varies by 2 to 2.5:1 and is a function of the energy stored in the hydraulic accumulator. The pressure variation requires oversized components capable of meeting the desired performance at the lowest system pressure resulting in bulky and heavy components and introduces control challenges.

In response to these limitations, the project leader invented the flywheel-accumulator, which combines hydro-pneumatic energy storage with rotating kinetic energy storage. Similar to the open accumulator designed in a graduated CCEFP project, the flywheel accumulator allows both air and hydraulic fluid to be independently added to a pressure vessel, theoretical improving the energy density by an order of magnitude. By modulating the method of energy storage, the hydraulic system pressure can be controlled independent of the quantity of energy stored.

The goal of the project is to develop a high energy density hydraulic storage system, the flywheel accumulator, through a coupled modeling, design, and experimental approach. The influence of baffles on fluid swirl will be studied using CFD and experiments with an existing low energy density system. A multi-energy domain dynamic model will be developed in levels of increasing complexity, focusing on the primary sources of energy loss. This model will be used to optimize parameters for a prototype design. A high-energy density demonstration prototype will be designed and fabricated and the used to experimental validate the dynamic model and further explore physical phenomena.

The project provides solutions to technical barriers in the compactness and efficiency thrusts. It directly addresses the transformational technical barrier of compact energy storage. The compact energy storage devices facilitate more compact integration. The project also addresses all three of the efficiency thrust barriers: efficient components and systems, efficient control and efficient energy management.

Project 2D: Multifunctional Fluid Power Components using Engineered Structures and Materials

Designing a component with multiple functions, for example load bearing and noise attenuation, can increase the effectiveness of the component and reduce the complexity of the overall system. Such multi-function components can reduce cost and potentially increase system efficiency. The goal of the project was to enable the design of passive, noise-reducing, heat-managing, fluid-power components (i.e. multi-functional components) with meso-scale meta-materials through the characterization of the structural-thermal-acoustic coupling of three of the five unit-lattice structure types identified earlier. Structural-acoustic and thermal-structural couplings will be defined through virtual testing; and, physical, non-destructive testing will be conducted for validation of the couplings. An additional goal is the inclusion of thermal-energy storage, recovery and conversion for improved component and system efficiencies. Future goals are to apply this multi-functional (structural, thermal and acoustic) design methodology to other components and systems, on the Center projects and test beds, and those being developed by industry, including aerospace and medical.

The project addresses the technical barrier of compact integration by integrating mass reduction, thermal management and noise reduction into the design of fluid-power components, minimizing the need for peripheral components or systems to achieve these multiple functions. In addition, the fluid-power technical barriers of efficient systems, safe and easy to use, quiet and leak-free are addressed by extension.

Project 2E: Model-Based Systems Engineering for Efficient Fluid Power

With the advent of electronic control, fluid-power systems have become increasingly integrated and multi-disciplinary in nature and the number of potential system architectures has exploded. With new demands on compactness, efficiency, and effectiveness, system engineers need to explore new system architectures that provide adequate tradeoffs across these often conflicting objectives. The main barrier that needs to be overcome is complexity: a very large amount and variety of knowledge is necessary to synthesize and analyze promising system architectures. Unless this knowledge is managed well, the cost of acquiring, validating and applying this knowledge will limit significantly the ability to optimize the functionality and performance of future fluid-power systems. To overcome this barrier, a systems engineering framework is required consisting of model repositories, algorithms for instantiating and linking these models, and algorithms for selecting appropriate models at each step of the design process

The goal of the project is to significantly reduce the time and effort required to formulate and solve systems engineering problems for compact and efficient fluid power systems. To achieve this, analysis knowledge about fluid power components from multiple disciplinary perspectives and multiple levels of abstraction were captured and organized in a modular, object-oriented knowledge repository using a standardized language (Systems Modeling Language, SysML) and synthesis knowledge about fluid power systems was captured in the form of model transformations. A systems engineering method and software framework was developed in which the synthesis and analysis knowledge from the repository is used to explore efficiently and comprehensively large spaces of system architectures with the goal to improve the compactness and efficiency of fluid-power systems while balancing other system objectives such as effectiveness, cost, and reliability.

The project provides a method and software framework to support the comprehensive and efficient exploration of integrated system architectures. This addresses the integration of the fluid power subsystem with structural subsystems (compact integration barrier) and enables the comparison between different system architectures for achieving desired system-level tradeoffs (efficient component and system barrier). The framework could also enable the evaluation of the impact of introducing new component technologies or higher pressures on system-level performance.

Both of the students doing this research received their PhD degrees in the Spring of 2012. The project leader decided to end the project and no research was done beyond May 2012.

Project 2F: MEMS Proportional Pneumatic Valve

The goal of the 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 rates on the scale of milliliters per minute. Our new valve design will be able to provide macro scale flow rates while maintaining compactness and efficiency. This will be achieved by a novel parallel architecture supported by design models that can predict the actuator behavior and fluid flow phenomena. The design is unique in obtaining macro-scale gas flow rates by ganging thousands of micro-actuator pallets and micro-orifices in parallel within a single flow stream. The effective orifice size is a composite of the individual orifices. The actuators and orifices are fabricated using MEMS batch fabrication techniques. The primary benefit of this approach is to dramatically lower power consumption through the use of piezoelectric actuation technology. In addition, the resulting valve package is compact and lightweight. Exploiting MEMS batch fabrication methods also enables the valve to be fabricated at low cost. The principle of the valve has been demonstrated on a proof of concept prototype which is larger than the MEMS valve, hence it is called a ‘meso-scale valve’. The meso-scale valve has a flow capacity of 25 slpm at a pressure drop of 6 to 5 bar with actuation power less than 1 mW.

This project has breakthrough potential toward the Center’s transformational technical barrier of developing efficient components and systems as well as the compact integration barrier. Although generic proportional valves are being developed, 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. One aspect 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 demonstrated on test bed 6, the ankle-foot orthosis.

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

Magnetic resonance imaging (MRI) is one of the most useful methods available to study neuroscience, evaluate rehabilitation therapies and perform image-guided interventions and surgeries. 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. This research will help open an entirely new industry to fluid power, Medicine, which represents about one sixth of the Gross Domestic Product of the U.S.

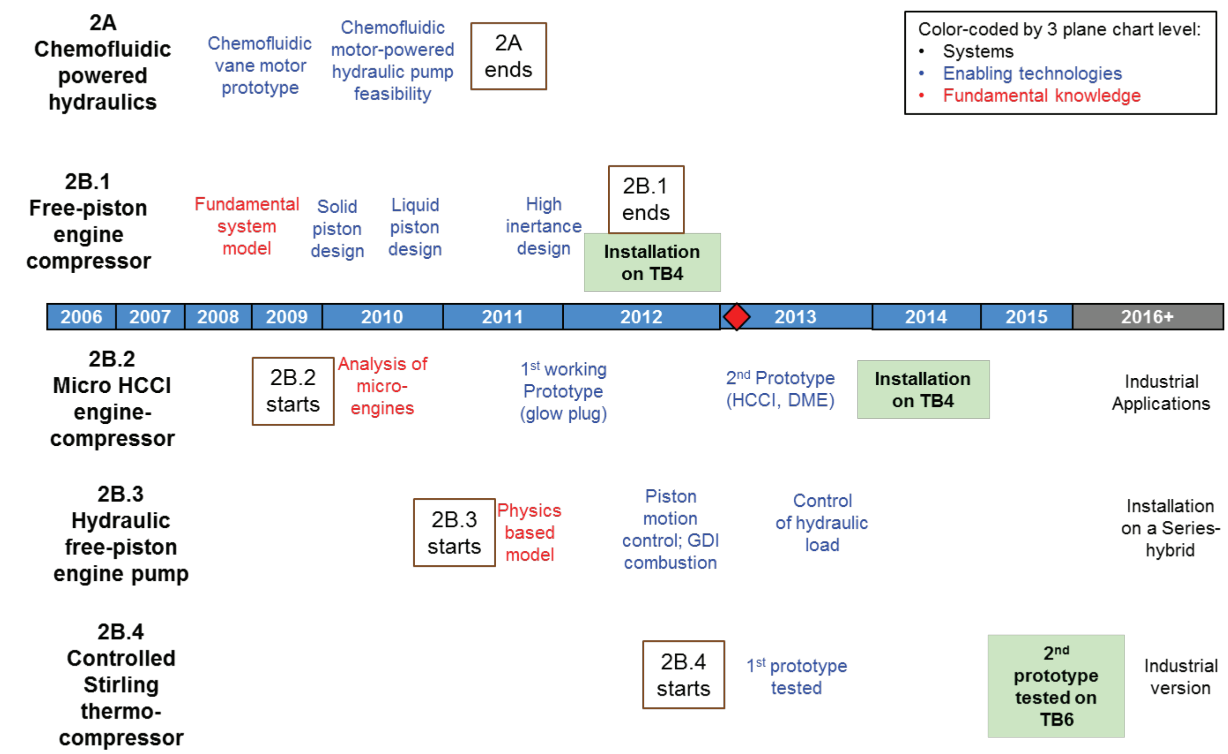
50 million people worldwide have epilepsy including some 2 million Americans. 30 percent of these patients suffer from seizures unresponsive to anticonvulsant drugs. Surgery offers a potentially

permanent cure by resection of the hippocampus, where seizures commonly begin, but the invasiveness of the procedure deters many from receiving treatment. A conceivable alternative to surgery is an MRI-guided robotic intervention whereby the hippocampus is thermally ablated. MRI provides the clinicians an imaging modality optimal for soft tissue distinction, as well as real-time monitoring of thermal therapy by MR thermometry. Fluid power offers a fully MRI-compatible form of actuation for the robot, thus enabling the use of intraoperative MRI.

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, a five degree-of-freedom robot was designed to steer a snake-like needle comprising superelastic nitinol tubes. The needle can curve around critical structures in the brain independently of reactive tissue forces. We 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.

The project addresses the technical barriers relating to compact integrated systems (by designing systems where valves, cylinders and sensors are not separate entities) and 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 supports the fourth CCEFP major goals, ubiquity, by applying fluid power in medicine.

Compact Power Supplies Technology Integration



Compact Power Supplies Milestone Chart

Multiple approaches have been taken in the Center to address the compact power supply barrier in order to enable long duration untethered human scale applications. They are:

- Chemofluidic actuated hydraulics (2A)
- Two free-piston engine-compressors at different scales, originally targeted for TB4 (2B.1) and for TB6 (2B.2)
- A hydraulic free-piston pump targeting vehicle application (2B.3)
- A newly added project on controlled Stirling thermo-compressor is targeted for TB6 (2B.4)

The chemofluidic vane motor driven hydraulic pump project (2A.1) ended in 2011. It aimed to take advantage of the energy density of hydrogen peroxide. Feasibility of this approach was demonstrated in 2009, albeit not at the desired efficiency. It was determined that much additional resources were needed to improve efficiency and performance.

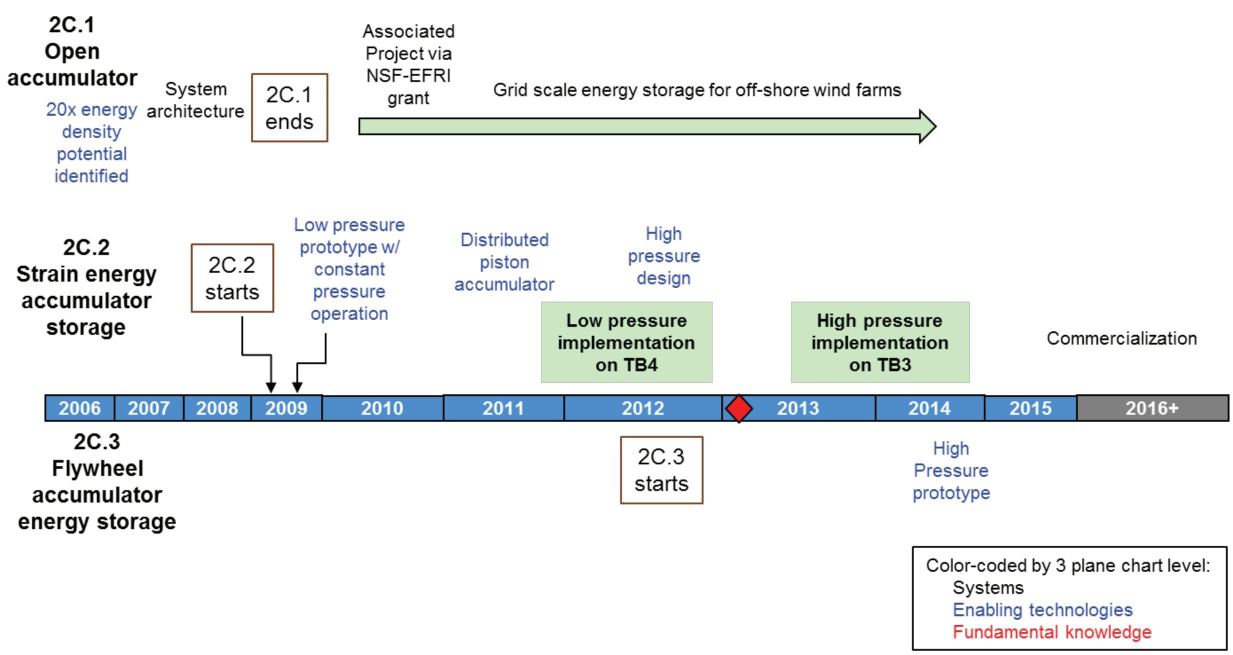
The small scale free-piston engine compressor (2B.1) which targets TB4 ended in 2012. Researchers developed a fundamental dynamic analysis of the engine-compressor in 2009 and subsequently developed tested several prototypes (solid piston in 2007, liquid piston in 2007, inertance tube in 2011) with efficiencies up to 6.6% and energy density up to 3750kJ/kg. The unit would enable a robot such as TB4 to operate for several hours without additional weight (thus outperforming all battery based electromechanical solutions). The compressor was implemented on TB4 in 2012, but a transistor failed before measurements were made.

The micro-scale free-piston HCCI engine-compressor (2B.2) was originally targeted for TB6-Orthosis. Detailed modeling and analysis was completed in 2010, leading to a learning prototype and first working protoyptpe in 2011. Detailed measurements were made in 2012. An improved prototype is expected in 2014. While a prototype will be implemented on TB4 in 2013, the anticipated heat and noise issues will hinder wearable applications. The long term prospect for this approach lies in collaboration with industry for applications such as hand-tools.

The hydraulic free-piston engine-pump (2B.3) takes advantage of the efficiency of a homogeneous charge compression ignition (HCCI) free-piston engine. A physics based model was developed in 2011. Control of the engine with GDI combusted was demonstrated in 2012. Control of hydraulic load is expected in 2013. Implementation on a series hydraulic hybrid vehicle is anticipated in 2016.

The Stirling thermo-compressor approach (2B.4) utilizes a Stirling heat engine to drive a compressor that uses high energy density hydro-carbon fuel. It is expected to be cool and quiet. Testing of the first prototype (now constructed) is expected in 2013. The second prototype is scheduled to be installed in TB6 in 2014 and an industrial version is to be developed in 2017.

Compact Energy Storage Technology Integration



Compact Energy Storage Milestone Chart

The energy density of a conventional hydraulic accumulator is nearly 2 orders of magnitude less than electric batteries. A 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. CCEFP has supported 3 approaches to date:

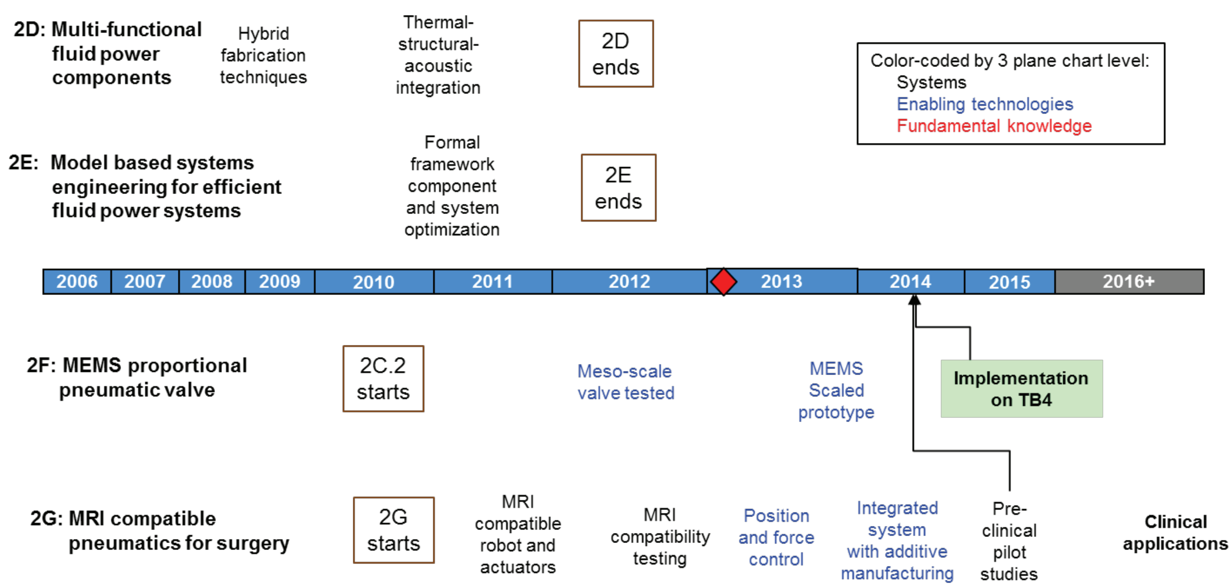
- Open accumulator (2C.1)
- Strain energy accumulator (2C.2)
- Flywheel accumulator (New project 2C.3)

Open accumulator (2C.1): This project 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 TB3 team found that the energy storage for ~200kJ would be sufficient for a hydraulic hybrid passenger vehicle. Thus, the target to increase energy density ten-fold can be relaxed. The open accumulator ended as a CCEFP core project and is now an associated project to develop utility scale wind energy storage with NSF-EFRI program support (2010). The technology has been licensed to two companies.

Strain energy accumulator (2C.2): This project proposes to storing energy in the strain energy of an elastomer. A low pressure prototype with near constant pressure operation and 85% efficiency was demonstrated in 2009. It suggested that a potential energy density improvement of 2-3 times is possible with the proper materials. Various improved architectures, including a distributed piston accumulator (DPA) configuration, were subsequently defined in 2011. Recent milestones include a high pressure DPA in 2012. A low pressure prototype was installed on TB6 (2012). Installation and testing of a high pressure prototype on TB3 is expected in (2013).

Flywheel accumulator (2C.3): This project was added in 2012. It uses a flywheel and gas-charged accumulator in combination and has the potential to increase energy density by an order of magnitude. Results from a high pressure prototype to establish the viability of this approach are expected in 2014.

Compact Integration Technology Integration



Compact Integration Milestone Chart

The Center has had two projects that address compact integration of hydraulics. Project 2D investigated how discrete components can be integrated to satisfy functional requirements. Project 2E focused on developing a formal system analysis and design methodology for fluid power systems. Both projects have ended and as of June 2012. There are at present no Center-funded projects focused primarily on developing methodologies for “compact integration”. However, component integration is being addressed in some manner by all but a handful of Center-funded projects..

On a component level, Project 2F, started in 2010, is developing a MEMS-based high flow, compact and low actuation power pneumatic valve to satisfy a need in TB6. This project 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 an alpha-MEMS prototype is expected in 2013. Implementation in TB6 is scheduled for 2014.

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 lists the effectiveness thrust projects funded during the reporting period and the barriers that they address. Further project details can be found in the following pages and in Volume II.

Thrust 3: EFFECTIVENESS	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	Supported projects and Test Beds
3A.1: Teleoperation Efficiency Improvements by Operator Interface	•	•					•			TB1, TB4
3A.2: Passivity Control for Fluid Power Systems		•					•			TB4
3A.3: Human Performance Modeling and User Centered Design	•	•					•			TB4, TB6
3B.1: Passive Noise Control in Fluid Power						•			•	TB3
3B.3: Active Vibration Damping of Mobile Hydraulic Machines	•	•				•	•		•	TB1
3D.1: Leakage and Friction 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: Multi-modal Human-Machine Interfaces

Fluid power applications potentially range from huge mobile excavators to human scale and smaller. In most of those systems, human operators directly interact with machines. The necessary communication between humans and machines directly impacts system performance and efficiency. Coordinated control and other more intuitive interfaces have been shown to reduce operator errors and shorten completion time. A negative aspect of the experimental devices used in prior studies was increased operator fatigue. Some potential interface improvements would be expensive to implement for an operator on the vehicle, but could be part of a system using teleoperation with minimal additional cost if teleoperation were preferred for reasons such as the remoteness of the work site or risk to an operator. Industry has seriously considered and in some cases adopted this option. Caterpillar robotic trucks operate in surface mines in remote areas of Australia today.

This project will establish the relationship between the user interface and fuel efficiency for a relevant range of dynamic system behaviors. The interfaces used will incorporate both traditional and experimental interface devices and sensory modalities appropriate to on-vehicle and remote operation relevant to deployment in mines and other hazardous locations. Prediction of the relative performance of interface approaches will be enabled for a range of applications. Implications for usability will be addressed through collaboration with researchers at NCAT.

Fluid power devices with improved operator interfaces will be used more effectively, thus reducing working time and hence the energy consumption (efficient components and systems, efficient control and efficient energy management barriers). New and existing devices will be able to safely perform their intended functions under human direction without undue workload on the operator (safe and easy to use barrier).

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

Traditionally, the human-machine interface (HMI) in many fluid power systems (e.g., an excavator)) rely predominantly on visual modality (e.g. levers, pedals) and to a lesser extent auditory modality (e.g. alarms) as the means of communicating between the human and machine. However, as operator workload/task increases, the visual modality can become overloaded due to the limited number of channels through which the machine and the operator can communicate. The overworking of the visual and speech modalities lead to operator fatigue that ultimately results in lower-performance and errors. The haptic modality has yet to be fully utilized in fluid power systems. A well-developed multimodal human machine interface has the potential to minimize user's cognitive workload when performing complex tasks as attentional resources will be drawn from different resource pools. Although the haptic interface promises reduced mental workload and improved operator performance over the traditional lever/pedal interface, its use as a control interface for the excavator has not been fully explored because the technology is still being developed.

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 addresses the effectiveness and efficiency barriers by comprehensively assessing fluid power system operator performance, by developing a quantitative human-machine interaction model that will help excavator designers better understand the limits of cognitive and physical capabilities of human operators of fluid power systems (efficient components and systems and efficient control barriers). These quantitative models are 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 and tools to improve the interfaces of emerging as well as existing fluid power systems.

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

Fluid power systems are routinely affected by oscillatory dynamics of moving parts which can lead to control stability issues. Undesired vibrations not only worsen controllability, but also reduce productivity and adversely impact operator comfort and fatigue and safety of operation. Despite research efforts to find solutions to control such oscillations, a general solution has not been found yet. Current damping methods are designed for specific applications and they can damp oscillations only in a limited range of operating conditions. Additionally, they usually introduce systems slowdown (capacitive methods) or energy dissipation (resistive methods). A first distinction among methods for vibration dampening is whether the hydraulic system is integrated with electronic control logic. According to this classification, there are pure hydraulic (essentially passive) solutions and electro-hydraulic (active) solutions.

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 (FP) applications. The solution should allow for a reduction of both amplitude and duration of actuator oscillation up to 70%. The solution also offers an energy consumption reduction. Using an adaptive control method based on pressure feedback (using pressure sensors located in well protected areas of the machine), the proposed techniques are suitable for all mobile applications without introducing significant cost increase.

This project primarily addresses the effectiveness technical barrier of safe and easy to use. Reducing the vibration levels in a machine will increase operator comfort, reduce and fatigue and improve the safety of operation. In addition, the project addresses the technical barrier of efficient energy management and the transformational technical barrier of efficient components and systems. In particular, the project proposes an innovative adaptive electro-hydraulic 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 novel electro-hydraulic damping method will allow the simplification of current hydraulic circuits through the removal of elements normally introduced to improve system dynamical behavior (compact integration barrier) and enlarge the area in which fluid power technology can be conveniently applied (ubiquity goal).

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

The fluid power industry has recognized that the reduction or elimination of leakage of hydraulic fluid from fluid power systems is a fundamental prerequisite for the expanded use of fluid power. There is also a need to reduce seal friction to both reduce energy dissipation and eliminate control problems. At the present time these seals are developed through empirical means, using trial and error techniques, since the fundamental physics of seal operation has been poorly understood.

The 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 addresses the effectiveness barrier of leak-free 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. The project also addresses the transformational technical barrier of efficient components and systems.

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

A fundamental rheological foundation for the field of elastohydrodynamic lubrication (EHL) has been lacking since its inception. For example, the proper definition has not been found for a parameter (a pressure-viscosity coefficient) to quantify the piezoviscous strength of any Newtonian liquid, regardless of the nature of the piezoviscous function, so that Newtonian film thickness may be predicted. In addition, the properties of a liquid that must necessarily be included in a film thickness calculation when the Newtonian prediction is inaccurate have not been specified. Also, the properties of a liquid that must necessarily be included in a full-film friction calculation have not been specified. This project is providing the rheological foundation to solve these important problems.

The goal of the project is to develop tools that may be used by engineers to design more compact, reliable and energy efficient fluid power components by improving the film thickness and reducing mechanical loss in the full-films occurring between non-conforming rolling/sliding machine elements

More compact components must necessarily have smaller radius of curvature of the contacting elements. A clear strategy for making compact components is also to increase the operating pressure. The resulting increase in contact pressure and decrease in radius of curvature of the sliding/rolling elements will result in diminished film thickness. The reduced film will impact the reliability. The ability to predict film thickness of any liquid from properties that can be measured and associated with the chemistry of the liquid will enable the formulation of fluids for improved durability at smaller scales.

Surprisingly, there has been little progress within EHL over the last forty years in explaining the mechanism of mechanical dissipation in full EHL films. In very recent related work using the temperature/pressure correlation devised by this project, the first experimentally validated EHL friction calculation was performed which included thermal-softening and shear-thinning. Fragility has been shown to be the principal property controlling friction. In particular, the results of this project may be used to rank the mechanical energy loss of contacts lubricated by fragile hydraulic oils.

The project addresses the technical barrier of safe and easy to use. Developing predictive techniques and design modeling tools makes it easier to design fluid power components and systems. In addition, the ability to understand the fundamental rheological foundation of EHL will facilitate the design of robust components in new regimes of operation, such as the higher pressures being investigated to reduce component and system size and increase the energy density of hydraulics (compact integration).

Project 3E.1: Pressure Ripple Energy Harvester

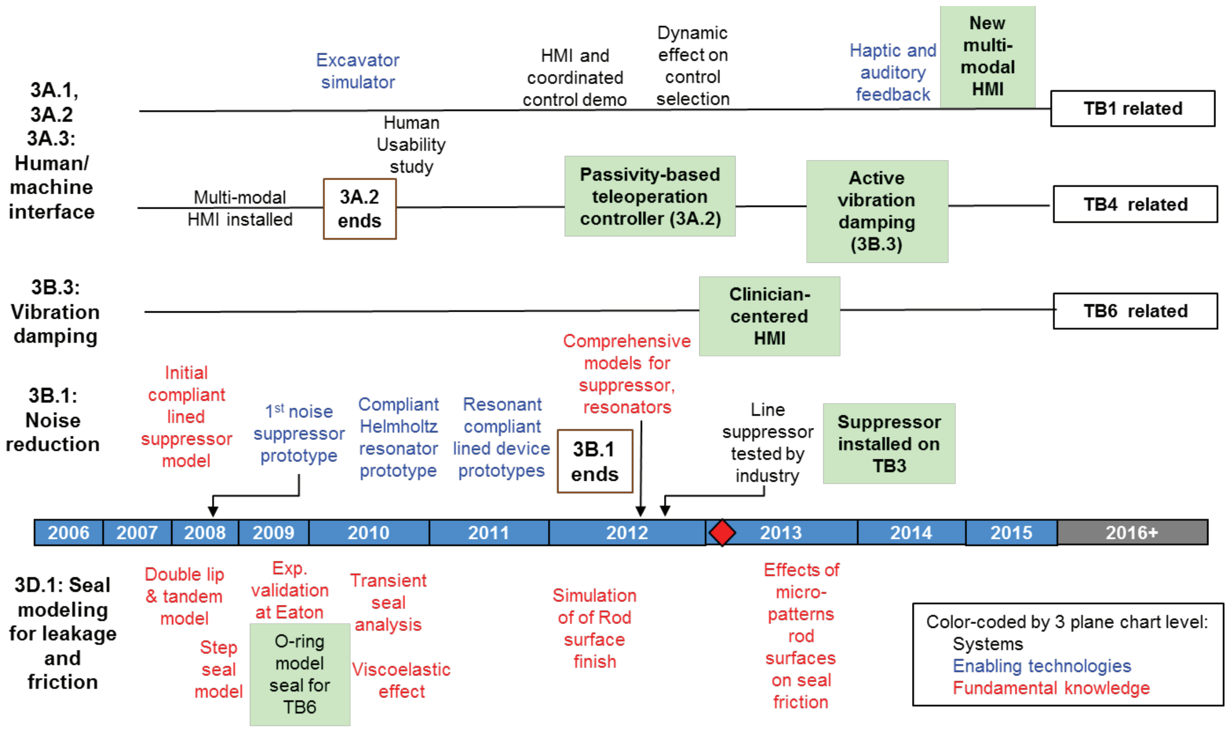
Hydraulic systems inherently have a high energy intensity associated with the mean pressure and flow. Accompanying the mean pressure is the dynamic pressure ripple, which is caused by the action of pumps and actuators. Pressure ripple is a deterministic source with a periodic time-domain behavior conducive to energy harvesting.

State-of-the-art hydraulic fluid connector systems (hoses, tubes and fittings) employ integral sensor nodes for structural health monitoring to avoid catastrophic failures. Energy harvesting in hydraulic systems could enable self-powered wireless sensor nodes and create an energy-autonomous structural health monitoring and prognosis system.

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 will be capable of being integrated into Test Bed 1 by Summer 2013; prototypes sized for sensor-node power requirements will be available by Spring 2014. An initial power response model will be available by Summer 2013; a refined model will be a major final deliverable in Summer 2014.

The research addresses the technical barrier of safe and easy to use since it enhances the utility and efficiency of hydraulic systems. In addition, it enables compact and efficient implementation of self-powered sensors and control capabilities which address the efficiency barrier of control and energy management. The technology could reduce the overall system complexity, improve reliability, and reduce maintenance costs. The technology will be demonstrated on test bed 1, the compact excavator.

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 passified control methods to ensure safe operation. Project 3A.3 is investigating fluid power system operator performance by developing a quantitative human-machine interaction model that will help excavator designers better understand the limits of cognitive and physical capabilities of human operators of fluid power systems. 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. Hatpic and auditory feedback for operator will be tested in 2014. A next generation multi-modal human interface will be developed and tested in 2016.

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

New TB4 - patient mover related: Active vibration damping will be applied in new TB4 in 2014.

TB6 related: A clinician-centered rehabilitation robot interface will be developed employing a user-centered approach and installed and tested in test bed 6 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 (2007-2012). 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, current work focuses on the modeling and then design of patterned rod surfaces to reduce seal friction.

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. A silencer is targeted to be installed on TB3 in 2013-2014.

TEST BEDS

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

The manner in which the test beds address the nine technical barriers is shown in the chart below.

Test Beds

	Technical Barriers								
	Efficient Components and Systems	Efficient Control	Efficient Energy Management	Compact Power Supplies	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet
Test Bed 1: Mobile Heavy 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: Precision Pneumatics	•	•	•	•	•	•	•	•	•

Technical Barriers Addressed by Test Beds

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

Research Team

Project Leader:	Monika Ivantysynova, Purdue University, School of Mechanical Engineering, Dept. of Agricultural & Biological Engineering
Other Faculty:	Andrew Alleyne, University of Illinois, Urbana-Champaign Wayne Book, Georgia Institute of Technology Paul Michael, Milwaukee School of Engineering Kim Stelson, University of Minnesota
Test Bed Manager/Staff:	Anthony Franklin
Graduate Students:	Rohit Hippalgaonkar, Enrique Busquets
Undergraduate Student:	Tridib Saha
Industrial Partners:	Bobcat, Caterpillar, Parker Hannifin, Moog, Husco, Sauer Danfoss, Sun Hydraulics.

1. Statement of Test Bed Goals

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

Beginning February 2012, the test bed has been transitioning to a demonstrator of a novel hydraulic hybrid configuration, called series-parallel hybrid DC system, for which a patent was applied in 2011. The series-hybrid architecture will introduce secondary controlled actuation for the swing drive in combination with the implementation of an energy storage system in parallel to the other DC actuators for the remaining working functions. Such architecture enables energy recovery from all actuators, capture of swing braking energy and 50% engine downsizing. It promises fuel savings beyond those achieved with the prototype non-hybrid DC excavator, as was previously shown through simulation studies in project 1A2 ('Multi-Actuator Hydraulic Hybrid Machine Systems'), which concluded in June, 2012.

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.

2. Test Bed Role in Support of Strategic Plan

The compact excavator test bed primarily addresses the efficiency thrust of the Center. The prime role of the test bed is to be a demonstrator of energy savings that are possible in multi-actuator machines, through efficient system architectures (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 is well positioned for testing of 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 accumulator, Project 2C.2).

The successful demonstration of DC will open new applications in both large scale mobile machinery and robots, and in human-scale applications like surgery robots or other portable devices where efficient and compact actuator technology is necessary.

3. Test Bed Description

A. Description and explanation of research approach

The state-of-the-art in hydraulic drive and actuation technology involves the use of different forms of resistance control through the use of valves. Most mobile applications use load-sensing (LS), negative flow control (NFC), positive flow control (PFC) or similar architectures. In those systems one or two hydraulically controlled variable displacement pumps provide flow to all actuators by adjusting the system pressure to the highest required pressure of all actuators. Control valves throttle flow from the operating pressure to the desired actuator pressure and meter flow in accordance with respective operator inputs. This leads to large throttling losses across the control valves supplying all actuators except the actuator operating at maximum pressure (in a typical cycle, only one or two actuators operate at high pressures, with the others at low or medium pressures). Further, energy from braking or lowering of actuators is either recovered very inefficiently or not at all, through these architectures.

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

In the hybrid DC version (Fig. 1) of the test bed (Feb 2012 onward), braking energy of the swing is captured in a hydraulic accumulator, by using a secondary-controlled, over-center, variable displacement motor for the swing drive, as opposed to a fixed displacement motor that was previously in use. The energy stored in the accumulator may be re-used either for reducing the load on the engine or for powering the swing at a later stage. The proposed system architecture does not require any additional units compared to the DC non-hybrid prototype, and energy from the boom, stick and bucket can be recovered through the DC circuits.

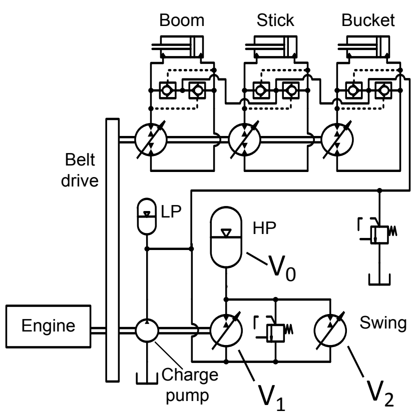


Figure 1: Series-Parallel Hybrid DC Excavator

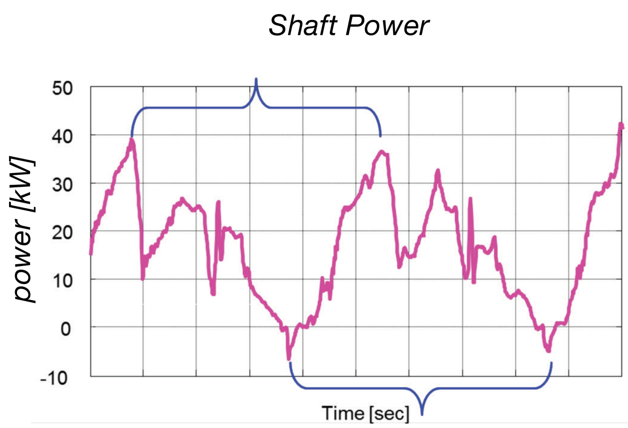


Figure 2: Excavator Truck-Loading Cycle Power Requirement

The typical cyclical operation of these machines, together with added energy storage capability, leads to the idea that engine downsizing is possible with appropriate power management. Peak power requirements would be met by assistance from the accumulator. On the test bed, the engine will not be downsized, however through the use of appropriate power management, engine load will be limited to 50% of peak power in order to demonstrate the feasibility of the concept in a functioning machine.

Caterpillar will soon be releasing (April 2013) the hydraulic hybrid version of a 37 ton excavator (336E H) and next year will announce the release of a hydraulic hybrid loader. The 336E H uses a parallel hybrid architecture, wherein an extra pump/motor is added to the engine shaft, in parallel to the pumps supplying the working actuators. The additional pump is responsible for charging and discharging the accumulator. Caterpillar has claimed 25% fuel savings over the 336E, and although details are not yet available, it is claimed that swing braking energy is captured. However, the addition of another pump in the Caterpillar system will introduce additional power losses to the system. This is not the case in the in CCEFP proposed new series-parallel hybrid DC architecture. Also, due to the fact that all remaining functions are still valve-controlled, it is not possible or very unlikely that energy can be recovered from other working functions like boom, arm or bucket in the 336E-H Caterpillar machine.

B. Achievements

Achievements Prior to Reporting Period

- Four variable displacement pumps were installed on TB1 (compact excavator) along with associated sensors and electronic control hardware. From 2008-2011, all 8 functions (swing, boom, stick, bucket, track drives, boom offset, and blade) were displacement controlled.
- Control laws for pump displacement, actuator position and actuator velocity control were designed and implemented on TB1.
- The DC hydraulic system was demonstrated by video at the CCEFP annual meeting on October 7, 2009 and in person to a delegation from Caterpillar on November 4, 2009.
- Simulation and measurement results determined that at least 50% of the cooling power requirement in the system could be reduced
- Productivity and fuel test for TB1 with DC hydraulics was conducted in cooperation with Caterpillar, Inc.; TB1 consumed 40% less fuel, on average, than the standard machine while moving the same amount of dirt and productivity was increased by 16.6%, which lead to a fuel efficiency (tons/kg) improvement of 69%.
- A proposed optimal power management algorithm from Project 1A2 was evaluated and fuel efficiency results indicated a 56.4% improvement for an artificial pipe-laying cycle, without power management.
- In April 2011, the prototype DC excavator was evaluated for fine actuator control to the satisfaction of a team of Bobcat expert operators, test and system engineers in Bismarck, ND.
- Through project 1A2, a feasibility study predicted that the novel series-parallel hybrid system could be limited to half of the maximum engine power, suggesting that the engine size could be reduced without sacrificing the productivity of the machine for the truck loading cycle.
- With a very conservative power management strategy demonstrated that this hybrid configuration together with downsized engine, can achieve 52% fuel savings compared to the standard machine (> 20% over the prototype DC excavator). Optimal power management promises around 27% fuel savings over the non-hybrid DC excavator.
- Optimal sizing studies using dynamic programming were undertaken that evaluated various possible unit (primary and secondary units) and accumulator sizes and pre-charge pressures, independent of system control strategy. Component sizing on the prototype hybrid DC excavator uses the results of the optimal sizing study.

Achievements During Reporting Period

Optimal Sizing of Series-Parallel Hybrid DC Architecture

The initial reported results of the series-parallel hybrid DC excavator system showed 20% fuel savings over the DC system and the potential for 50% engine downsizing in a simulation using a conservative static sizing methodology as well as a conservative power management strategy. Within the reporting period, an optimal sizing study was undertaken that evaluated various possible primary and secondary units and accumulator sizes, as well as pre-charge pressures, independent of system control strategy.

Component sizing on the prototype hybrid DC excavator was made using results from the sizing study – with closest available components being used to the optimal sizes (Table 1).

Table 1: Actual Component Sizes Used on Hybrid DC Prototype Excavator

$V_{d,1}$	$V_{d,2}$	$p_{hp,min}$	V_0
18 cc/rev	40 cc/rev	250 bar	6 L

System Integration
The detailed circuit currently implemented for the swing drive on the test bed, is shown in Fig. 3.

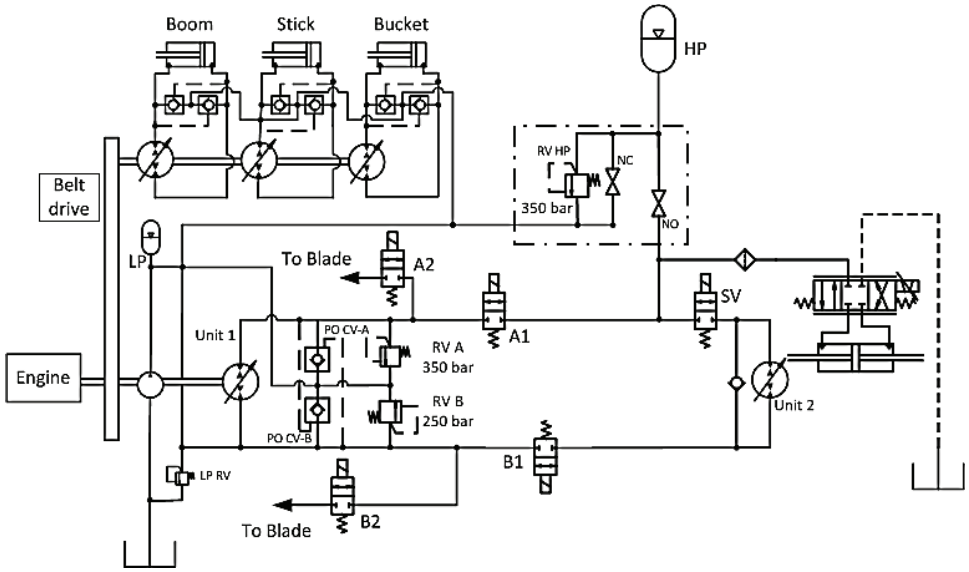


Figure 3: Detailed Schematic for Swing Drive on Prototype Excavator

The fixed displacement swing motor (820 cc) previously used on the DC non-hybrid prototype, has been replaced with a secondary-controlled, variable, over-center swing motor (40 cc, bi-directional, 'unit 2' in Fig. 3). Unit 2 is secondary-controlled and is part of a series-hybrid configuration together with unit 1 (same 18.3 cc variable pump/motor as the non-hybrid version of the test bed, which was used as pump to drive swing on DC, non-hybrid test bed).

A 2-stage planetary gear-box (ratio 19.46) used on the latest M-series of Bobcat excavators (which use 31 cc fixed displacement swing motor) has also been incorporated on the test bed. It provides a higher gear reduction (i_g = 147.2) between unit 2 and cab (previously i_g = 5.35), thus allowing unit 2 to run at higher speeds (up to 1350 rpm), with cab speeds as before (up to 9.5 rpm).

Unit 2 is operated in a speed controlled manner, with the operator joystick command being interpreted as a speed command for the swing motor. The requisite sensors for speed and swash-plate position sensing have been instrumented on the test bed. A position sensor has also been added for closed-loop position control to hold the cab at rest against unexpected loads (gravity, side-loads during digging or from tracks).

Logic valves A1, B1 are opened (while A2 and B2 are simultaneously closed) provide flow from unit 1 to swing circuit. In the opposite configuration, with A2 and B2 open (with A1 and B1 closed) unit 1 provides flow for actuating the blade. A safety-valve 'SV' is used to shut-off unit 2 from the high pressure accumulator during loss of power. Swash-plate adjustment for unit 2 is done using high pressure from the accumulator. A safety block between the accumulator and both units houses a high pressure relief valve ('RV HP', 350 bar), a bleed valve 'NC' to empty the accumulator after operation, and an enabling valve 'NO' that is kept open during operation.

Results from Preliminary Testing
The hybrid hydraulic DC system is now operational on the test bed. The linear working actuators (boom, stick and bucket) are functional as before, while the secondary-controlled swing motor is now showing desired behavior (Fig. 4(a) and 4(b)).

In preliminary testing, the speed command is followed reasonably well by unit 2 (Fig. 4 (a)), while unit 1 is currently controlled so as to maintain a high pressure (200 bar) in the accumulator. It can be seen from Fig. 4(b) that unit 2 moves over-center during braking of the swing motor. There are still certain issues that need to be addressed such as the over-shoot in speed and the lag in response during start-up.

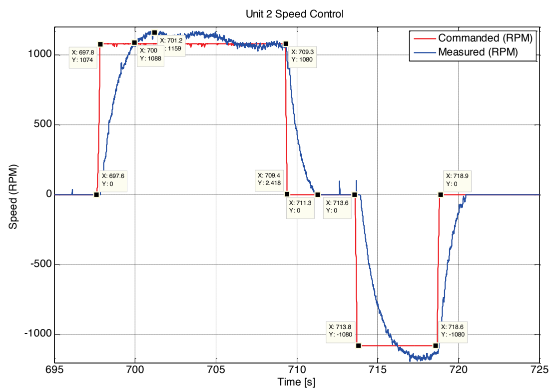


Fig. 4(a): Speed Control of Unit 2

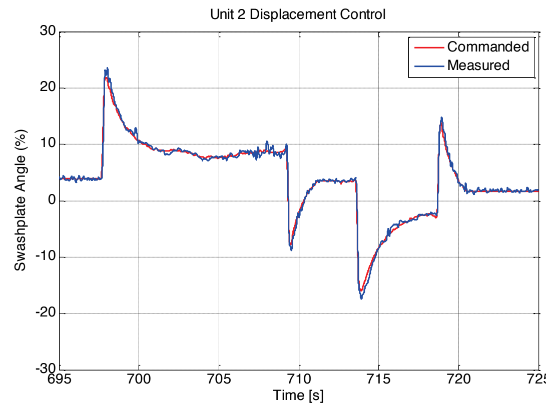


Fig. 4(b): Displacement Control of Unit 2

Significant progress has been achieved on the excavator in the past three months, and testing will resume from March, 2013 to meet the planned achievements on the test bed.

<u>Planned Achievements following the reporting period</u>
Deliverables driven by results from Project 1A2

- Further improvements to the speed control of the swing motor will be made. [03/15/2013]
- Simulations will be performed that will predict the fuel and energy consumption of hybrid DC excavator for a typical digging cycle, with the full-sized engine. [03/15/2013]
- The excavator will be operated in a typical excavator loading cycle, for demonstration purposes. [04/10/2013]
- 'Single-point' power management strategy will be implemented on the test bed during the expert truck-loading cycle. [06/01/2013]
- Fuel testing and measurements will be done on the test bed, after sufficient development of energy-saving control, for an expert truck-loading cycle. [06/15/2013]
- Advanced power management strategies that exploit all possible degrees of freedom available on the system, including variation of engine speed. [09/15/2013]
- Incorporation of pump-switching architectures and control strategies that would enable maximum number of combinations of actuators to be used with the minimum number of pumps in DC hybrid machines (from new project 1A2). [10/01/2014]
- Incorporation of system prognostics schemes. [06/01/2015]

Deliverables for results related to associated projects

- Integration of high speed valves from project 1E2 to create a virtual variable displacement pump for low pressure system and measurements or resulting energy savings [03/01/2014]
- Comparison of energy consumption of the test bed using standard hydraulic oil and energy efficient fluids developed in project 1G1 [06/01/2014]
- Integration of next generation of efficient pumps from project 1B1 for control of a single actuator [2016]

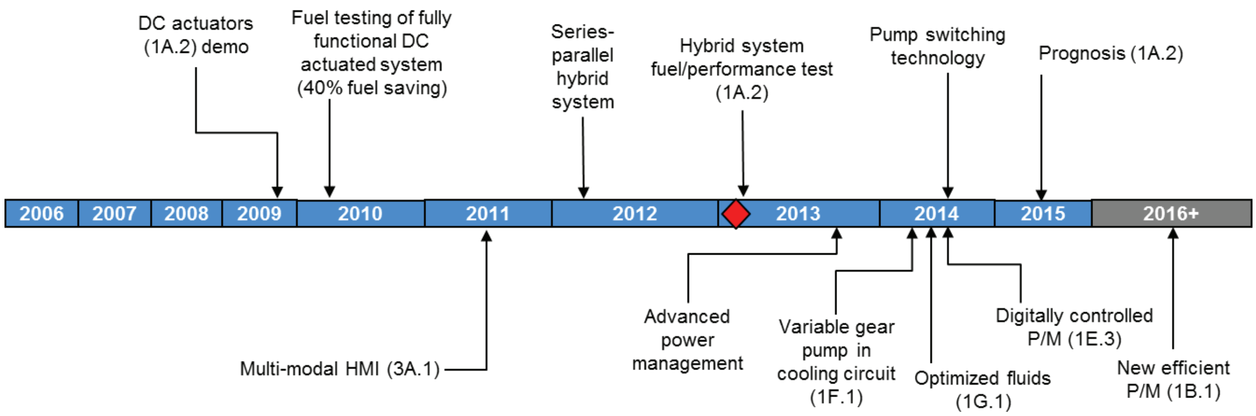
C. Member company benefits

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

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

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

Test Bed 1 Technology Integration



Test Bed 1 Milestone Chart

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

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

- A variable displacement gear pump to reduce throttling loss in the cooling system will replace the fixed displacement pump and be tested in 2014. (1F.1)
- The effects of optimized hydraulic fluid and non-optimized hydraulic fluid will be tested in 2014. (1G.1)
- The high efficiency digital displacement pump will be tested in 2014. (1E.3)
- A high efficiency pump based on optimized gap surfaces will be tested in 2016. (1B.1)

Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Research Team

Project Leader:	Perry Y. Li, University of Minnesota
Other Faculty:	Thomas R. Chase, University of Minnesota
Graduate Students:	Kai-Loon Cheong, Jonathan Meyer, Zhekang Du, Stephen Sedler and Henry Kohring
Undergraduate Students:	David Rose, Andrew Harm
Industrial Partners:	Bosch-Rexroth, Eaton, Parker Hannifin, Sauer-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 drastic 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: (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) meeting California emissions standards; and (v) size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market. Resulting powertrains 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 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.

3. Test Bed Description

A. Description and explanation of research approach

The high power density of hydraulics makes it an attractive technology for hybrid vehicles since it should be able to provide both high mileage and high performance. 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 drivetrains must overcome limitations in component efficiency, energy storage density, and noise. These barriers represent worthwhile challenges that stretch the envelope of existing fluid power technologies.

Electric hybrids provide the closest competition to hydraulic hybrids. While hydraulic hybrids cannot match the energy density provided by electric batteries, they have superior power density. This is particularly valuable for regenerating braking energy. Furthermore, hydraulic hybrids eliminate the need for batteries, and thereby eliminate the cost, life and environmental concerns associated with them.

Three possible families of architectures for hybrid drivetrains are series, parallel and power split. A series drive transmits all power from the engine to the wheel with hydraulic pumps and motors. This architecture enables running the engine at its most efficient combination of torque and speed; however, it cannot take advantage of the high efficiency of purely mechanical power transmission through a shaft. A parallel architecture augments the engine with a pump/motor. It transmits power to the wheels through the efficient mechanical shaft, but it has less ability to keep the engine at its best operating point. TB3 focuses on power split architectures, which combine the positive aspects of both approaches.

This test bed is currently developing two hydraulic hybrid passenger vehicles, each of which offers unique research benefits. The “Generation I” vehicle (see Fig. 1) was built in-house using the platform of a utility vehicle (Polaris “Ranger”). The vehicle has been outfitted with a modular powertrain. This enables experimenting with different pump, motor and energy storage technologies, including those developed in complementary CCEFP projects. However, this vehicle cannot be driven at speeds higher than about 25 MPH due to concerns about vehicle stability.

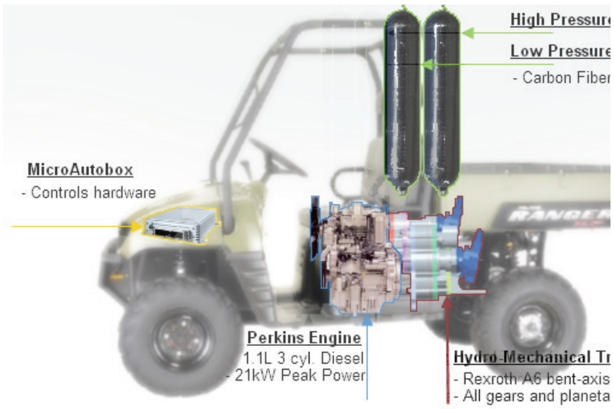


Figure 1: Test Bed 3 Generation I vehicle

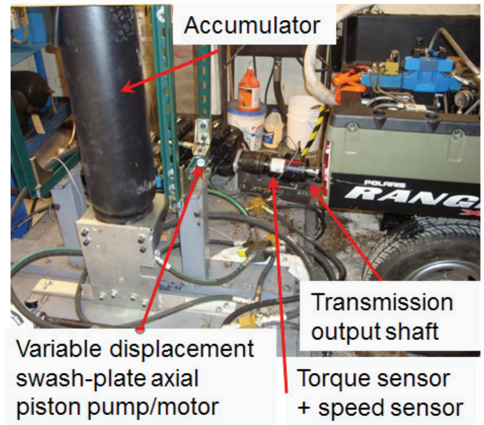


Figure 2: Hydrostatic dynamometer connected to the output shaft of the vehicle transmission

The “Generation II” vehicle is being developed in partnership with Folsom Technologies International (FTI). It is built on the platform of a 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 powertrain is built as a compact, integrated, self-contained package. However, the integrated package prevents changing 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 I” vehicle is being continued despite the pending availability of the roadworthy “Generation II” vehicle.

B. Achievements

Achievements Applicable to Both Vehicles

Controls firmware upgrades (previous years): The Generation I vehicle has previously used “xPC Target” firmware to interface the controller with the powertrain. We have converted to real time firmware that is popular for automotive systems, “Micro-Autobox”. The conversion improves both the hardware and software robustness. Since Micro-Autobox is a standard system for automobiles, utilizing it for implementing the TB3 controllers simplifies migration of the controller to the Generation II vehicle.

Energy Management Strategy (previous years): An energy management strategy which can be applied to the control of either vehicle has been developed based on the Lagrange Multiplier method. The original method is limited by two restrictions: (1) the accumulator is assumed to remain at a constant pressure, which is equivalent to assuming that it is infinitely large, and (2) the drive cycle must be known beforehand. The new strategy overcomes the first restriction. Two alternative implementations of the new strategy are possible. The first approach is more computationally intensive in real time, while the second gains in computational efficiency by optimizing it in advance of applying it in real time. Both alternatives are able to maintain the state of charge of the accumulator within its physical limits. The new approaches exhibit only a 3-5% penalty on fuel economy compared to dynamic programming, which is the best, but most computationally expensive, optimization method.

Achievements Applicable to the Generation I Vehicle

Drivetrain Redesign (previous years): The original drivetrain for the Generation I vehicle utilized differentials which did not meet the torque specifications of the drivetrain, and it had poor reliability due to excessive usage of chains and belts. Therefore, the drivetrain was completely redesigned in 2010 to utilize gears exclusively. Assembly of the new transmission was completed in August 2011.

Hydrostatic Dynamometer System Design and Implementation (2011-12): A hydrostatic dynamometer was designed in-house in 2011 and constructed in 2012. The dynamometer is designed to test mid-size vehicles through EPA’s Urban Dynamometer Driving Schedule and Highway Schedule. The reason for building an in-house dynamometer is to provide rapid and repeatable experimental evaluation of the hybrid powertrain's performance. The dynamometer eliminates the need to transport the vehicle to a test track or an off-site chassis dynamometer with motoring capability, neither of which is conveniently available. It also enables testing with reasonably repeatable environmental conditions during all seasons. Figure 2 shows the dynamometer connected to the output shaft of the transmission of the Gen I vehicle.

A novel controller was implemented to enable the dynamometer to exert the desired torque on the vehicle output shaft. First, a system identification procedure was performed on the pump/motor utilized within the dynamometer. Since the dynamometer is used to mimic the road load as if the vehicle is driving on the ground, the inertia torque of the vehicle must be estimated and included in the dynamometer torque. However, calculating the inertia torque requires the acceleration, which in turn requires information from the future; i.e., it is a non-causal parameter. In order to solve the causality problem, a "virtual vehicle" concept was devised. The controller tracks the virtual vehicle speed instead of estimating the acceleration directly. This approach guarantees that the dynamometer output torque is correct. This algorithm also allows fuel economy evaluation for vehicles of different weights.

Regenerative braking event experimentally tested (2012): The dynamometer was designed with the ability to motor so that regenerative braking events can be simulated, which constitute an important benefit from hybridizing the powertrain. A maximum motoring torque of 85 Nm was achieved and the equivalent vehicle speed decreased from 50 mph to 9 mph. The pressure in the vehicle's accumulator increased from 82 bar (1200psi) to 102 bar (1500psi), indicating successful energy recuperation. Graphs showing the experimental data corresponding to this event are shown in Fig. 3.

New Engine Installation and Characterization (2012): The vehicle originally had a 1.1L diesel engine. That engine was damaged in Fall 2012. We had learned that the original engine was undersized due to the underestimation of the losses from the valves and pump/motors. Simulations using actual loss data revealed that the engine size should be 1.5L, so a replacement engine of that size was purchased and installed. The new engine required extending the vehicle frame. However, it is now capable of driving the vehicle through federal cycles in the presence of valve and pump/motor losses.

An engine efficiency map is necessary to optimize the drivetrain operation of the vehicle. Engine performance data provided by the manufacturer is inadequate to create this map. Therefore, our hydrostatic dynamometer was utilized to characterize the engine. Figure 4 shows engine efficiency map created from our experimental results.

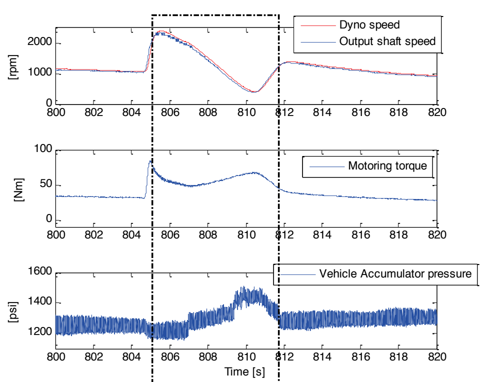


Figure 3: Regenerative braking event experimental data. Top: Drive shaft speed. Center: Motoring torque. Bottom: Vehicle accumulator pressure.

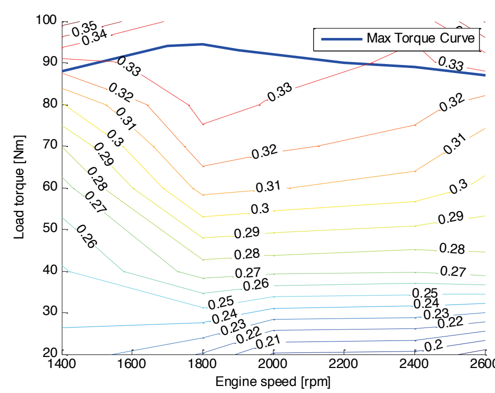


Figure 4: Engine efficiency map generated from experimental results. Note: curves above max torque curve are artifacts of extrapolation.

Hardware and Electrical Upgrades (2012): Three significant mechanical upgrades were made on the Generation I vehicle chassis to improve performance and reliability. First, the engine throttle control was upgraded from a problematic stepper motor and cable based system to fuel solenoid control. Second, the charge pump was removed from the transmission and replaced with an electric motor to drive it. This change eliminated potentially problematic scenarios where charge pressure would not be sustainable.

Third, a hydraulic circuit to facilitate start-up of the vehicle was developed. The original design had a flaw that the valves utilized to set the direction of the vehicle's pump/motors require pressure to operate. However, the pressure was obtained from the high pressure accumulator, which required flow from one of the pump/motors to pressurize it. The problem was temporarily solved by replacing one of the directional valves with a cross-over plate, which eliminated the ability to reverse one of the pump/motors. The new start-up circuit enables developing initial pressure in the high pressure accumulator with the charge pump. Once enough pressure is developed to operate the directional valves, the charge pump is switched out of the high pressure circuit, eliminating the need for the cross-over plate.

The vehicle's wiring was also improved. We discovered that many of the vehicle's electrical circuits were unintentionally routed through a switch. This arrangement was resulting in a 25% voltage drop to many of the vehicle's systems. The vehicle chassis was re-wired, which resulted in significant simplification and improved electrical performance.

<u>Achievements Applicable to the Generation II Vehicle</u>
Efficiency Map Test Plan and Test Results (previous years): In order to fully optimize the operation of the hybrid hydro-mechanical transmission, one must identify the overall efficiency of the transmission in various hybrid operating conditions. A method has been developed at the University of Minnesota for approximating this efficiency even though the pump/motors in this transmission are intrinsically coupled and cannot be tested individually. The efficiency of the FTI transmission is determined using a 400 HP dynamometer available at the FTI facility. Two different types of transmission fluid have been tested: conventional automatic transmission fluid (ATF) with a viscosity of 5 cSt and an Evoniks Rohmax fluid with a viscosity of 15 cSt. A graph in the Year 6 report reveals that the Rohmax fluid has greater or equal efficiency under all conditions tested, peaking at 92%.

Transmission Test Data Analysis (2012): FTI provided what was expected to be a final set of performance data for the Generation II vehicle transmission, obtained using their dynamometer, in mid-2012. However, Minnesota's anaylsis of that data revealed that the transmission was leaking excessively. FTI identified the source of the leakage as broken seals in the transmission's pump/motors. At the time of this writing, the problematic seals have been replaced, and we are waiting to gain access to the FTI dynamometer to obtain corrected performance data.

Controls Hardware Integrated (2012): Minnesota prepared a Micro-Autobox unit for the Generation II vehicle and shipped it to FTI. Development proceeds in three stages. The first is "software in the loop" (SIL), in which all hardware functions are simulated. The second is "hardware in the loop" (HIL), in which actual sensors and actuators are connected, but the engine and transmission performance are simulated. The third is full hardware implementation. We are currently in the SIL phase. Ford is developing signall conditioning and actuation circuits for the HIL phase, which they will donate to the project.

<u>Plans for the Generation I Vehicle</u>
Plans for the Generation I vehicle include: testing the redesigned transmission in continuously variable transmission (CVT) mode, integrating the Project 1A.1 high level control strategies, testing the efficiency of advanced hydraulic fluids, determining the efficiency of a virtually variable displacement pump/motor created in Project 1E.1, and testing two novel accumulators. These plans are described in order below.

Initially, the Generation I transmission will be operated in a degenerate CVT mode rather than as a full hydraulic hybrid. These experiments have two purposes. First, operation as a CVT serves to prove the effectiveness of the low level control strategy. Second, the fuel economy obtained from operation as a CVT provides a benchmark for comparing improved energy management strategies.

A project which utilizes the Generation I vehicle as a test bed for Project 1G.1 (Tribofilm Structure and Chemistry in Hydraulic Motors) is planned. A synthetic biodegradable ester will be utilized as the hydraulic fluid, which is expected to exhibit higher efficiency at low speeds [10]. The new oil will be compared with a shear stable high viscosity index hydraulic fluid which serves as the baseline oil for the vehicle. The new vehicle dynamometer will be utilized for these tests.

Hybrid operation will be tested next with the implementation of various energy management strategies. Both the modified Lagrange multiplier strategy and Project 1A.1's rule-based control strategy will be implemented. 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 2013.

The vehicle will be tested on ground in a parking at the University of Minnesota. After that, the synthetic biodegradable ester will be utilized as the hydraulic fluid and tested on the vehicle again in hybrid mode. The controllers will be fine-tuned using data gained from these tests.

The bent axis pump/motor used as pump/motor "S" will be replaced with a pulse width modulated virtually variable displacement pump/motor (VVDPM) designed in Project 1E.1 during Fall 2013. Simulations have been performed to optimize the gear ratios for the pulse width modulated pump/motor [8]. The actual efficiency using the new pump/motor will be experimentally determined and compared to the baseline efficiency.

Two new accumulator designs will be tested during the 2013-2014 period. Discussions are currently in progress for testing an efficient accumulator developed by an outside corporation that operates at near isothermal conditions. Also, a prototype of the strain energy accumulator being developed by Project 2C.2 is expected to be ready for testing next year. The strain energy accumulator will have the advantage of constant pressure operation, thereby improving its energy density. The modular architecture of the redesigned transmission enables the pump/motors to be changed out.

<u>Plans for the Generation II Vehicle</u>
Dynamometer tests will be performed to generate a performance map for the transmission in the same state as it is expected to be installed in the F-150 truck. Much of the controller development that has been completed for the Generation I vehicle will be adapted to the Generation II transmission with only fine tuning required to account for architectural differences. After the Generation II vehicle is fully functional, a continuously variable transmission control strategy and hybrid control strategy will be tested.

<u>Milestones and Deliverables</u>
Gen I:

- Efficiency evaluated in continuous variable transmission (CVT) mode (3/13)
- Efficiency of alternative hydraulic oils compared in CVT mode (4/13)
- Project 1A.1 control schemes compared using MN dynamometer (6/13)
- Ground driving tested (7/13)
- Efficiency of alternative hydraulic oils compared in hybrid mode (8/13)
- Project 1E.1 pump/motor installed as Pump/Motor "S" in Generation 1 vehicle (10/13)
- Project 2C.2 strain energy hydraulic storage integrated on Gen 1 vehicle (1/14)

Gen II:

- Transmission dynamometer testing completed (6/13)
- Dynamometer testing data analyzed and model correlated (7/13)
- Transmission installed in F150 chassis (8/13)
- CVT control strategy demonstrated (11/13)
- Hybrid control strategy demonstrated (3/14)
- EPA cycle fuel economy evaluated (5/14)

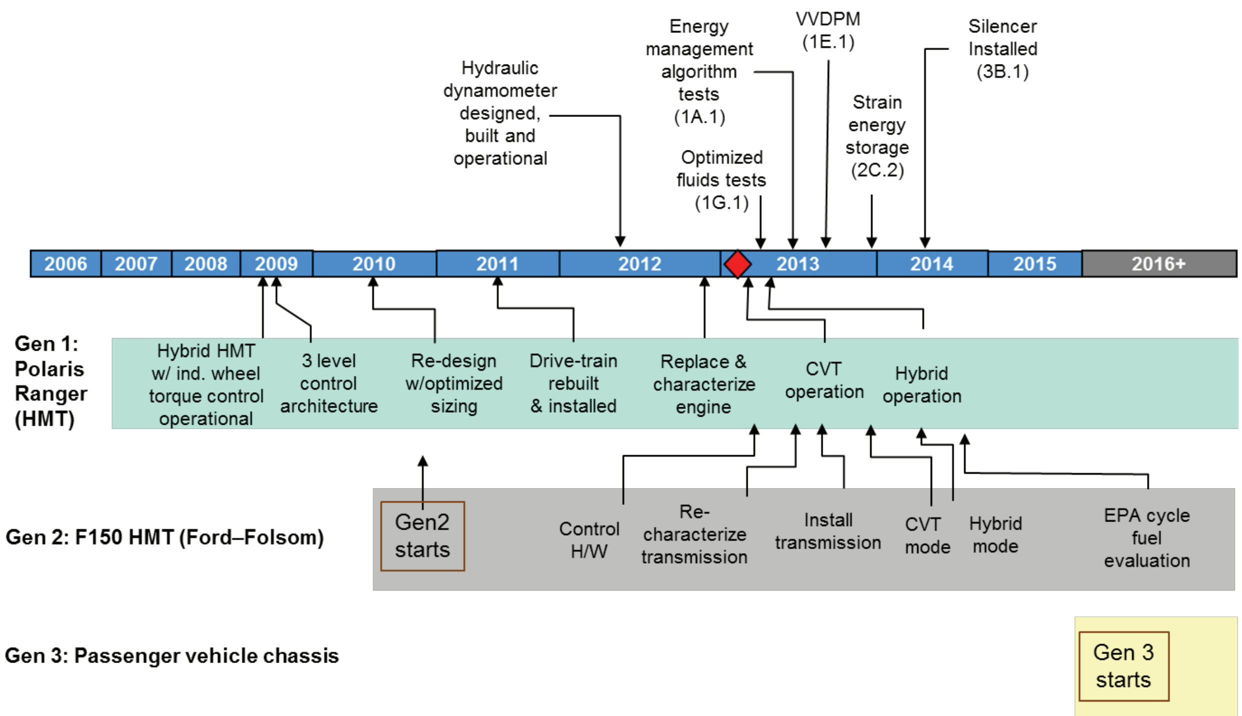
Gen III:

- Initiation of Generation 3 transmission design on mid-size sedan vehicle (5/14)

C. 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 utility vehicle chassis with a UMN designed and custom built hybridized input coupled hydro-mechanical transmission (HMT). The Gen 2 vehicle is a Ford F150 pickup equipped with an output coupled HMT provided by Folsom Technologies.

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

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

- The effect of two hydraulic fluids on fuel economy will be tested in 2013. (1G.1)
- Various energy management control algorithms that have been designed will be tested in 2013. (1A.1)
- The rotary spool-valve based virtually variable displacement pump/motor will replace the bent-axis “speeder” P/M and undergo testing in 2013. (1E.1)
- A strain-energy storage prototype will be installed and tested in 2013/2014. (2C.2)
- A silencer will be installed and tested in 2014. (3B.1)

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. It is expected that the transmission will be re-characterized and installed on the F150 later in 2013. A control approach similar to Gen 1 will be implemented and tested afterwards.

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

Test Bed 4: Patient Transfer Device (formerly Rescue Robot)

Research Team

Project Leader:	Wayne J. Book, Mechanical Engineering, Georgia Institute of Technology
Other Faculty:	Stephen Sprigle, School of Applied Physiology, Georgia Institute of Technology James Huggins, Research Engineer, ME, Georgia Institute of Technology
Graduate Student:	Heather Humphreys
Undergraduate Student:	Michael Baker
Industrial Partners:	Parker-Hannifin, Eaton

1. Statement of Test Bed Goals

The goal of this test bed is to demonstrate a mobile fluid powered patient transfer device, an example of a portable, un-tethered human scale fluid power application. It is intended to transfer mobility-limited patients, including bariatric patients, for example, 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 (all day for typical transfers), produce sufficient force to transfer bariatric patients (up to 500 lbs), and have precise, intuitive control.

2. Test Bed Role in Support of Strategic Plan

The Patient Transfer Device occupies the power range from ~100W~1kW in the CCEFP's efforts to apply to the full power range of applications. 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.

3. Test Bed Description

D. Description and explanation of research approach

Overview

Test bed 4 is a human scale CCEFP test bed. Originally, TB4 was targeted as a rescue robot which will be dealt with briefly here and in the advancement section. We are now redirecting this effort to a patent transfer device intended for moving mobility-limited patients, for example, from bed to wheelchair, wheelchair to shower chair, or floor to wheelchair. This application fits well with the CCEFP goals in that a system for this application requires attributes of a fluid power system that the CCEFP is working to achieve, such as compactness, low leakage, low noise, high power, reliability, and intuitive, effective control. Similar research challenges occur in both the rescue crawler and the patient transfer device, such as interaction with human operators and impaired individuals. Furthermore, we can take advantage of advancements in the same areas as the rescue robot without some of the obstacles irrelevant to fluid power research. For example, the large number of degrees of freedom and multiple copies of custom hardware made the rescue robot highly sensitive to failure; the patient transfer device requires fewer degrees of freedom and fewer custom hardware components. Also, DoD and DARPA have invested large sums of money into development of robots with challenges similar to the rescue crawler, including fluid powered devices such as Big Dog. Meanwhile patient transfer, a less glamorous but widely acknowledged need, has been largely ignored. The ultimate commercial potential of an improved patient transfer has stimulated considerable interest among our industrial stakeholders. Finally, complimentary interests with the Quality of Life Technology (QoLT) ERC have prompted collaboration and cooperation in our separate areas of expertise. QoLT pursued electrically actuated devices with the attendant advantages and limitations. Hydraulic systems provide advantages over the conventional electrical systems for these devices in several aspects. They allow for higher force-to-weight ratios than electrical actuation. Furthermore, fluid power technology allows for the power source to be located away from the joints. This is advantageous for implementing a design with multiple degrees of freedom, which are needed in this application. It also allows for the use of the power source as a counterweight.

The rescue robot idea was conceived at the proposal stage of the CCEFP as a cooperative effort between Vanderbilt University and Georgia Tech. The initial power supply was to be chemofluidic (hydrogen peroxide) of high purity. Restrictions placed on the access to this fuel at high purity levels became onerous, and air and nitrogen were used in development. Operator interface, passivity based control and pneumatic power supply were the primary projects linked to the test bed. The last of these to be tried was the free piston engine/compressor. It was developed and fitted to the robot in the previous year and was able to demonstrate functionality but was not a reliable source of power for sustained operation. The planned change to hydraulic power depended on one project for a light weight, untethered source: the hot gas vane pump. When that project was discontinued the rescue robot was no longer an attractive test bed. An alternative that could reliably demonstrate hydraulic power in this power range was needed. The interaction with the Quality of Life Technology Center at the Annual ERC Conference led to a choice of a patient transfer device as a substitute.

We believe there is a significant market need for an improved patient lift device. Current devices are antiquated, with only one actuated degree of freedom, and insufficient for the needs of many current users. Back injuries are a major risk to clinicians and caretakers with more than 10% resulting from patient transfers. The population of older Americans is dramatically increasing, as are the obesity rates. Fluid power is particularly useful in handling bariatric patients. Family caregivers in the home are the largest source of long-term care in the United States, and an estimated 29% of the U.S. adult population is providing care to someone who is ill or disabled; there is a significant need for an improved patient transfer device, particularly targeted to home settings.

High Level Needs and Goals

Hydraulics provides the capability for a compact device design that is capable of producing high forces with multiple actuated degrees of freedom. These features are most beneficial in a home environment, where there are more obstacles and often less accessibility than in clinical settings. It is also helpful in serving a broader range of weight limits, including bariatric patients.

The device should be capable of performing most typical home transfers, with maneuverability sufficient to work within the space constraints of a typical home, and adequate lift capacity in any kinematic configuration. In a home setting, often only one caregiver is present; therefore, the device must be operable by a single caregiver, with an intuitive control strategy and minimal user effort. It must also be smooth and stable under all working conditions.

Background and Needs Assessment
The first step in developing a new patient transfer device was to gain an understanding of the currently available devices. The most commonly used type of patient lift is shown in Figure 1. This design has remained essentially the same for several decades. The patient sits in a sling, which is attached to the hanger bar. The device has only one actuated degree of freedom, the rotational lifting joint. It rolls on casters, and the base can spread to a wider V-shape. The devices are actuated either electrically or by a manual hydraulic pump.

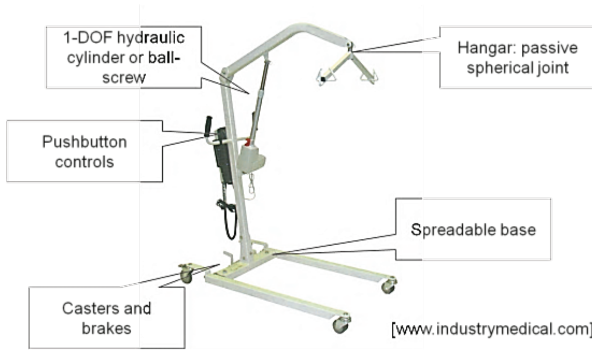


Figure 1: Conventional patient lift

Early in the project we visited QoLT ERC in Pittsburgh, spending the day with Dr. Rory Cooper and Dr. Chris Atkeson. This informed us of the target population of their “StrongArm” device, enabling us to take a complimentary approach. Further consultation with Prof. Stephen Sprigle of Georgia Tech’s Center for Assistive Technologies and Environment Access (CATEA) has also guided our direction. We have performed an extensive needs assessment for the patient lift device. Our research has consisted of two forms of input, informal one-on-one interviews and a formal focus group. As for the individual interviews, we met with representatives from the lift device industry, a number of clinicians, and a wife of a bariatric paraplegic patient. The focus group included six clinicians, three spinal cord injury patients, and two home caregivers. These have provided us with a sound understanding of the current state of the art, as well as some ideas for additional needs, some of which are categorized below.

- *Maneuverability*: The current devices, with only one actuated degree of freedom, are difficult to maneuver into places where they’re needed. Bariatric patients are particularly difficult to move, because of their larger size and weight. It is the large, rigid rolling base that encounters the most obstacles, such as chair legs, couches, bathtubs, toilets, bed frames, etc. Many current lifts do not reach floor level. Car transfers are particularly difficult because of limited space.
- *Caretaker Interface*: With the current devices, the sling and hanger bar provide substantial freedom to adjust the orientation and position of the patient manually, while the device actuates only the lifting. The caretaker maneuvers the patient by pushing on the body. It is often very difficult to position/orient the patient while simultaneously maneuvering/controlling the lift device.
- *Capability to Handle Bariatric Patients*: Bariatric patients present a few additional considerations. First, the device must be capable of lifting heavier load, up to at least 500 lbs. Second, powered wheels on the base are needed, particularly for moving the device on carpet.
- *Slings*: A time consuming aspect of a transfer operation is getting the patient in a sling. However, this ‘soft goods’ design is outside the core competencies and interests of the CCEFP, so we will focus on other aspects.
- *Cost*: Cost is a substantial limitation for new devices, since most are purchased through insurance. However, the availability of powered assist devices has improved greatly in recent years.

Figure 2 shows some of the feature ideas that were proposed to the focus group. In addition to mechanical design ideas, we also proposed a new form of user input, using a force/torque sensor mounted near the patient for coordinated force-amplifying control of the device.

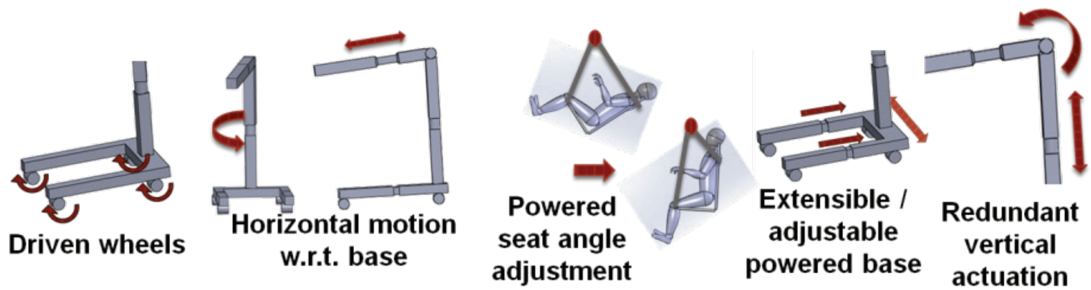


Figure 2: Some ideas presented to focus group

The additional degrees of freedom with adjustable base should help considerably with maneuverability, especially with bariatric patients. In order to implement horizontal motion with respect to the base, the device will need a control strategy which maintains stability and prevents any motion which could risk tipping. The participants generally responded positively to the proposed features.

E. Achievements

Rescue Robot

The primary achievement of the rescue robot test bed during this reporting period was testing of the free piston engine/compressor in May of 2012. The robot was equipped with outriggers to enable the demonstration of both mobility and manipulation using its limbs. The robot was extensively checked for robustness and modifications made where appropriate. The engine was brought to Georgia Tech, tested on the bench and mounted on the robot as shown in Figure 3.

The engine showed promise but was subject to a material failure in a fuel line component while testing and before real studies while mounted on the robot could be performed.

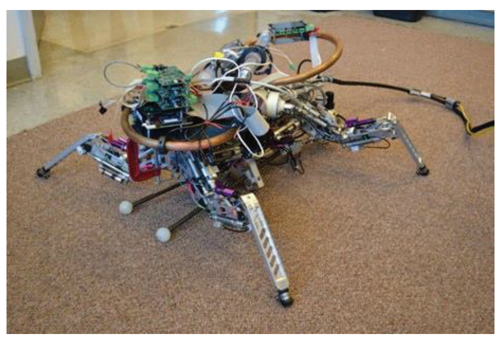


Figure 3: Rescue robot with free piston engine/compressor mounted.

In addition to serving as the engine test bed, the rescue robot served as test bed for passivity based control conducted by Venkat Durbha and Prof. Perry Li. Although this project graduated, the Ph.D. thesis experimentation of Mr. Durbha was not completed until this reporting period. The hardware will continue to be available for associated projects, including the Ph.D. dissertation work of Hannes Daepp who is applying model reference adaptive control to pneumatic systems. He is funded by a NDSEG fellowship.

Pre-prototype

As a first step, we chose to create a simple pre-prototype device for the purpose of gaining experience performing transfer operations and controlling the hydraulic device. The pre-prototype (Figure 4) is a repurposed device from an earlier project. It is currently fully functional with two degrees of freedom, vertical and horizontal; however, it is not mobile. It is also helpful for determining suitable operating parameters (e.g. speeds, forces from the operator, etc.).

Figure 4: Exploratory pre-prototype patient lift device

The pre-prototype is controlled using a coordinated force-amplifying control strategy. The operator input is measured from a force sensor mounted on the end of the boom. The input force corresponds to the speed and direction in which the patient moves. This setup allows for testing of appropriate speeds for device motion, appropriate locations and types of user inputs, suitable input force ranges from the caretaker, and testing of controllers. It has also exposed some critical aspects such as required range of motion and placement of the control handle and force sensor.

Design and Simulation of Prototype Device

The next step in the design is to create a simulation of the patient lift device. First, a simple CAD model was created with an appropriate kinematic configuration and inertia properties. The lift device model can then be used to answer several key questions. First, what is an appropriate range of motion for the device? This question can be answered primarily using motion studies in CAD software, as illustrated in Figure 5. The device can be moved through typical configurations and limiting conditions to determine the smallest appropriate range of motion for each joint.

The dynamics of the device are being analyzed, for the purpose of determining needed joint forces and torques, in order to find parameters for the hydraulic system and the controller. Simulink provides the capability to import the CAD model, including inertia properties, and create a block diagram simulating the mechanical dynamics. We can use that information to develop requirements for both the hydraulic system and the control system performance. We can then integrate the dynamic models of the mechanical system, the controller, and the hydraulic system, all within Simulink. As a first step, a Simulink simulation of a simplified version of the device is shown in Figure 5.

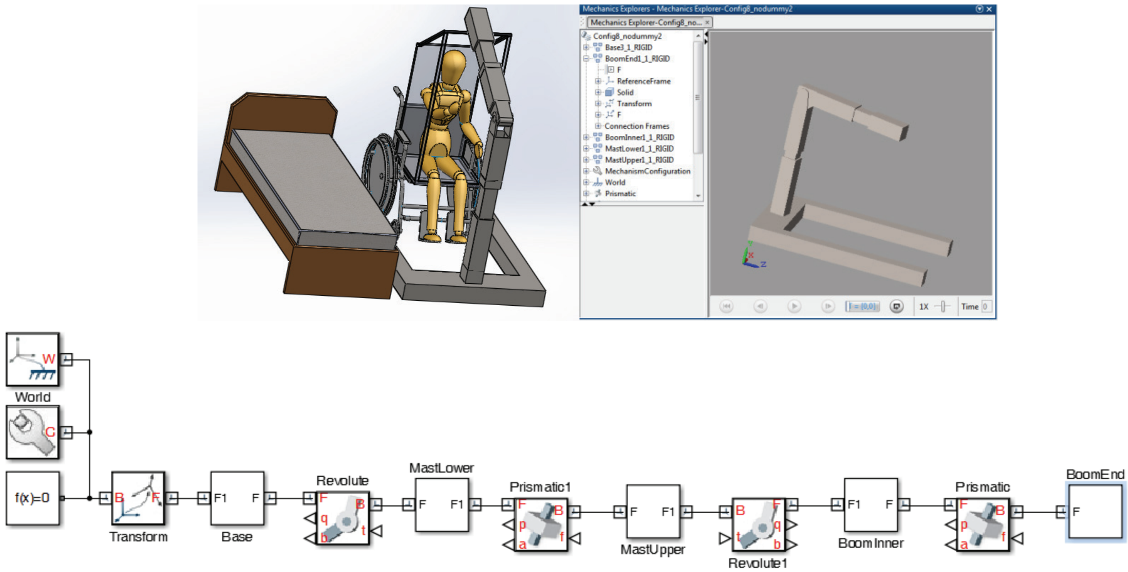


Figure 5: Simplified lift device mechanical system dynamic model in Simulink

The hydraulic system design will include a battery powered pump with mobile, onboard hydraulic power. The system will use a small pump and flow control servo valves, and it will be actuated by hydraulic cylinders and motors.

Control and User Interface Features

We are proposing three main unique control features.

1. The operator input will be from a force sensor mounted near the patient, within reach of the caregiver. This will provide a method for coordinated control, and give the caregiver an intuitive means to control the device with one hand, while maneuvering the patient as needed with the other hand. There are several ways to implement such force-amplifying control, one of which is a passivity based method that is a former CCEFP project.
2. Clinicians have indicated that oscillation tends to occur primarily when the base hits an obstacle (e.g. rolling over a cord). This oscillation can be cancelled using active vibration compensation, which is a current CCEFP project 3B.3. This method will be implemented on the patient transfer device.
3. Avoiding tipping is critical in this application; however, this presents a tradeoff with maneuverability. It is desirable to maximize the maneuverability of the arm with respect to the base, for the purpose of avoiding obstacles. Therefore, an anti-tipping stability control strategy will be implemented, similar to that which was implemented on the compact rescue crawler. It utilized a model predictive-shared control scheme to prevent any motion which would cause the device to tip over.

CCEFP Project Integration and QoLT ERC Collaboration

This test bed provides an opportunity for collaboration with the Quality of Life Technology Engineering Research Center (QoLT). The QoLT has considerable experience with developing assistive devices for mobility limited patients. We have visited the QoLT and toured their facilities, and we intend to continue this collaboration throughout the project. There are four main CCEFP component projects that will be implemented and tested on Test bed 4. Other CCEFP projects will also provide input to the design (e.g. minimizing noise and leakage).

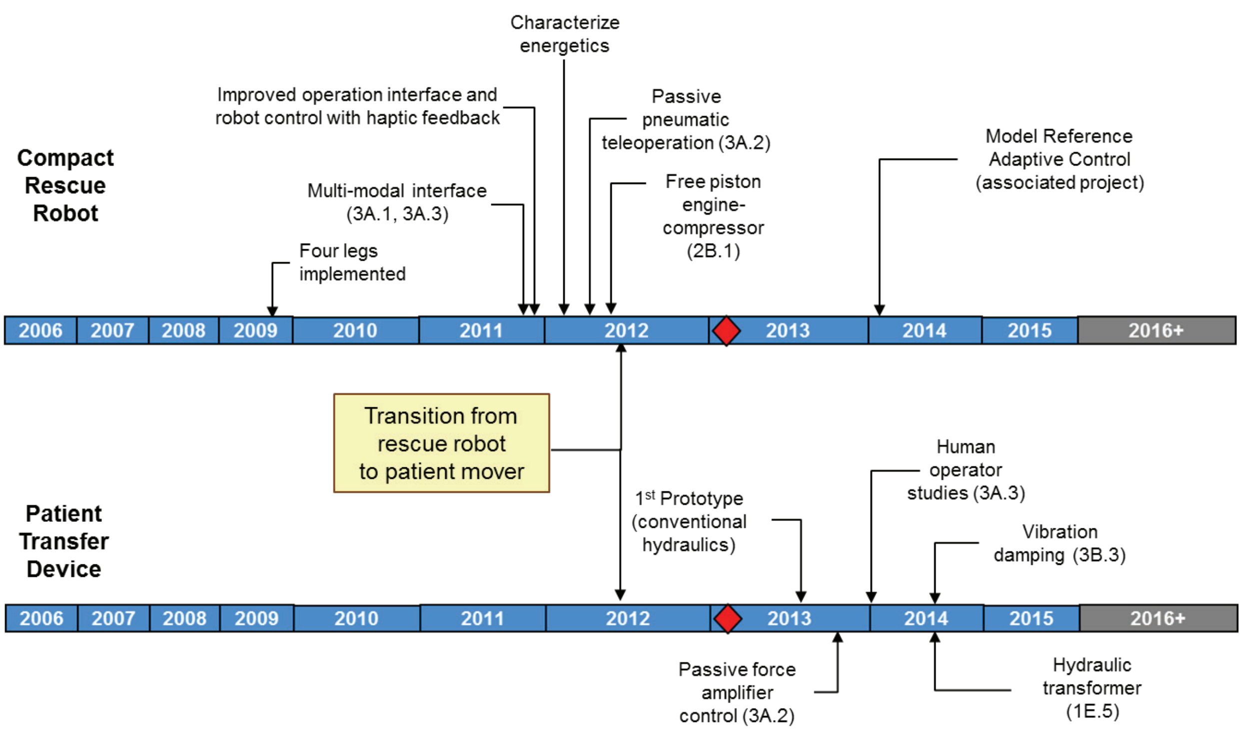
- Hydraulic transformer (1E.5) –Perry Li, U. Minnesota
- Active vibration damping (3B.3) – Andrea Vacca, Purdue
- Human-centered design (3A.3) – Eui Park & Steven Jiang, NCAT
- Operator interface design (3A.1) – Wayne Book, Georgia Tech

The first generation prototype will be built with conventional hydraulic components, and the CCEFP hardware component technologies will be integrated and tested at a subsequent stage.

Next Steps
The next step for this test bed is to complete the detailed design of the device, as well as the simulations. Then the hardware system can be implemented and tested, along with the control system. The CCEFP component projects will be integrated. Finally, human operator studies will be performed to evaluate the effectiveness and performance of the design.

F. Member company benefits
Fluid power component manufacturers stand to gain additional new sales from the expansion of fluid power into this new healthcare based application. We may also be able to recruit new member companies who manufacture patient lifts.

Test Bed 4 Technology Integration



Test Bed 4 Milestone Chart

Test bed 4 began as a compact 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 the summer of 2012, TB4 transitioned to a patient transfer device platform and will be pursued in collaboration with the Quality of Life Technology (QoLT) ERC. In addition to the design and construction of the platform, several projects have targeted the new TB4. In 2013, a passive force amplifier control in will be installed and tested (3A.2) and human centered design and operator studies will be completed (3A.3). In 2014, active vibration damping (3B.3) and hydraulic transformers (1E.5) will be integrated and tested.

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:	UIUC: David Li; Morgan Boes, Mazharul Islam UMN: Kathy (Braun) Houle, Jicheng Xia
Undergraduate Students:	UIUC: Lee Ann Monaghan (undergrad diversity supplement), Megan Hodgson (REU – Johns Hopkins) UMN: Ellen Weburg (REU), Kali Johnson, Connor Mulcahy
Industrial Partner:	Parker Hannifin

1. Statement of Test Bed

The goal of this test bed 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 test bed is the development of novel ankle-foot-orthoses (AFOs) to assist gait. An AFO with its stringent packaging constraints was selected because the ankle joint undergoes cyclic motion with known dynamic profiles, and requires angle, torque, and power ranges that fit within the test bed goals.

2. Test Bed Role in Support of Strategic Plan

This test bed facilitates the creation of miniature fluid power systems by pushing the practical limits of weight, power and duration for compact, untethered, wearable fluid power systems. This test bed benefits society by creating human-scaled fluid power devices to assist people with daily activities and is creating new market opportunities for fluid power, including opportunities in medical devices.

3. Test Bed Description

A. Description and explanation of research approach

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. These designs often fail to restore normal ankle function because they 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. The lessons learned during this design process were used to accelerate the design of a portable fluid powered AFO. 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. In 2008, University of Minnesota students were added to the test bed team to examine opportunities to increase propulsion torque and power through high pressure hydraulics. Over subsequent years, Illinois and Minnesota teams have been using the portable fluid powered AFO platform to explore lower pressure pneumatics and higher pressure hydraulics, respectively, as promising technology paths for tiny fluid power systems suitable for untethered human assist devices.

B. Achievements

Portable Pneumatic AFO (PPAFO) UIUC

In 2010, we constructed our first generation portable powered ankle-foot orthosis (PPAFO) using off-the-shelf (OTS) components 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 dorsiflexor (toes-up) and plantarflexor (toes-down) torque actuation at the ankle. A U.S. patent on the technology embodied by the PPAFO has been filed; co-inventors are CCEFP students and faculty from the U Illinois, U Minnesota, Georgia Tech, and MSOE. While the Gen 1.0 device demonstrates the feasibility of utilizing low pressure pneumatics to provide torque assistance at the ankle, this test bed platform highlights the need for advancements in miniaturized fluid power systems.

Over the years, we have been working on improving the efficiency, compactness, control, usability, and possible applications of the PPAFO. Using an off the shelf pneumatic rotary actuator located lateral to the ankle and a canister of compressed CO_2 at the waist to serve as a placeholder for a more compact power source, the Gen 1.0 PPAFO can generate up to 12 Nm at 100 psig with run times less than 30 minutes.

To address efficiency improvements, we have performed efficiency studies, explored regenerating exhaust gas with an accumulator, and investigated thermal regulation of the CO_2 power source. Preliminary theoretical component and system efficiencies of the Gen1.0 PPAFO system suggest 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 plantarflexor actuation (100 psig) could be captured into an accumulator and then recycled to power the lower pressure dorsiflexor actuation (30 psig). In 2012, bench-top tests, conducted by REUs during the spring and summer, found 11 J of total work loss across all components, and expected fuel savings of up to 30% with a fixed volume accumulator. Recent testing on the effect of two actuation control schemes on net work and fuel consumption during walking tests found that the regenerative scheme improved fuel consumption by 17%. Working with students at Vanderbilt on Project 2C.2 (strain energy accumulator), we constructed a pneumatic elastomeric accumulator for use with the recycling scheme that was tested during the walking tests (Figure 1). In 2013, we are investigating the bench-top and walking test differences in fuel savings, issues with losses and actuation timings, and additional design changes to the accumulator. We will also explore the implementation of a thermal regulation scheme on the CO_2 power source. Our previous REU and E&O sponsored senior design team studies in 2011 suggested that the thermal cooling nature of liquid CO_2 and subsequent pressure decrease over time could be mitigated by maintaining an isothermal condition for the canister or hoses.

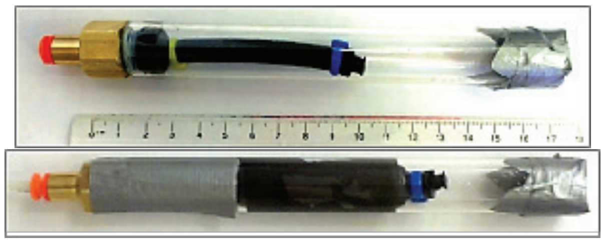


Figure 1: Elastomeric Accumulator

To address compactness, we have been developing pneumatic ankle actuation systems with higher torque output than commercially available (target: 25Nm @ 120 psig), modular and integrated shell structures and promote the need for miniature pneumatic valves and power sources. We realized that the compact integrated rotary actuator developed by MSOE in 2010 would not be a viable design (max capable 50psig for 6 Nm). Therefore, in effort to continue to drive a technology pull for a compact pneumatic actuator, we pursued three avenues. (1) In 2011, MSOE tried to improve their original design and also proposed a new design based on bellows technology (35Nm @ 115psig). (2) In 2011, we began collaborating with CCEFP industry partner to utilize their expertise in pneumatic rotary actuators to design a custom product. This work has substantially slowed in 2012 due to industry work priorities and manpower issues. The design is nearly complete, but there are issues with finding cost-effective fabrication methods. (3) During the 2011-12 and 2012-13 academic years, CCEFP sponsored a Mechanical Engineering capstone design team each year at Bradley University in Peoria, IL. The first team developed a prototype using additive manufacturing to create a novel rotary actuator with integrated planetary gear train; unfortunately the design had leakage problems and could not be tested. The current team decided to design a completely different actuation system using a linear actuator and modified rack & pinion configuration. We continue to seek solutions for compact and higher torque actuation systems. In 2012, we developed a lighter and less complex structural shell design for the Gen 2.0 PPAFO, which will allow for swapping of modular components. The new shell no longer requires metal vertical struts and has no medial support (Figure 2). We are currently awaiting multiple sized (S, M, L, XL) foot and shank bilateral shells to support testing on a variety of sized test subjects. We continue to work with Project 2F (MEMS proportional valves), Project 2B.2 (HCCI engine) and Project 2B.4 (Stirling engine) to address compact pneumatic valves and power sources.

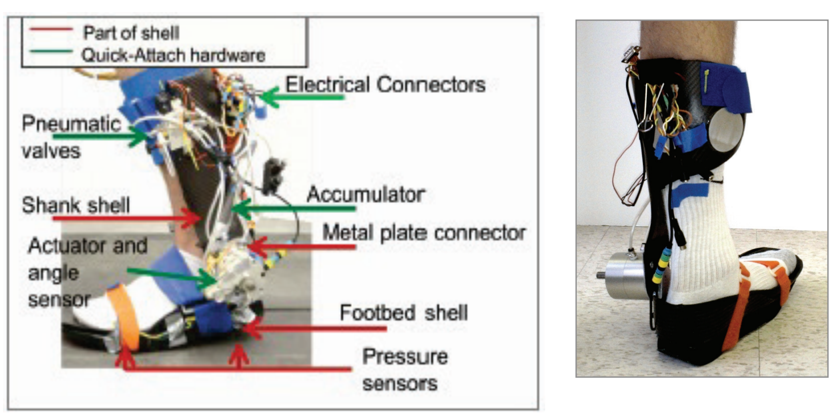


Figure 2: Gen 2.0 PPAFO. Includes elastomeric accumulator, revised valving, and new shell without metal struts or medial side. Modular hardware can be swapped between different sized shells.

To address PPAFO control for appropriate gait function across a variety of user populations (able-bodied and impaired) and walking environments (level ground, stairs, ramps), we have examined different actuation-timing control strategies, solenoid vs. proportional control and recognition and control for different gait modes. Our initial controller for level ground walking was a simple direct event threshold-based control using just the heel and toe sensors. To better accommodate impaired gait, we developed a model-based state estimator controller that also added the angle sensor. In 2012 and 2013, we are examining how the pneumatic system (work and fuel use) are affected by these two controllers. A simulation and bench-top study highlighted that proportional valve control has better tracking and efficiency performance compared to solenoid valves; however, due to low torque generation ability of current actuator systems, inclusion of proportional control on the PPAFO has not yet been implemented. These results again highlight technological barriers to compact fluid-powered orthoses. In 2011, we began work in recognition and control for different gait modes using a 6DOF inertial measurement unit (IMU). Progress in 2012 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 requires a different control scheme than level ground or stair/ramp ascent, and differential gait mode control has been implemented. Control issues will continue to be addressed based on applications for the device.

We have targeted the PPAFO to be a portable gait assistance and rehabilitation device. Starting in 2011, CCEFP faculty and students at NCAT began development of two user interfaces: (1) a computerized 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 2012 and beyond, an associated project at UIUC is determining if the PPAFO can be used as a gait initiation cueing device for people with Parkinson's disease. A highlight story on this associated project is included in the Y7 report. We are also working with clinical researchers about possible applications in stroke and partial foot amputee rehabilitation.

Hydraulic AFO (HAFO) activity at Minnesota

In 2009, we identified high pressure hydraulics as a promising technology path for tiny fluid power systems suitable for applications such as the untethered AFO. In 2010, theoretical analysis of tiny hydraulic systems was conducted to understand their limits. Additionally, a compact fluid power electrohydraulic actuation system was assembled with LiPoly battery, Maxxon motor, Oildyne cartridge pump and Bimba hydraulic cylinder to demonstrate the capabilities and limits of using off-the-shelf components.

During 2011 and 2012, continuing theoretical analysis of tiny hydraulic systems resulted in identifying the design guidelines of the HAFO. The analysis showed that a piston pump and a gear head should be used to minimize the weight of the system. Further analysis showed that the power unit of the HAFO must be separated from the actuator unit to capitalize on the weight advantage of hydraulic actuation over the equivalent electromechanical system.

In 2012, we identified the key design parameters for the pumping and actuation components for the HAFO. We finished sizing the electric DC motor and gearhead based on the AFO requirements and the available electromechanical components in the market. We also built a test stand to validate the mathematical efficiency models of the O-ring sealing element that is crucial to tiny hydraulic systems. The seals were tested under different speeds and loading conditions. Key validation results are shown in Figure 3. The experimental validation of the seal efficiency model is significant because it justified the system level comparison between the small-scale hydraulic systems and electromechanical systems we executed in 2009. The validation results also set the foundation for the subsequent HAFO system design and performance prediction.

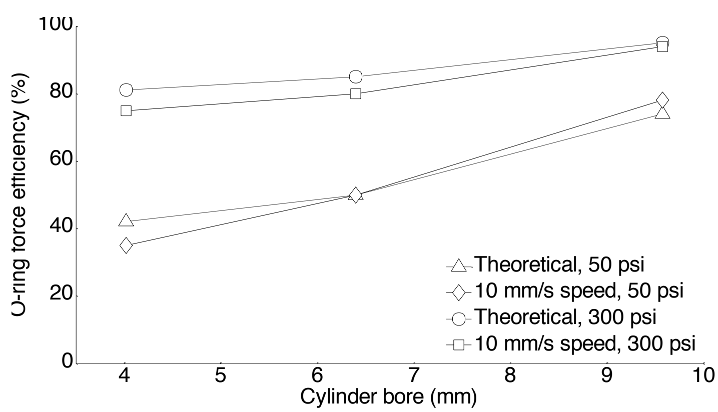


Figure 3: Experimental validation of the O-ring efficiency models

Plans, Milestones and Deliverables for Next Year

PPAFO:

- (Spring 2013) Investigate bench-top and walking test differences in fuel savings, and issues with component losses and actuation timings. Continue to work with Bradley and Parker actuators.
- (Summer 2013) Develop comprehensive model for design elastomeric accumulators. Identify and implement thermal management intervention.
- (Winter 2013) Demonstration of HCCI engine with PPAFO
- (Spring 2014) Demonstration of MEMS proportional valves on PPAFO

HAFO:

- (Summer 2013) Full system efficiency analysis of ver2 HAFO, for dynamic load application; Finish customizing piston pump (modified from Oildyne pump) and cylinders
- (Fall 2013) Fully functional and integrated ver2 HAFO; Design a control strategy for ver2 HAFO

Plans, Milestones and Deliverables for Next Five Years

Over the next five years of this test bed, we will future develop the current technologies and explore new ones to continue driving new technology and clinical needs.

Planned work:

Pneumatics: Push development of compact proportional valves, actuators, power sources; increase run time through thermal regulation of portable CO_2 power source and improved component/system efficiencies. Continue to develop user interfaces and clinical applications for PPAFO.

Hydraulics: Continue theoretical analysis of tiny hydraulic systems, with experimental validation though component and system testing.

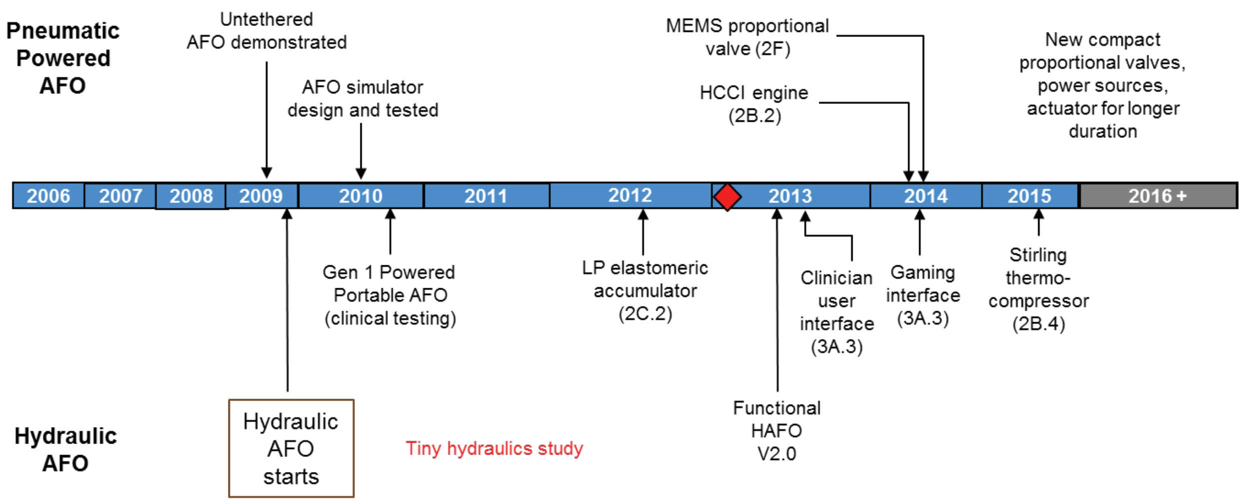
New areas:

1. Develop comprehensive and accurate mathematical model of complete pneumatic AFO system. Use model to create pneumatic AFO devices that optimize efficiency with the goal of increasing run-time and decreasing weight. Explore pressure & air flow control for torque & rotational velocity control. Explore additional energy harvesting through human power harvesting.
2. Create new knowledge on a high pressure pneumatic AFO device where "high pressure" means around 500 psi. First assess this technology with comprehensive mathematical models, then validate the models by designing, constructing and evaluating physical devices.
3. Continue to research tiny hydraulic devices operating at about 2,000 psi. Critical needs include (a) validated, comprehensive mathematical models that can be used to predict behavior of hardware, (b) concepts for generating pressurized fluid from either battery or hydrocarbon fuel stored energy sources, (c) comprehensive assessment of safety when high pressure tiny hydraulic devices are used in close proximity to humans.
4. In collaboration with Gillette Children’s Hospital, St. Paul MN, develop child-size AFO emulator based on tiny hydraulics for use in a novel automatic AFO prescription system for children with gait impairments resulting from cerebral palsy.

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 Ankle Foot Orthosis (AFO) test bed is to represent human assistive devices in the 10W-100W range. Initially, the AFO was targeted to use pneumatics. In 2009, it was decided to investigate using tiny hydraulics to achieve the required compactness for the device. A hydraulic AFO is under development in parallel with the pneumatic AFO.

The pneumatic-powered AFO platform has demonstrated un-tethered operation and was tested in clinical settings in 2010. The need for specialized components in this test bed have given rise to new projects such as the compact MEMS pneumatic valve (2F) and portable power sources (2B.2 and 2B.4). A strain energy accumulator (2C.2) was installed in 2012 to regenerate energy in the exhaust gas to improve overall efficiency.

A number of projects will be integrated and demonstrated in the next few years including:

- A clinician-centered user interface will be implemented in 2013. (3A.3)
- A rehabilitation game interface for patients will be implemented in 2014. (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 2014 (2B.2)
- The controlled Stirling thermo-compressor will installed and tested in 2015. (2B.4)

A fully functional hydraulic AFO is expected in 2013.

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.

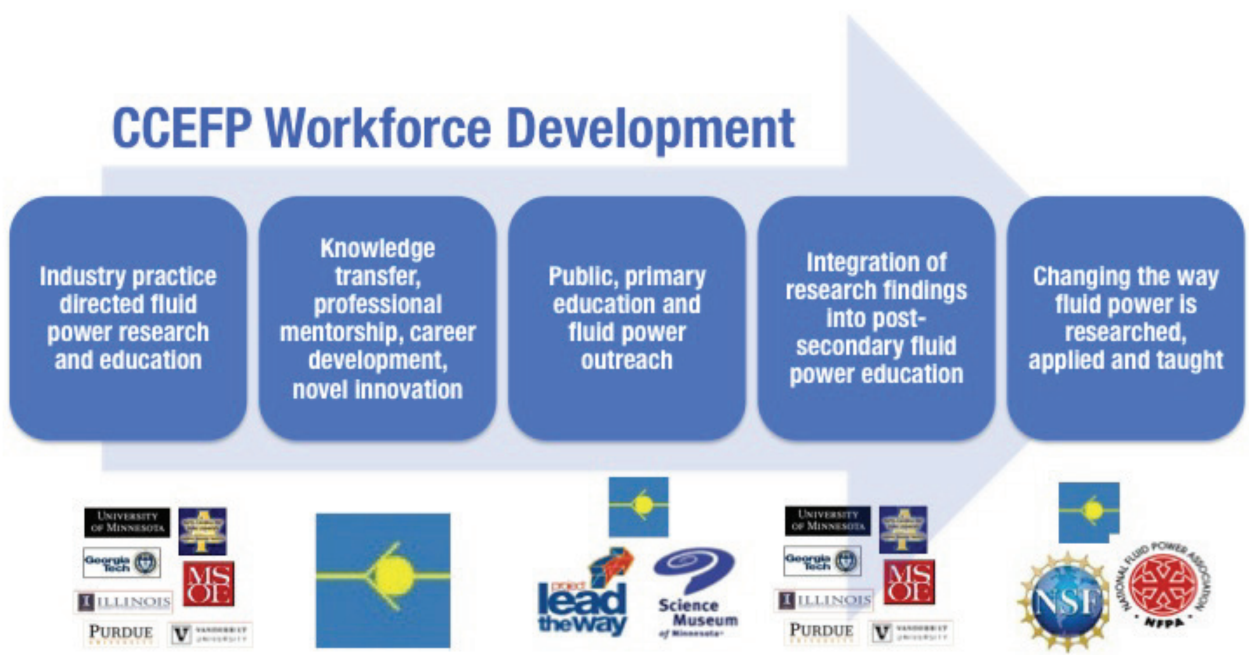
The current state of the Center's diversity portfolio is promising and encouraging. Efforts in this area are paying dividends, although there is still work to be done. The vast majority of center affiliates are US Citizens or Permanent Residents, so we will focus on those.

Women – Representation is near or above national averages in all categories. It is notable that 28.3% of Undergrad Non-REU students are women as compared to 18.7% nationally. Among REU students the Center percentage of women is 30.0%, well above the national average. Women were 13.8% of the faculty and 33.3% of the leadership team of the CCEFP, as compared to the national average of 13.8%

Racial Minorities – The CCEFP greatly exceeded national averages in all categories. We are particularly pleased with the percentage of Undergrad Non-REU students who are racial minorities because this number comes from a large pool of 100 students.

Hispanic/Latinos – Numbers of Hispanic/Latinos and persons with disabilities remain small. The Center takes this problem seriously and has taken steps, and put plans in place, to address these issues, as detailed in section 5.2

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 following 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 Education Integration
Thrust A: Public Outreach **Bringing the message of fluid power to the general public**				
A.1 Interactive Exhibits Fluid Power	x	x		x
A.3 Multimedia Educational Materials	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 OpenCourseWare	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 Undergraduate Research Diversity Supplement (URDS)	x	x		x

C.10 NSF and CCEFP Graduate Research Diversity Supplement (GRDS)	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
D.6 Graduate Internships in Fluid Power (Proposed)		x		x
Thrust E: Evaluation **Measuring CCEFP program goals, it's effectiveness and sustainability**	x	x	x	x

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

- **Leadership** - A transition in leadership and administration under the Education and Outreach program included the departure of Education Industry Program Coordinator, Ms. Linda Western. Ms. Cherie Bandy joined the E&O team in late 2012 as a part-time Education Program Coordinator. Professor Paul Imbertson, (Electrical Engineering, University of Minnesota), continues to serve as Education Director; Alyssa Burger continues as Education Outreach Director. Professor Jim Van de Ven, University of Minnesota, continues to support the Education and Outreach team as the leader of undergraduate and graduate fluid power curriculum efforts.
- **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** - The CCEFP is leading the effort to develop new courses and is making substantial modification to courses 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. 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)
- **Student Retreat** - The 2012 Student Retreat was held in Ames, Iowa at Sauer-Danfoss, a corporate member of the Center. The two-day event featured an orientation to the company, team building activities for students, a tour of the Sauer-Danfoss facility, and the SLC General Meeting. Additionally, tours at a few other local companies were organized, along with dinner at an arcade followed by a casual dinner with Sauer-Danfoss 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 2013 Student Retreat are underway and corporate industry member Caterpillar, Inc., has graciously agreed to host the upcoming event. (Project C.8)
- **Graduate Internships** - The SLC has led the effort to pilot a graduate student internship program, through promotion of graduate internships in fluid power. Contacts have been made with CCEFP member companies through the Industrial Advisory Board. A number of companies expressed interest in having graduate internships and work is underway to list specific company internship postings to CCEFP graduate students. (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 CCEFP has received commitment from an industry member and a CCEFP university, and plans are in place to identify the CCEFP GEM Fellow in the Spring 2013. (Project C.10)
- **Science Museum of Minnesota** - The fluid power exhibits at the Science Museum of Minnesota are now in a special fluid power area of the physical exhibit floor 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 11 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 Training Series by Industry Experts** - A proposed expansion of the Center's popular webcast series includes a fluid power training webcast series led by industry experts provided on the opposite schedule of the regularly scheduled webcast series. Following the webcast model, the Center proposes to recruit industry instructors to present a long-term and detailed fluid power training program for CCEFP graduate and undergraduate students. (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 2012, 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)
- **Hydraulic Hybrid Passenger Bus** - At the intersection of research and education is the Hydraulic Hybrid Passenger Bus headquartered at GeorgiaTech. A team of graduate and undergraduate students are realizing the potential of greater fuel efficiencies for school buses everywhere and providing a synergistic model for effectively engaging college and pre-college students in hands-on learning about eco-friendly fluid power. (Project C.3c)
- **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. 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 new, contracted external evaluator of CCEFP 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.

- **Combined CCEFP NFPA Meetings** – In the Fall of 2012, the CCEFP partnered with NFPA to host the first NFPA Workforce Summit and CCEFP Annual Meeting at the University of Illinois, Urbana-Champaign. The event provided networking opportunities for industry and students with a student poster session and competition, followed by an industry networking kiosk session where all attendees were able to mingle over appetizers. More than 17 companies hosted kiosks during the reception. The event hosted a resume exchange for students and industry as well as panel presentations and discussions by fluid power leaders. Immediately after the “Workforce Summit”, the CCEFP launched into the traditional Annual Meeting, where students made presentations on CCEFP research and toured UIUC laboratories. The meeting included closed-door meetings between the Industry Advisory Board and the Scientific Advisory Board regarding the sustainability of the Center. Overall, a powerful meeting was achieved by NFPA and CCEFP. (Project D.2)
- **Undergraduate Research Diversity Supplement (URDS) and Graduate Research Diversity Supplement (GRDS)** - 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 two Research Diversity Supplement Programs to support undergraduate and graduate students in fluid power. To date the CCEFP has supported five undergraduate and four graduate students, between the two supplements. (Project C.9 and C.10)
- **International Recognition for CCEFP-Supported Student Organization** - The CCEFP-supported student organization Innovative Engineers at the University of Minnesota, received international recognition for their wind energy project in Nicaragua. The group's work is included in Sustainia100, a guide to the 100 top global solutions in sustainability, unveiled in June 2012 at the Rio+20 United Nations Conference on Sustainable Development in Rio de Janeiro, Brazil. (Project C.11)
- **REU and Fluid Power Boot Camp** - Twenty-three enthusiastic REU students conducted research in CCEFP labs at the Center’s seven universities during the summer of 2012. REU students participated in the Center’s second Fluid Power Boot Camp for REUs at Purdue University, June 2012. To date, 123 REU students have participated in Center research. (Project C.1)
- **Fluid Power Scholars** - The Fluid Power Scholars Program is in its fourth year. To date, 25 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%. (Project D.1)
- **RET** - Six RET participants conducted research in CCEFP labs. Thirty-five 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. More than 130 REU students have participated in the CCEFP program--more than in many REU site programs. Based on responses by 54 undergraduates to a recent longitudinal study, we discovered that 22 of them are working with or in or pursuing fluid power in some way, with three of them working for CCEFP member companies. Thirty are or have attended graduate school after their REU experience, and ten are currently PhD candidates. In other words, 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.

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 and 2012 and is underway for 2013. Twenty-five scholar/interns were named during the program's first three years and plans call for naming eight more in 2013. 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. This is to be expanded in Y8.

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, 11 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, four 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 (2nd 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.

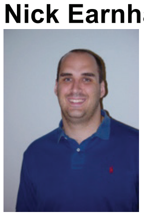
Integration of Fluid Power into Core Curriculum: The Fluid Power OpenCourseWare (Project C.2) site exists to digitally publish and disseminate high-quality, college-level teaching materials in fluid power. The materials can be used in fluid power elective courses, but more importantly they can be inserted 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 7, 28 courses and 5 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.

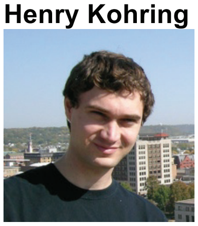
Professor Jim Van de Ven, University of Minnesota, continues to lead efforts to develop undergraduate and graduate fluid power curriculum. Preliminary plans and actions for fluid power curriculum design and dissemination include:

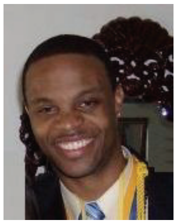
- Continue to encourage the incorporation of fluid power content into existing courses throughout the Center.
  - The Fluid Power OpenCourseWare project makes it easier for instructors within and outside of the CCEFP network to include college-level fluid power material in their course.
  - Encourage 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.
- 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 0.6 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 approaching the goal of 0.5 (or 2.0 undergrad/grad) and 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 **Institution** **Graduation** **Course of Study**	**An Outstanding Achievement**	**Current Employment and Contributions to the Field**
Diana Cardona  Vanderbilt University M.S., May 2012	Thesis: "Magnetic Resonance Imaging (MRI) Compatible Steerable Needle Robot".	**Baker Hughes** *Research and Development Engineer.* Developed novel equipment to test cement's mechanical properties under high-pressure temperature. Designed and conducted experiments to understand cement's mechanical fundamentals under extreme environmental conditions. Implemented mechanical and electrical improvements
Rahul Dutta  University of Minnesota M.S., August 2012	Developed simulation models. Proposed and simulated short-term wind energy storage methods. Upgraded and built new test stand for the fluid power lab course.	**Case New Holland** *Engineer*. Responsible for developing electro-hydraulic systems and controls for construction and agricultural equipment. Resolve issues related to hydraulic systems and controls on next generation of products. Responsible for evaluating applications of advanced fluid power technologies to reduce fuel consumption and increase productivity of construction equipment.
Nick Earnhart  Georgia Institute of Technology PhD, Dec 2012	Leo Beranek Student Medal for Excellence in the Study of Noise Control. Achievement Rewards for College Scientists (ARCS) Fellowship.	**InSciTech** *Engineer*. An engineering consulting firm specializing in accident reconstruction, biomechanics, human factors, and medical science. Role in investigation and reconstruction of automobile and heavy vehicle accidents including injury mechanism analysis.

Mark Elton  Georgia Institute of Technology PhD, Dec. 2012	Inaugural SLC president for the CCEFP. Served several years as the SCL industry liaison.	**HUSCO** *Senior Development Engineer*. Designing new hydraulic valves.
Jose M. Garcia  Purdue University PhD, May 2011	2009 Graduate Mentor of the year, Purdue.	**College of Technology, Purdue University** *Assistant Professor*. Currently responsible for preparing and delivering Mechanical Engineering Technology courses. Researching: Contamination resistant electro-hydraulic valves, small power electric-hydraulic vehicle and wind power drive trains, and tools to deliver science and engineering content.
Kathy Braun Houle  University of Minnesota MS, May 2012	Presented a poster of research at six different conferences.	**Medtronic** *Reliability Test Engineer*. Responsible for the premarket testing of pacemakers and cardiac leads. This includes all electrical and mechanical stress tests and tests to failure. Test method validation and gaining understanding of new tests as well as troubleshooting problems during testing.
Henry Kohring  University of Minnesota MS., July 2012	Developed a purpose-built hydrostatic dynamometer.	**John Deere** *Engineer*. Testing hydraulic systems for excavators and articulated dump trucks. Ensuring that customers receive durable, reliable, efficient, and productive machines.

Antonio Lee  North Carolina A&T State University Ph.D., Dec 2012	Alpha Pi Mu Industrial Engineering Honors Society Human Factors and Ergonomics Society	**Wells Fargo Banking-Signature Consultants** *Research and Development Engineer*. Collaborate with Interaction Designers/Information Architects, site owners, developers, and graphic designers. Conduct research studies via expert reviews. Manage remote usability testing sessions for Wells Fargo healthcare intranet sites.
Bo Yang  Georgia Institute of Technology PhD, Aug 2012	Tribology Transactions, “2008-2010 most-cited articles”, *A numerical model of a reciprocating rod seal with a secondary lip*	**General Motors** *Engineer*. Developing new analysis methods applied on tribology related components in automotive powertrain system, such as bearings, pumps, pistons, seals and hydraulic actuators.
Josh Zimmerman  Purdue University PhD, May 2012	CCEFP Annual Meeting 2011 - Best Poster Award, International Fluid Power Expo, Las Vegas, NV 3 Awarded Patents 2 Patents Pending	**Case New Holland (CNH)** *Project Engineer*. Comparing new fluid power technologies for the next generations of hydraulic construction machines. Formerly, Chief Engineer of Smart Hydraulic Solutions, LLC. Consulting projects with the mobile hydraulics industry relating to PhD research within the CCEFP on energy efficient displacement controlled hydraulic systems.

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. Through the REU program, the Fluid Power Scholars program, the Undergraduate Research Diversity Supplement Program (C.9), 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. Our 2012 longitudinal survey revealed the following: 61% of all former CCEFP students are working in fluid power in some capacity, 50% of all former CCEFP students are working in industry, 11% of all former CCEFP students are employees of CCEFP fluid power industry member companies, 67% of CCEFP fluid power scholars are hired into the fluid power industry, 55% of all former CCEFP undergraduate researchers enter graduate school, and 33% 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 proposed 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 proposed 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.

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, securing external grants such as 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.

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 and 2012, the Fluid Power Challenge has reach more than 200 8th grade students in metropolitan and out-state Minnesota communities. More than 12 unique schools have participated, many with Project Lead The Way curricula as well as 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.

gidaa robotics Program: Year 7 saw yet another expansion in the suite of education programs targeting Native American students of all ages. With support from the CCEFP, 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 60 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 fourth annual RoboFest Competition in the Spring 2013. 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. This program also includes a teacher workshop enrichment element to entice other local schools to offer similar educational opportunities. Due to the successful Robotics Teacher Training held in the spring of 2012, the CCEFP now supports a sister robotics program at a neighboring middle school in Cloquet, Minnesota. The program continues to rapidly expand.

Research Experiences for Teachers Program: In the recent reporting year, six RET teacher participants conducted research in the CCEFP laboratories of Purdue University and North Carolina A&T State University. The CCEFP has sponsored 35 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 2012 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. High school students will assist local villagers with the task of retrieving fresh water by using fluid power technology and equipment. In addition, 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.

Priorities for the Future

With the CCEFP now in its seventh 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 Y7, 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 expanded to include graduate level internships in Y8.
- CCEFP Webcast Series
  - Popular on-line research seminar series on CCEFP progress, presented by students. Plans exist for Y8 to expand the seminar series to including a training component for students led by industry experts on specialized topic areas.
- CCEFP Student Retreats hosted by Industry
  - The 2012 summer retreat was hosted by Sauer-Danfoss in Ames, Iowa. Caterpillar, Inc. has committed to hosting the 2013 summer retreat 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.
- NFPA Workforce Summit and 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.
- 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.

Priorities for the Future

The CCEFP will continue to develop networking opportunities for students and industry, connect industry to the OpenCourseWare project, 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

3.4 WEAKNESSES IDENTIFIED BY 2012 SITE REVIEW TEAM

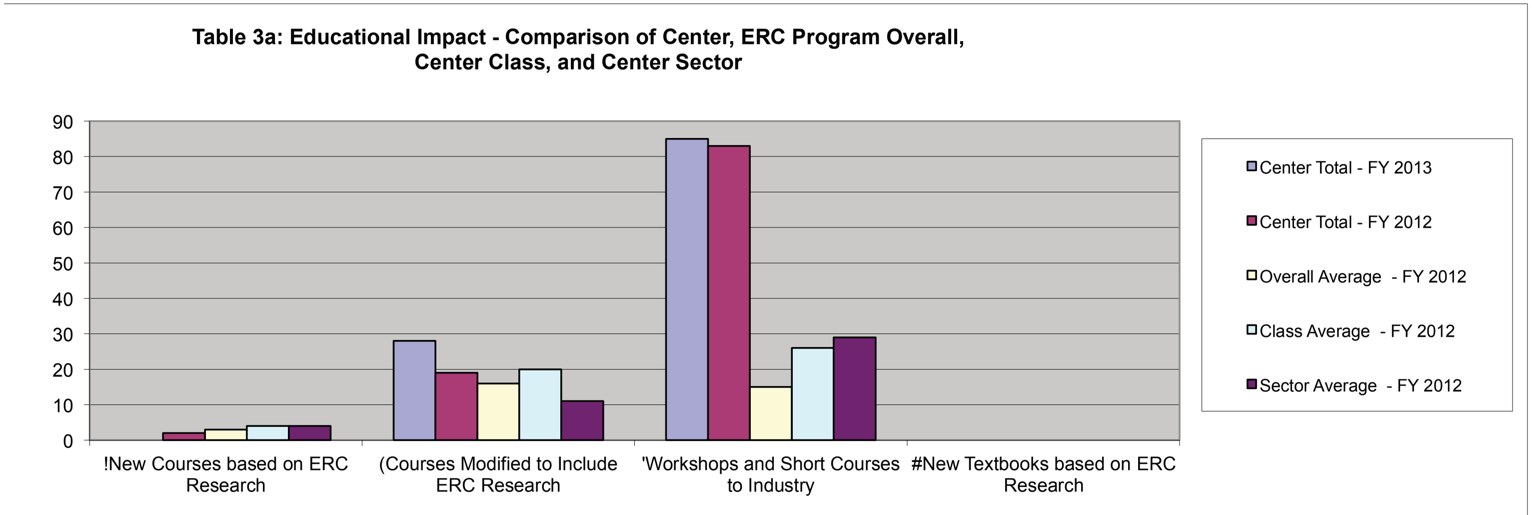
Weakness	Response
Center should develop and implement a program to increase student interaction with industry members and employment opportunities.	The Center has heeded this recommendation and has coordinated efforts to engage students and industry together in a variety of ways. The specifics are addressed in the Industry Engagement section of this report (section 3.3), as well as EO Project D.2 in Volume II.
Specific details on membership model with the National GEM Consortium and the new CCEFP Diversity Supplement Programs.	The Center is pleased with the work that has transpired to address this important issue. These efforts are addressed in sections 3.0 and 3.3 above and in EO Projects C.9 and C.10 in Volume II.
Additional activities to further disseminate all curricular materials should be accelerated in the upcoming year.	Significant work is underway in the area of fluid power undergraduate and graduate curriculum. Specific details are addressed in the University Education section of this report (section 3.1), as well as EO Projects C.2, C.3 and C.4 in Volume II.
The plans for evaluation do not reflect the educational goals and objectives of the NSF ERC Program. Instrument development and data collection efforts of the evaluation should be suspended until this framework is updated.	The Center's external evaluator, Quality Evaluation Designs, successfully developed program objectives that align with the NSF ERC program. Modification to QED's scope of work and subsequent approval by NSF was given shortly after the Site Visit Report was issued. More information on Center evaluation efforts and QED can be found in EO Project E.1 in Volume II.

Table 3a "Curricular Impact" and Table 3b "Ratio of Graduates to Undergraduates" appear on the following pages.

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 0.6 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 approaching the goal of 0.5 (or 2.0 undergrad/grad) and 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.

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, 2012-Jan 31, 2013	Percent	Feb 01, 2012-Jan 31, 2013	Percent	Feb 01, 2012-Jan 31, 2013	Percent	Feb 01, 2012-Jan 31, 2013	Percent	Feb 01, 2012-Jan 31, 2013	Percent	Feb 01, 2012-Jan 31, 2013	Percent	
New Courses Currently Offered [1]	0	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	16
Currently Offered Ongoing Courses With ERC Content [2]	28	28	100%	0	0%	0	0%	0	0%	0	0%	0	0%	N/A
Workshops, Short Courses, and Webinars	85	13	15%	0	0%	0	0%	0	0%	0	0%	0	0%	217
New textbooks based on ERC research	0	0	0%	0	0%	N/A	N/A	0	0%	0	0%	0	0%	4



[1] New courses currently offered and approved by the curriculum committee are only counted in the first year that they are offered so there is no multiple counting of these courses.

[2] The cumulative totals for "Currently offered, ongoing courses with ERC content" may count the same course more than once.
This is due to the fact that a single course can be modified in multiple years and therefore will be included in the cumulative total multiple times.

Table 3b: Ratio of Graduates to Undergraduates

Center Grouping	Undergraduates	Graduate Students	Ratio Grad/UG	REU Students	Total College Students	Young Scholars	Total Students (Graduate, Undergraduate, Young Scholar, and REU Students)
Average All Active ERCs FY 2012	40	75	1.9	15	130	19	149
Average Advanced Manufacturing Sector FY 2012	84	86	1.0	15	185	55	240
Average for Class of 2006 FY 2012	66	81	1.2	26	173	42	215
Minnesota Twin Cities-CCEFP FY 2012	123	81	0.7	19	223	0	223
Minnesota Twin Cities-CCEFP FY 2013	**137**	**81**	**0.6**	**26**	**244**	**0**	**244**

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

Industry interest in the CCEFP remains high with ten new member companies joining in the past two years. More importantly these members were strategically targeted to fill missing or poorly represented providers of the fluid power value chain. These targeted areas include 1) suppliers, fluids and lubricants 2) OEM system integrators and 3) members headquartered outside the USA. We continue to recruit new members in these strategic areas with significant interest.

4.1 VISION, GOALS, AND STRATEGY

The industrial collaboration vision for the CCEFP 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 are through meaningful communication and strong relationships. It is crucial that the CCEFP continue to develop these close relationships with industry to achieve long term sustainability. With so many members, the CCEFP enjoys broad industry representation but that can make it challenging to achieve the necessary level of engagement to ensure long term commitment. Members have different reasons for affiliating with the CCEFP. Besides the obvious research benefits, some members are simply interested in advancing the state of the fluid power industry. Others are motivated to gain access to students well trained in fluid power. Some members are driven by the opportunity to improve society. Because of these varying motivations, we need to engage members at all organizational levels. This will benefit the center by positioning us to gain greater support from these members as we turn our focus towards long term sustainability.

Our primary goals are to maintain annual industry membership dues income at approximately $600,000 while growing industry sponsored research to more than $1 million per year. Our secondary goals are to have at least five patent 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 is achievable. Discussions with our members have identified a preliminary membership value proposition that will allow us to achieve this. Further refinement is ongoing. Besides the benefits described above, we have learned that providing industry direct access to CCEFP technology experts is very desirable and often leads to affiliated research projects. This has been considered in our sustainability planning efforts.

We will continue to invite all interested companies to become members of the CCEFP; however, our focus going forward will be on companies that can help sustain the center long term. Members interested in sponsoring affiliated research are of particular interest. Typically this would suggest that we focus on larger companies but technically orientated members exist at all sizes. Once on board we will work to upgrade them to higher level memberships.

4.2 MEMBERSHIP

Our industry membership changed in year seven from 48 to 40. This was primarily due to a lack of focus caused by a vacant ILO position for the last quarter of 2012. Other contributing factors were loss of key industry champions due to retirement or job reassignment and a decision by some members to not renew after their initial 5-year commitment was completed. Although the reduction in membership is unfortunate it is more important to focus on recruiting and retaining strategic members. In the process of identifying these strategic partners, we have identified gaps that are leading us to pursue other relationships. A review of our industrial membership identifies these opportunities:

- Most of our members are in the hydraulics sector of the fluid power market. Yet industry uses significant pneumatic power. We have begun a project to understand that industry base and recruit as appropriate. Early feedback indicates that our increased focus on medical applications is being well received.
- We need to strategically focus on 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.

- 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.
- In 2012 we began efforts to understand the significant impact of fluid filtration on fluid power with promising results. One of our new members, Pall Corporation, is focused in this area. Director Stelson gave a keynote presentation at the University of Minnesota's Center for Filtration Research annual meeting, hosted by Donaldson Corporation, a leading supplier of filtration solutions. We are currently developing an accompanying research agenda with the Center for Filtration and by leveraging our existing members' network. This will likely lead to new recruiting opportunities.
- The wind energy market is another strategic focus for the CCEFP as demonstrated 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 traditional approaches.
- Fluid power is critical to aerospace control surfaces and landing gear applications. Its compactness and high power to weight ratio are major selection criteria for components and systems in the aerospace industry. Unfortunately, we have received industry feedback that our existing test beds are not aligned with the aerospace industry. Although the CCEFP strategy is clearly aligned with the needs of the aerospace market we have decided not to aggressively pursue aerospace industry members. Furthermore, adding an additional test bed to the Center research strategy at this time, would dilute funding of other projects or test beds.

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 disconcerting with respect to inadvertent public disclosure of potential IP during Center meetings with industry members present. Our approach is to assume that everything presented has been publicly disclosed and to regularly remind our faculty and students to exercise caution. The membership agreement is currently being reviewed for possible improvements. Industry has indicated that implementing a new MA contract was not desirable because of the legal effort and cost required to do so. Therefore, we are implementing clarifying changes into 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 currently in use 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 comprised 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. Monthly IAB Conference calls are held to discuss topics of particular interest. These calls are run by the IAB chair who establishes an agenda in concert with the ILO. Topics can cover a wide range, from future research project areas to sustainability planning. Three times per calendar year the IAB meets face-to-face, on-site at a member university, according to a rotating schedule. The first day of these meetings is dedicated to technical presentations by the researchers and includes a tour of the university laboratory facilities. An informal dinner is held during the evening which provides an excellent networking opportunity for industry members, PIs and students. The second day includes a feedback session on the technical presentations as well as an opportunity to discuss special topics. It is common to invite potential industry members to these site meetings which allows them 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 the same organizational framework that was co-developed by 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. Continuity of leadership is assured by a transition policy wherein 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).

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

Summary:
40 - Industrial/Practitioner Members
1 - Innovation Partner
0 - Funder of Sponsored Projects
5 - Funders of Associated Projects
5 - Contributing Organizations

Section 1: 40 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
Bobcat	Industry	Vehicle OEM	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No	0	0
Bosch Rexroth Corporation	Industry	Fluid power components and systems	In-Kind Donations	Member of Center's Industrial Advisory Board Involvement in Technology Transfer	Foreign	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	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	Foreign	Medium (500-1000 employees)	No	0	0
Eaton Corporation	Industry	Fluid power components and systems	Unrestricted Cash Donations Associated Project Support	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	2
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

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
Evonik Industries	Industry	Chemical manufacturer	Unrestricted Cash Donations	Member of Center's Industrial Advisory Board 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
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
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
Linde Hydraulics Corp.	Industry	Fluid power components and systems	Unrestricted Cash 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
Moog, Inc.	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Large (>1000 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
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

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
Nitta Corporation	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	No	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
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
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
Sauer-Danfoss	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
Simerics, Inc.	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
Sun Hydraulics	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects Involvement in Technology Transfer	Domestic	Medium (500-1000 employees)	No	0	0
Takako Industries	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Foreign	Small (<500 employees)	No	0	0
Tennant	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	Large (>1000 employees)	No	0	0
The Lubrizol Corporation	Industry	Petrochemical	Unrestricted Cash Donations Associated Project Support	Member of Center's Industrial Advisory Board	Domestic	Large (>1000 employees)	No	0	1
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
Walvoil Fluid Power	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects	Foreign	Medium (500-1000 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

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

Section 2: 1 Innovation Partner

Organization	Sector	Product Focus (Industry only)	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Partner (Yes/No)
Eolos Wind Energy Research Consortium	Other Sector	N/A	Participates in science/engineering research projects	Domestic	N/A	Yes

Section 3: 0 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
There are no organizations of the organization type Funder of Sponsored Projects for which support has been received.								

Section 4: 5 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 Participation in translational research Involvement in Technology Transfer	Domestic	N/A	Yes	15
DARPA	U.S. Government (Not NSF)	N/A	Associated Project Support	Participates in science/engineering research projects Participation in translational research	Domestic	N/A	No	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 Participation in translational research	Domestic	N/A	No	2
Total Oil Company	Industry	Petrochemical	Associated Project Support	Participates in science/engineering research projects	Foreign	Large (>1000 employees)	No	1

Section 5: 5 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.							
Festo Corporation	Industry	Fluid power components and systems	In-Kind Donations		Foreign	Large (>1000 employees)	No
NorthStar STEM Alliance	U.S. Government (Not NSF)	N/A	Unrestricted Cash Donations	Participation in education/outreach activities	Domestic	N/A	Yes
Precision Associates	Industry	rubber products	Unrestricted Cash Donations In-Kind Donations	Participation in education/outreach activities	Domestic	Small (<500 employees)	No

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
Tol-O-matic	Industry	Fluid power components and systems	Unrestricted Cash Donations	Participates in science/engineering research projects Participation in education/outreach activities	Domestic	Small (<500 employees)	Yes	N/A	N/A
Contributing Organizations That Will Provide Support by the End of the Current Award Year.									
International Fluid Power Society	Industrial Association	N/A	Unrestricted Cash Donations	Participates in science/engineering research projects	Domestic	N/A	No	N/A	N/A

Section 6: Summary					
Sector	**Industrial/Practitioner Members**	**Percent Foreign**	**Percent Small**	**Percent Medium**	**Percent Large**
Industry	39	21%	38%	10%	51%
Industrial Association	1	0%	N/A	N/A	N/A
Total	**40**	**20%**	**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, 2009 - May 31, 2010	Jun 01, 2010 - May 31, 2011	Jun 01, 2011 - May 31, 2012	Jun 01, 2012 - May 31, 2013 [1]
Industrial/Practitioner Members	54	54	48	40
Innovation Partners	0	0	1	1
Funders of Sponsored Projects	0	0	0	0
Funders of Associated Projects	5	15	8	5
Contributing Organizations	2	5	9	5
Total Participating Organizations	**61**	**74**	**66**	**51**
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	$616,265	$636,250	$708,817	$506,600
Membership Fees Expected from Prior Year Members [2]	N/A	N/A	N/A	$72,500
Member-Sponsored Projects Total Dollar Amount	$0	$0	$0	$0
Member-Associated Projects Total Dollar Amount	$121,067	$166,864	$95,295	$78,336
Member In-Kind Total Dollar Amount [3]	$18,300	$121,261	$92,150	$12,257
Total Dollar Amount, Industrial/Practitioner Member Support to Center	**$755,632**	**$924,375**	**$896,262**	**$669,693**

[1] Partial Award Year data only.

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

[3] Data for this row is from the In-Kind Support reported in the Organizations section. There is no data prior to 2010 since it is a new field that year.

Table 5a - Technology Transfer Activities

Organization Name	Faculty On Site at Organization	Faculty Instruction to Organization	Individual from Organization on Lead Institution Campus	Licensed Software	Licensed Technology (other than software)	Graduate Hired by Organization	Student On Site at Organization	Participation in Test Bed	Other Activities
Afton Chemical Corp.		✔							1B.1: New Material Combinations...,
Air Logic									
Bobcat									
Bosch Rexroth Corporation	✔				✔	✔		✔	
Casappa S.p.A.									
Caterpillar, Inc.		✔					✔	✔	Technology Licensing Opportunities Fluid Power Scholars
CNH America, Inc.									Fluid Power Scholars Internship Program
Concentric AB/Haldex									
Confidential Organization (optional use for associated or sponsored projects only)		✔							
DARPA									
Deltrol Fluid Products							✔		
Eaton Corporation	✔	✔			✔	✔	✔		
Enfield Technologies									Research project support CEO on Executive Committee
Eolos Wind Energy Research Consortium									
Evonik Industries		✔							
Exxon Mobil		✔							IAB representative
Festo Corporation									
Freudenberg - NOK									Support Research Projects
Gates Corporation									
Heco Gear, Inc.									
Hoowaki, LLC									
Husco International, Inc.						✔			Fluid Power Scholars Intership Program
International Fluid Power Society									
Linde Hydraulics Corp.		✔							Research project support
Main Manufacturing Products, Inc.									
Master Pneumatic-Detroit, Inc.									
Moog, Inc.									
National Defense Science and Engineering Fellowship Grant (NDSEG)									
National Fluid Power Association		✔							Fluid Power Scholars
National Tube Supply Company									
Netshape Technologies									
Nexen Group, Inc.									
Nitta Corporation									
NorthStar STEM Alliance									
Parker Hannifin Corporation							✔		Fluid Power Scholars Internship Program
Poclain Hydraulics		✔							
Precision Associates									
Quality Control Corporation									
Ross Controls									
Sauer-Danfoss		✔			✔				Fluid Power Scholars Internship Program
Simerics, Inc.									
StorWatts Inc.									
Sun Hydraulics									Fluid Power Scholars Internship Program
Takako Industries									
Tennant									
The Lubrizol Corporation									
Tol-O-matic									
Total Oil Company									
Trelleborg Sealing Solutions									
Walvoil Fluid Power									
Woodward, Inc.									

Figure 5b: Lifetime Industrial/Practitioner Membership History

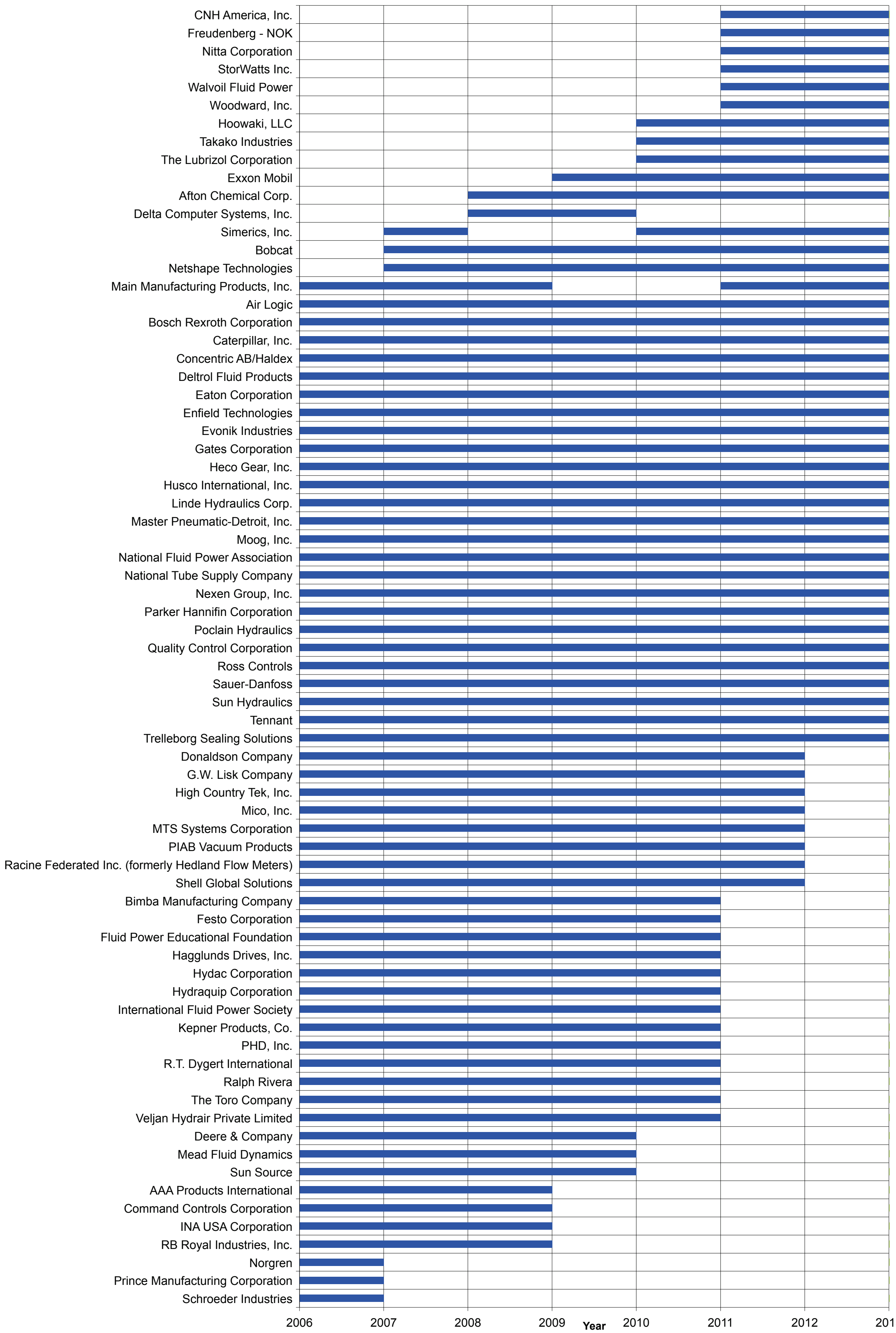


Figure 5c: Total Number of Industrial/Practitioner Members

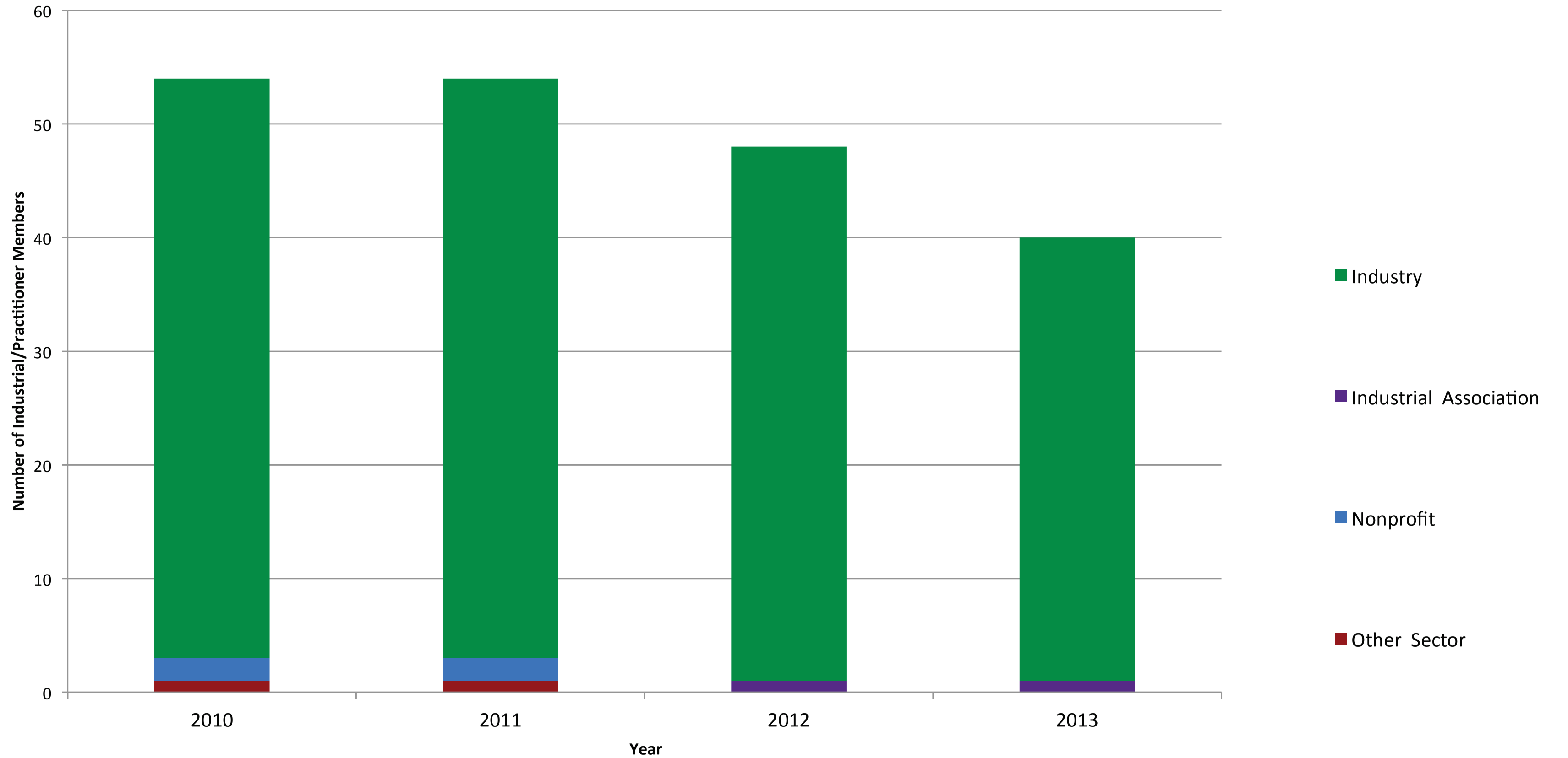
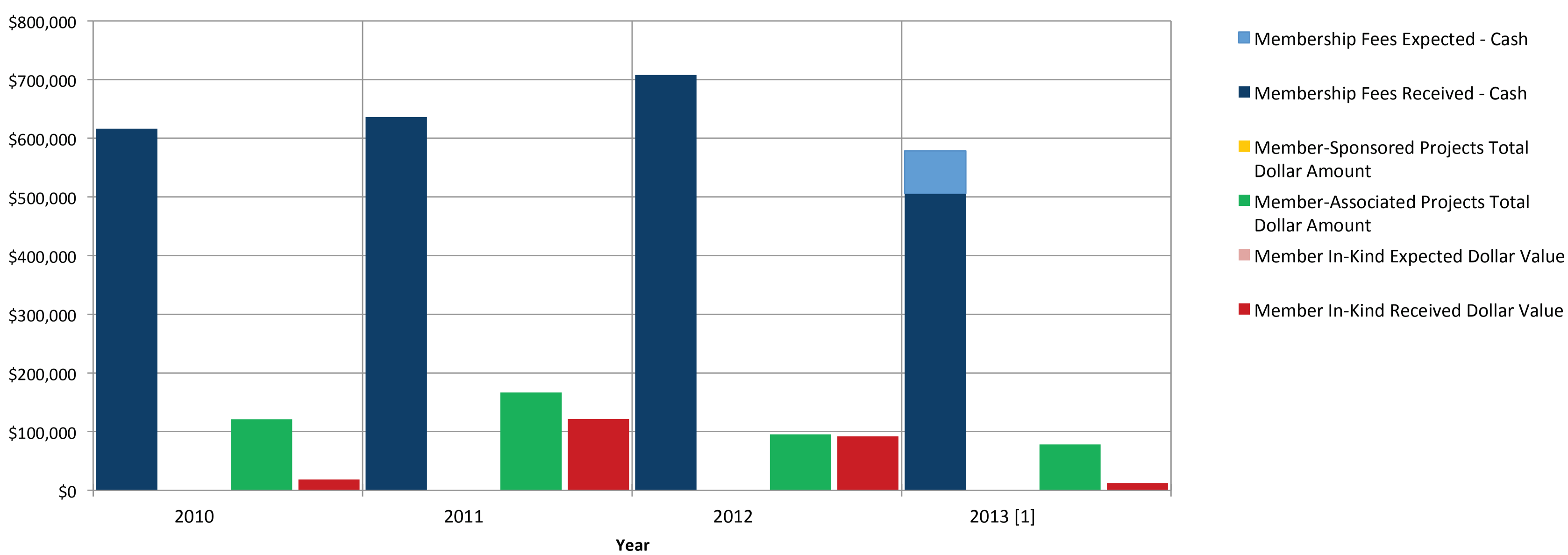


Figure 5d: Industrial/Practitioner Member Support by Year, FY 2013



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

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 three invention disclosures, six patent applications filed, one patent awarded, two licenses issued and one spin-off company started this past year. Since its inception the CCEFP has produced 46 disclosures, 30 patent applications filed, five patents awarded, four licenses issued and two spin-off companies. The fluid power industry has historically been slow to adopt new technologies but these statistics support that the CCEFP is beginning to make a difference. The table below summarizes the CCEFP Invention disclosures that have occurred since the Center started in 2006.

ERC Intellectual Property Table:

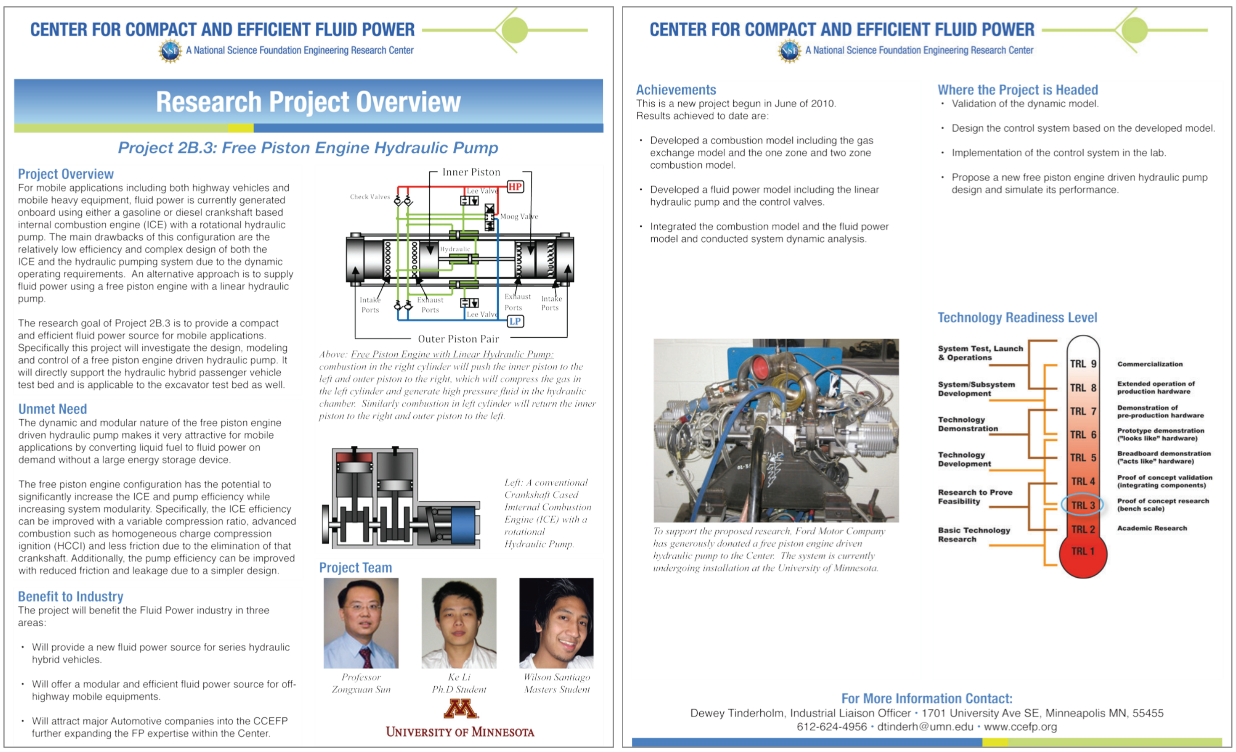
IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	Existing or possible licensing opportunities
Z07054	Minnesota	Open Accumulator Compact Energy Storage for Regenerative Fluid Power Applications	10/10/06	6/30/09	12/445,176	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	

IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	Existing or possible licensing opportunities
VU09108	VANDERBILT UNIVERSITY	High Energy Density Elastomeric Accumulator	4/6/09	3/31/10	PCT/US10/29361	Discussions underway with CCEFP member
VU09107	VANDERBILT UNIVERSITY	High Inertance Liquid Piston	4/6/09	4/5/10	8,297,237	
	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			

IP File number at the Home University	Home University	IP Title	Provisional Application Date	Patent Application Date	Patent Number	Existing or possible licensing opportunities
VU1172	VANDERBILT UNIVERSITY	Elastic Hydraulic Accumulator /Reservoir System	N/A	1/31/11	US 13/017,118 AND PCT PCT/US11/23120	
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		
	VANDERBILT UNIVERSITY	Motive Apparatus for use in Magnetically-Sensitive Environments	11/16/11	11/16/12		

The Center has created an excellent communication tool to facilitate technology transfer that is both simple and effective. These are non-confidential single page 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. 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. These summaries have proven to be valuable tools for communicating to potential new members the value of CCEFP research projects. By way of example, a company found a description of our work on the ccefp website, contacted the center and is now a member of the CCEFP working with a project researcher on an associated project.

The project summary sheets 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. The project summary sheets are easily available for download in pdf format from the CCEFP website.


CENTER FOR COMPACT AND EFFICIENT FLUID POWER

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Research Project Overview

Project 2B.3: Free Piston Engine Hydraulic Pump

Project Overview

For mobile applications including both highway vehicles and mobile heavy equipment, fluid power is currently generated onboard using either a gasoline or diesel crankshaft based internal combustion engine (ICE) with a rotational hydraulic pump. The main drawbacks of this configuration are the relatively low efficiency and complex design of both the ICE and the hydraulic pumping system due to the dynamic operating requirements. An alternative approach is to supply fluid power using a free piston engine with a linear hydraulic pump.

The research goal of Project 2B.3 is to provide a compact and efficient fluid power source for mobile applications. Specifically this project will investigate the design, modeling and control of a free piston engine driven hydraulic pump. It will directly support the hydraulic hybrid passenger vehicle test bed and is applicable to the excavator test bed as well.

Above: Free Piston Engine with Linear Hydraulic Pump: combustion in the right cylinder will push the inner piston to the left and outer piston to the right, which will compress the gas in the left cylinder and generate high pressure fluid in the hydraulic chamber. Similarly combustion in left cylinder will return the inner piston to the right and outer piston to the left.

Unmet Need

The dynamic and modular nature of the free piston engine driven hydraulic pump makes it very attractive for mobile applications by converting liquid fuel to fluid power on demand without a large energy storage device.

The free piston engine configuration has the potential to significantly increase the ICE and pump efficiency while increasing system modularity. Specifically, the ICE efficiency can be improved with a variable compression ratio, advanced combustion such as homogeneous charge compression ignition (HCCI) and less friction due to the elimination of that crankshaft. Additionally, the pump efficiency can be improved with reduced friction and leakage due to a simpler design.

Left: A conventional Crankshaft Cased Internal Combustion Engine (ICE) with a rotational Hydraulic Pump.

Benefit to Industry

The project will benefit the Fluid Power industry in three areas:

- Will provide a new fluid power source for series hydraulic hybrid vehicles.
- Will offer a modular and efficient fluid power source for off-highway mobile equipments.
- Will attract major Automotive companies into the CCEFP further expanding the FP expertise within the Center.

Project Team

Professor Zongxuan Sun | Ke Li Ph.D Student | Wilson Santiago Masters Student

University of Minnesota

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Achievements

This is a new project begun in June of 2010. Results achieved to date are:

- Developed a combustion model including the gas exchange model and the one zone and two zone combustion model.
- Developed a fluid power model including the linear hydraulic pump and the control valves.
- Integrated the combustion model and the fluid power model and conducted system dynamic analysis.

Where the Project is Headed

- Validation of the dynamic model.
- Design the control system based on the developed model.
- Implementation of the control system in the lab.
- Propose a new free piston engine driven hydraulic pump design and simulate its performance.

To support the proposed research, Ford Motor Company has generously donated a free piston engine driven hydraulic pump to the Center. The system is currently undergoing installation at the University of Minnesota.

Technology Readiness Level

For More Information Contact:

Dewey Tinderholm, Industrial Liaison Officer • 1701 University Ave SE, Minneapolis MN, 55455

612-624-4956 • dtinderh@umn.edu • www.ccefp.org

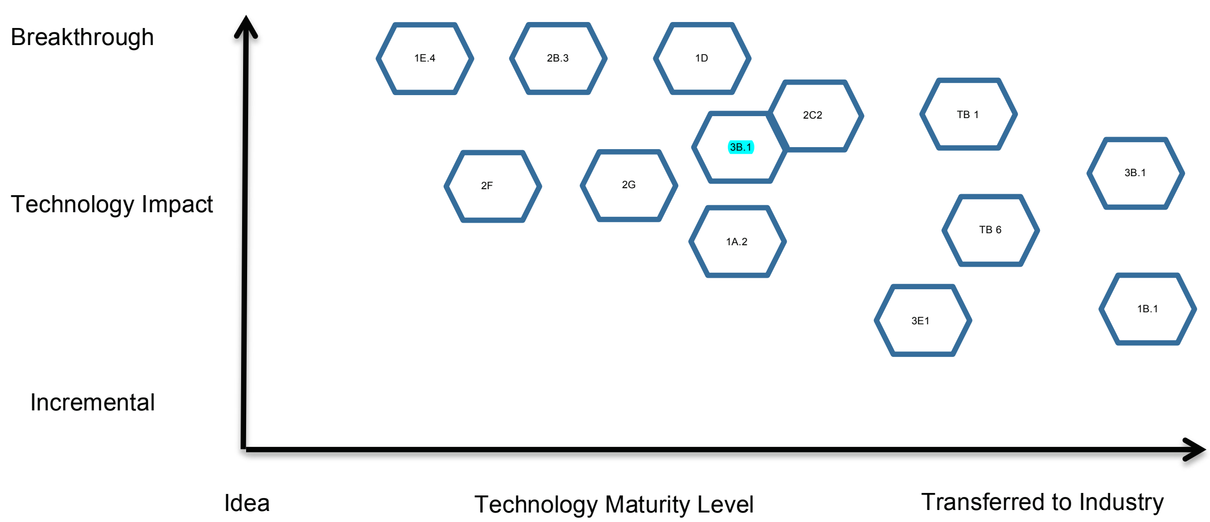
Project Summary Sheet

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

CCEFP Technology Transfer



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. CCEFP industry members are the some of the most dominate in the fluid power 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, 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, but most do not know how this is accomplished. The CCEFP will implement a program modeled after the Quality of Life ERC Foundry. This program will 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 packets will be developed and distributed to all incoming students. Annual training sessions to ensure students know how to navigate the path to start-ups. The CCEFP is committed to fostering an environment whereby anyone 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 areas once deemed by industry as "weaknesses" have grown to become strengths. This transformation continues to occur with the IAB providing positive feedback on the new project review process and with 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 will continue.

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 and the best way to do so is through active and meaningful participation. The CCEFP is actively working with the National Fluid Power Association (NFPA) to improve our industry engagement. Going forward we envision the CCEFP-NFPA-industry partnership to become a critical cornerstone of our long-term sustainability strategy. We must leverage each organization's strengths while eliminating unnecessary duplication of efforts and associated administration overhead. The CCEFP will take the lead on owning and maintaining the research strategy while NFPA will do so on the workforce development strategy with strong input from one another.

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.

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

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.

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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

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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 one of the most important products of the CCEFP is its 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 CCEFP Fluid Power Scholars industry internship program. Interns participate in a 3-day training course on fluid power at a member university before their internship begins.

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, 38% women and 27% or underrepresented racial or ethnic minority status and 8 Fluid Power Scholar students, 0% 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 2011 REU and FPS program include: Case Western Reserve University, Clarkson University, Humboldt State University, Illinois Institute of Technology, Loyola University Chicago, Louisiana State University, Montana State University, Minneapolis Community and Technical College, New Mexico State University, Princeton University, Texas A&M, University of Florida, University of Michigan, University of Missouri-Columbia, University of South Florida and 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, 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. The Director’s decision to change from a one year to a two year funding cycle in Year 5 has been well accepted by all Center participants. An effective budgeting process has been implemented where resource allocations and project efforts are closely coupled. Also, the practice of reallocating unspent funds annually has been suspended. This has simplified the budget process and made it less arbitrary and contentious. This approach is also more appropriate as the Center has matured and all member universities have shown themselves to be capable of more independently managing their own finances. 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. In year 8, a stricter billing and payroll process will be implemented as delays can cause an inaccurate picture of the Center's financial standing. 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 has returned 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 Director meets biweekly with the Industrial Liaison Officer and Sustainability Director to maintain focus on key issues including research strategy, industry membership and Center sustainability. A successful initiative from this group has been the hosting of three to four on-site IAB visits at CCEFP universities annually. This process has greatly improved communication between university researchers and industry. 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.

CCEFP is a complex, distributed multi-institutional organization. It is important to augment the leadership team with a group that has broader representation. The CCEFP is led by the Executive Committee (EC). The Director is Chair of the EC which includes a representative from each member university, one SLC representative and four industry representatives. The EC meets at least three times a year, with additional meetings needed in the alternate years where the project renewal process is implemented. Responsibilities include defining and updating of the Center strategy, new project selection and progress tracking.

The CCEFP multi-disciplinary research team has the depth and breadth of disciplines needed to achieved the CCEFP systems vision. The question of disciplinary composition must be considered carefully, since it is an important factor in determining CCEFP success. The QRC data system defines disciplines in terms of departments, but the two are not the same. A department is a university administrative entity. A discipline is a research entity where the members have a common background and understand and are aware of each other's work.

Table 2a (section 2.1) shows the CCEFP disciplinary composition as shown by the QRC data system. It can be seen that the majority of the faculty belong to mechanical engineering, with smaller numbers belonging to aeronautical engineering, agricultural and biological engineering, chemistry and industrial engineering.

The SLC updated its SWOT analysis in December 2012. The analysis and CCEFP leadership response are shown below.

Y7 SLC SWOT

Year 7 has been the second year since the Student leadership Council (SLC) underwent significant restructuring. This restructuring gave the SLC a larger role in overall leadership capabilities by funding the SLC as an education and outreach project and reducing the number of representatives and officers to streamline the SLC structure. The change in funding allows the SLC to run our student travel and project grant programs.

For the year 7 SWOT analyses the SLC conducted a survey of current students to determine how they felt the strengths, weaknesses, opportunities, and threats are at present within the SLC and throughout the Center. For each category students were ask to specify whether they strongly agreed or strongly disagreed with the items from the previous SWOT analysis using a 5 point scale (Strongly agree: 5, Agree: 4, Neutral: 3, Disagree: 2, Strongly disagree: 1), however for the purpose of better display, strongly agree and agree are grouped together in the following graphs as well as grouping strong disagree with disagree. “Don’t know” was the sixth option presented at each question. A breakdown of the response from each institution is shown in Fig. 1 and a total of 23 students participated in the online survey.

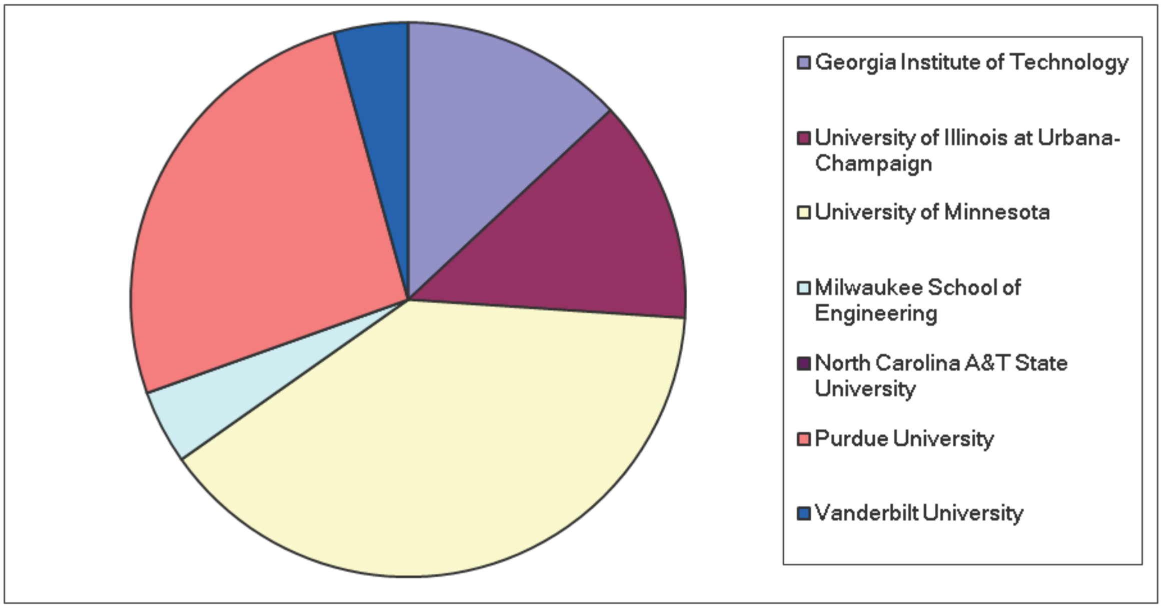


Figure 1: Demographic information of responses

The results of the strengths analysis are shown in Fig. 2. From this data one can see that students feel the Center has maintained its strengths since the year 6 review and strongly agree that they are conducting multidisciplinary research that is impactful and meaningful. In addition, students agree that the REU program and the new travel grant program are also strengths of CCEFP. Some of the lowest consensus was regarding the CCEFP project center and inter-university collaboration. It is somewhat understandable that students might not directly see the advantage of the project center as part of its main purpose is to streamline reporting for CCEFP headquarters instead of directly benefiting students. It is somewhat disheartening to see inter-university collaboration ranked lower; however its rating remained at a similar level to that of last year. Nevertheless, it bolsters support for the SLC travel grant program, which intends to address that exact issue.

<u>CCEFP Response</u>: We are pleased the students recognize that the Center’s multidisciplinary research is impactful and meaningful and the various education projects, REU Program and SLC Travel Grant Program are viewed as strengths. The CCEFP Project Center, our new integrated database and project management tool designed to capture important data on the research and educational activities across the Center, is a relatively new endeavor and continues to be improved upon. We agree the value of the Project Center should be better articulated, which in turn, when better understood, would help the Center capture more information on the significant achievements. We recognize the challenges in being geographically distant and seek the input from the students how to better create inter-university collaboration.

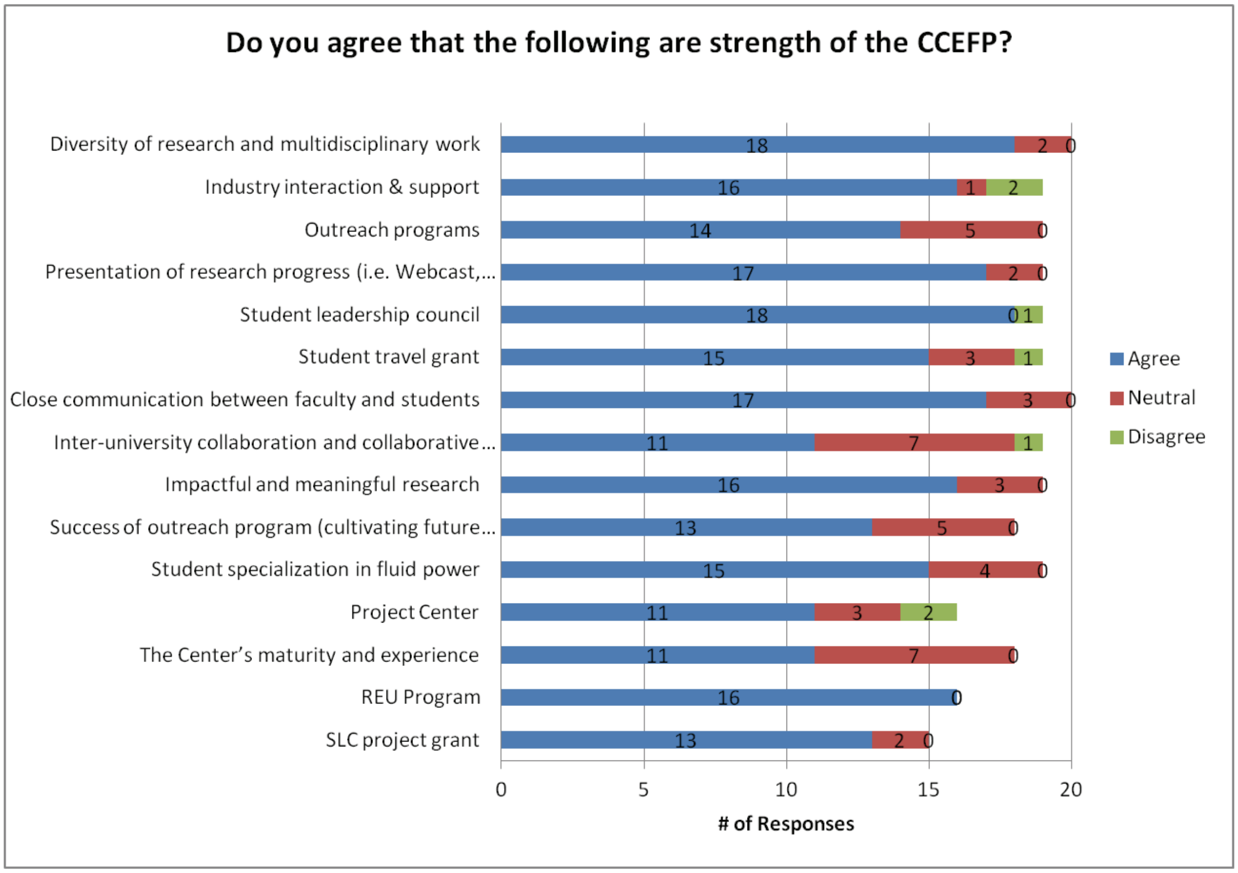


Figure 2: Student responses to Strength assessment of the CCEFP

The weakness assessment results are presented in Fig. 3. The strongest weakness is lack of student participation in the bi-weekly webcasts. This has remained rather consistent from year-to-year although the SLC has attempted to reduce this by offering project grants aimed at purchasing pizza to incentivize students to attend and introducing "special topic" speakers. Nevertheless, graduate students constantly face many demands for their time, and thus convincing them to attend another event will always persist as a challenge. The stronger agreement with "Lack of synchronization of efforts between closely related projects" likely reflects the weaker agreement with inter-university collaboration of the previous question. The agreement on loss of interest or maintaining vision increased slightly over last year. It is hard to know if this is a result in the redirection of test bed 4 or other core center projects.

CCEFP Response: The Center is committed to reviewing the current webcast model for information dissemination. While we have a strong industry audience, we realize participation by students is not consistent. We recognize the communal experience is more effective in technology transfer and collaboration across the Center. An expansion of the webcast program is planned in Year 8 and includes a fluid power training series exclusively for CCEFP research students. Experts in the fluid power industry and those in companies that are corporate members of the Center would present the training series. Perhaps this expansion could increase interest in the traditional research presentations in the webcast series. The Center currently presents "project updates" during the webcast series. Perhaps the Center should consider other options for information dissemination, rather than project updates, on the CCEFP research projects. Naturally, the lack of synchronization between projects might identify the weakness assessment for both webcast attendance and interest in other research projects across the Center. Without synchronization, there will be a lack of information and knowledge about various research initiatives across the Center. In Year 8, the Center will be employing a project management system to address this very issue.

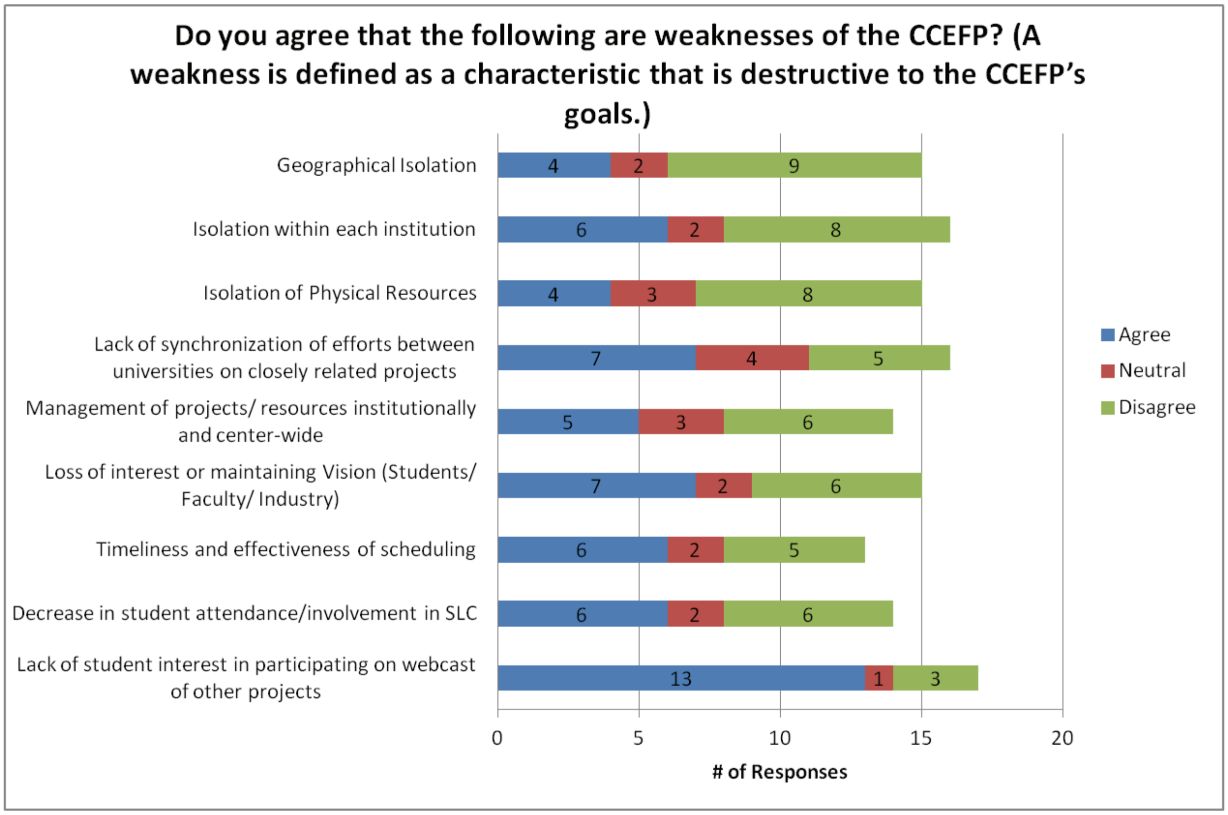


Figure 3: Student responses to Weakness assessment of the CCEFP

Students agreed with all of the characteristics identified as opportunities for the Center. For a list of characteristics and assessment results see Fig. 4. The characteristic, which had the strongest agreement, was the international fluid power communities indicating that the Center should seek out opportunities to have students share their work with the global fluid power community. The weakest agreement was a resume repository for companies interested in hiring students familiar with fluid power. This is likely in part due to the multitude of methods for resume sharing already in existence today. However, the stronger agreement for post-graduate employment opportunities reflects students' appreciation for the personal connections they build while part of the CCEFP with center member companies.

<u>CCEFP Response</u>: It is true; the global fluid power community has a great internal presence than in the United States. The CCEFP does promote collaboration and participation in international conferences wherever possible. The CCEFP is planning our upcoming annual meeting jointly with the ASME Bath Symposium on Fluid Power and Motion Control in October 2013. This meeting draws a significant amount of international attention. Many of the Centers faculty and graduate students regularly present research at the FPNI PhD Symposium, also an international event. Another opportunity includes the International Fluid Power Expo (IFPE) to be held March 2014. IFPE is the leading international exposition and technical conference dedicated to the integration of fluid power with other technologies for power transmission and motion control applications. The CCEFP has attended IFPE during the previous two events, in 2008 and 2011.

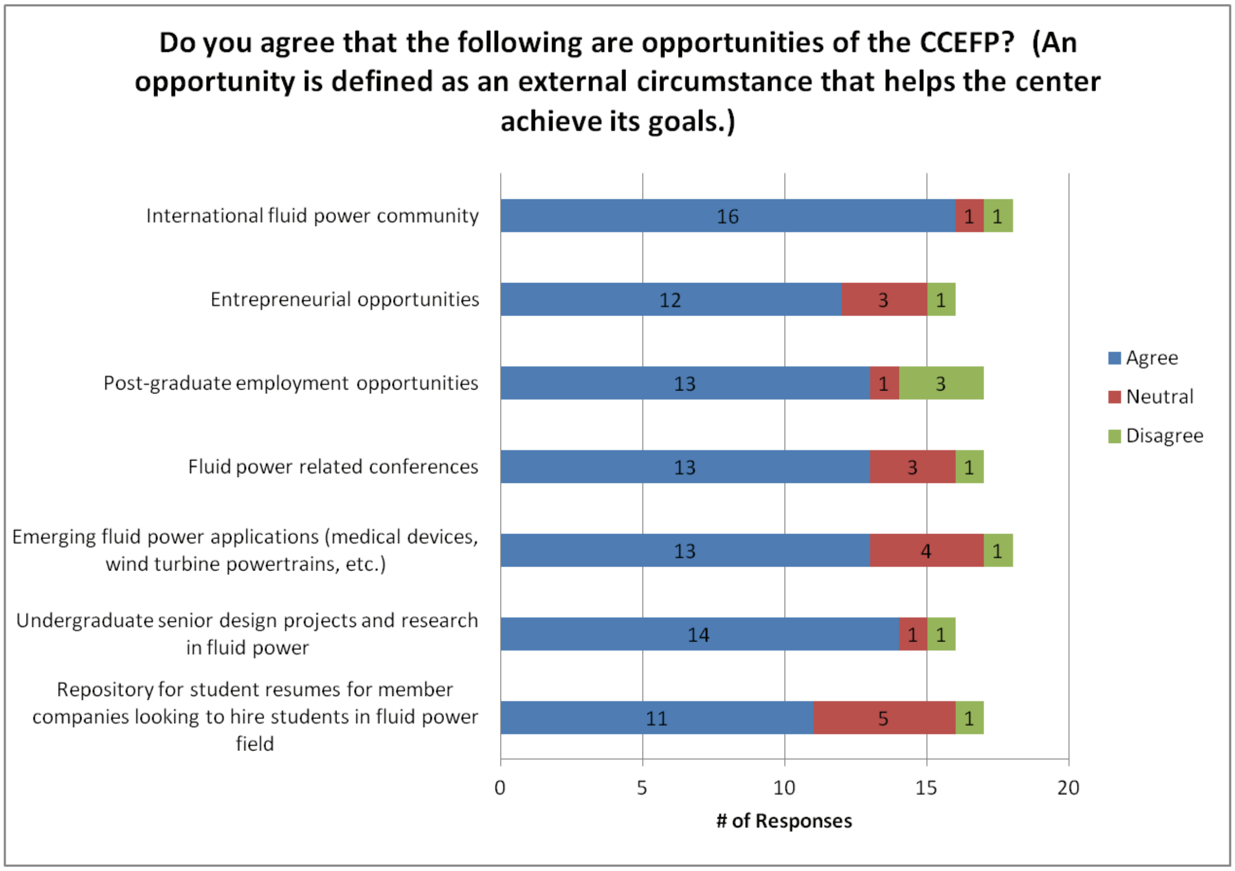


Figure 4: Student responses to Opportunity assessment of the CCEFP

Of the threats identified by the SLC, decrease in NSF financial support had the strongest overall agreement among students. This is not surprising as the sustainability of the Center is dependent upon bringing in additional resources and this is one of the major challenges faced by the CCEFP today.
CCEFP Response: We agree that sustainability is the greatest challenge of the CCEFP and we are working hard on a viable plan.

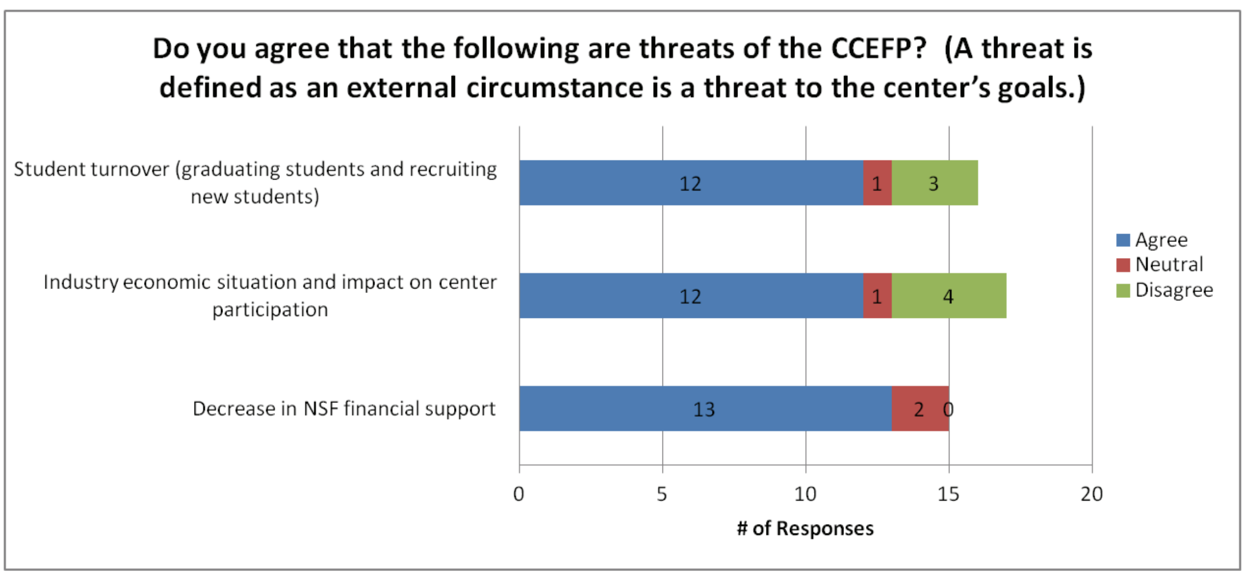


Figure 5: Student responses to Threat assessment of the CCEFP

Overall, the student assessment of the CCEFP is consistent with the expectations of the SLC and as the Center moves forward it is important that it continues to find ways to promote collaboration and integration within the Center and bring new companies and researchers into the Center.

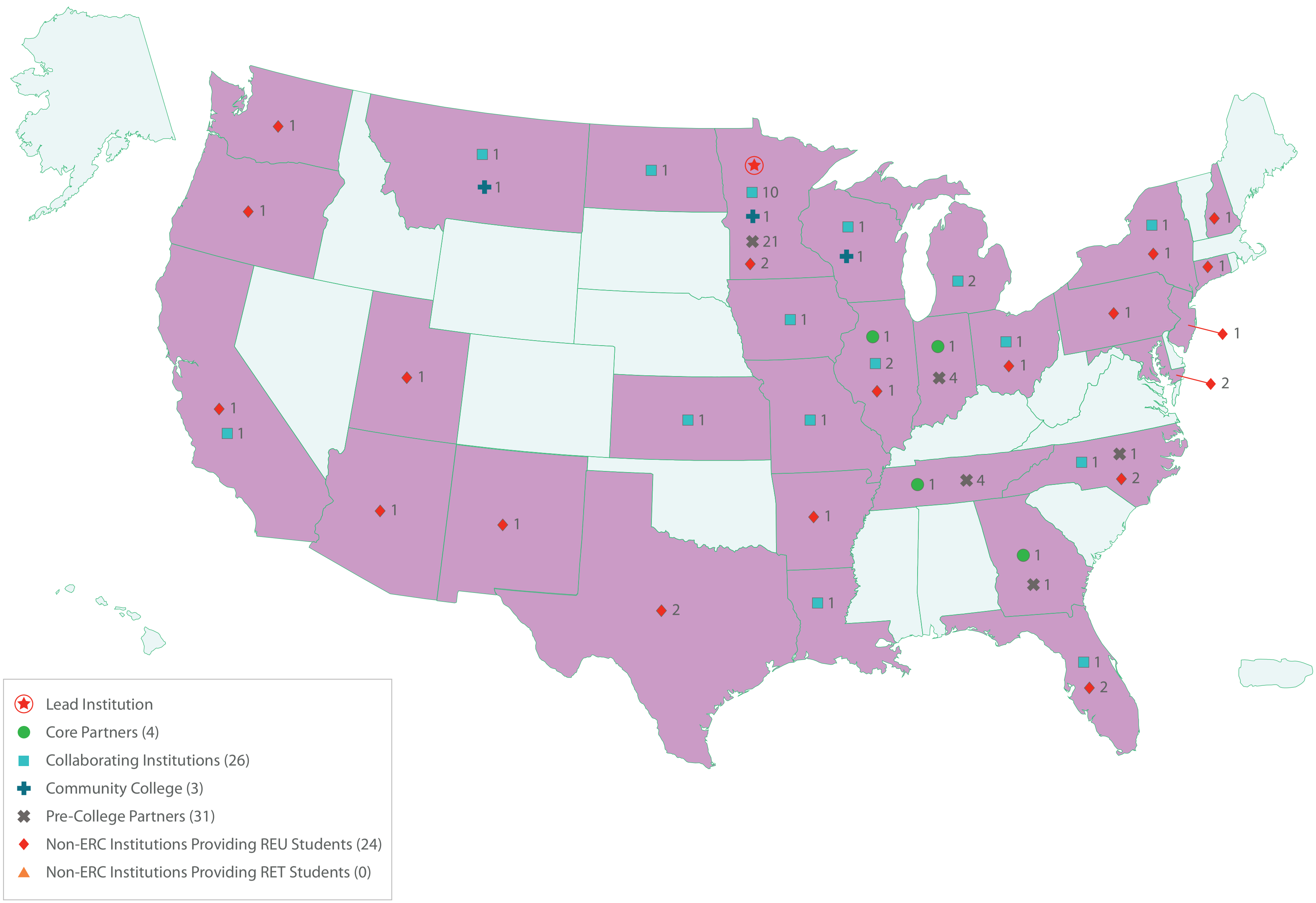
CCEFP Response: We would like to thank the Student Leadership Council and the student members of the Center for the thorough evaluation of the CCEFP. We appreciate the review and recommendations for improvement. We commend the SLC for initiating the student-led travel and project programs, and graduate-level internship program to be launched in Year 8, which fall under the Education and Outreach Program. The Center applauds the vision of its officers, the cooperation of its representatives and the entire student body for helping us achieve our short and long-term goals.

Table 6: Institutions Executing the ERC's Research, Technology Transfer, and Education Programs															
Institutions							Personnel in ERC Activities [1]								
									Students				Teachers		
											Graduate				
Name and Type	Total	Female Serving	Minority Serving	HBCU	Hispanic Serving	Large Number of URM Students in Engineering	Faculty	Post Docs	UG Non-REU	REU	Masters	Doctoral	Non-RET	RET	Young Scholars
I. Lead	**1**	**0**	**0**	**0**	**0**	**0**	**11**	**2**	**38**	**1**	**10**	**18**	**N/A**	**N/A**	**N/A**
University of Minnesota, Minneapolis, MN							11	2	38	1	10	18	N/A	N/A	N/A
II. Core Partners	**4**	**0**	**0**	**0**	**0**	**0**	**17**	**0**	**38**	**12**	**8**	**32**	**N/A**	**N/A**	**N/A**
Georgia Institute of Technology, Atlanta, GA							7	0	12	1	3	11	N/A	N/A	N/A
Purdue University, West Lafayette, IN							3	0	10	7	2	12	N/A	N/A	N/A
University of Illinois at Urbana-Champaign, Urbana, IL							4	0	11	1	2	4	N/A	N/A	N/A
Vanderbilt University, Nashville, TN							3	0	5	3	1	5	N/A	N/A	N/A
III. Collaborating Institutions	**26**	**0**	**3**	**0**	**1**	**2**	**5**	**0**	**50**	**6**	**6**	**7**	**N/A**	**N/A**	**N/A**
Bemidji State University, Bemidji, MN						✔	0	0	1	0	0	0	N/A	N/A	N/A
Bradley University, Peoria, IL							0	0	2	0	0	0	N/A	N/A	N/A
Case Western Reserve University, Cleveland, OH							0	0	0	0	0	0	N/A	N/A	N/A
Clarkson University, Potsdam, NY							0	0	1	0	0	0	N/A	N/A	N/A
Eolos Wind Energy Research Consortium, Minneapolis, MN							0	0	0	0	0	0	N/A	N/A	N/A
Hennepin Technical College, Brooklyn Park, MN							0	0	4	0	0	0	N/A	N/A	N/A
Illinois Institute of Technology, Chicago, IL							0	0	2	0	0	0	N/A	N/A	N/A
Iowa State University, Ames, IA							0	0	2	0	0	0	N/A	N/A	N/A
Kansas State University, Manhattan, KS							0	0	1	0	0	0	N/A	N/A	N/A
Leech Lake Tribal College, Leech Lake, MN			✔			✔	1	0	3	0	0	0	N/A	N/A	N/A
Louisana State University, Baton Rouge, LA							0	0	1	0	0	0	N/A	N/A	N/A
Michigan Technological University, Houghton, MI							0	0	1	0	0	0	N/A	N/A	N/A
Milwaukee School of Engineering, Milwaukee, WI							1	0	4	2	4	0	N/A	N/A	N/A
Montana State University, Bozeman, MT							0	0	0	0	0	0	N/A	N/A	N/A
National Center for Earth-surface Dynamics, Minneapolis, MN							0	0	0	0	0	0	N/A	N/A	N/A
North Carolina Agriculture and Technical State University, Greensboro, NC			✔				3	0	5	4	1	7	N/A	N/A	N/A
Science Museum of Minnesota, St. Paul, MN							0	0	0	0	0	0	N/A	N/A	N/A
St. Cloud State University, St. Cloud, MN							0	0	3	0	0	0	N/A	N/A	N/A
Stanford University, Stanford, CA			✔		✔		0	0	0	0	0	0	N/A	N/A	N/A
STEM Education Center, Minneapolis, MN							0	0	0	0	0	0	N/A	N/A	N/A
University of Michigan, Ann Arbor, MI							0	0	0	0	0	0	N/A	N/A	N/A
University of Minnesota - Duluth, Duluth, MN							0	0	1	0	0	0	N/A	N/A	N/A
University of Minnesota - Morris, Morris, MN							0	0	16	0	0	0	N/A	N/A	N/A
University of Missouri-Columbia, Columbia, MO							0	0	2	0	0	0	N/A	N/A	N/A
University of North Dakota, Fargo, ND							0	0	1	0	1	0	N/A	N/A	N/A
University of South Florida, Tampa, FL							0	0	0	0	0	0	N/A	N/A	N/A
IV. Non-ERC Institutions Providing REU Students	**24**	**1**	**1**	**0**	**1**	**0**	**N/A**	**N/A**	**N/A**	**7**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Dartmouth College, Hanover, NH							N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A
Duke University, Durham, NC							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Embry-Riddle Aeronautical University, Daytona Beach, FL							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Humboldt State University, Arcata, CA							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Johns Hopkins University, Baltimore, MD							N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A
Lehigh University, Bethlehem, PA							N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A
Loyola University Chicago, Chicago, IL		✔					N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Minneapolis Community and Technical College, Minneapolis, MN							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
New Mexico State University, Las Cruces, NM			✔		✔		N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
North Carolina State University, Raleigh, NC							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Northstar STEM LSAMP, Minneapolis, MN							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Princeton University, Princeton, NJ							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Stony Brook University, Stony Brook, NY							N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A
Texas A&M University, College Station, TX							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
University of Arizona, Tempe, AZ							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
University of Arkansas, Fayetteville, AR							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
University of Cincinnati, Cincinnati, OH							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
University of Florida, Gainesville, FL							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A

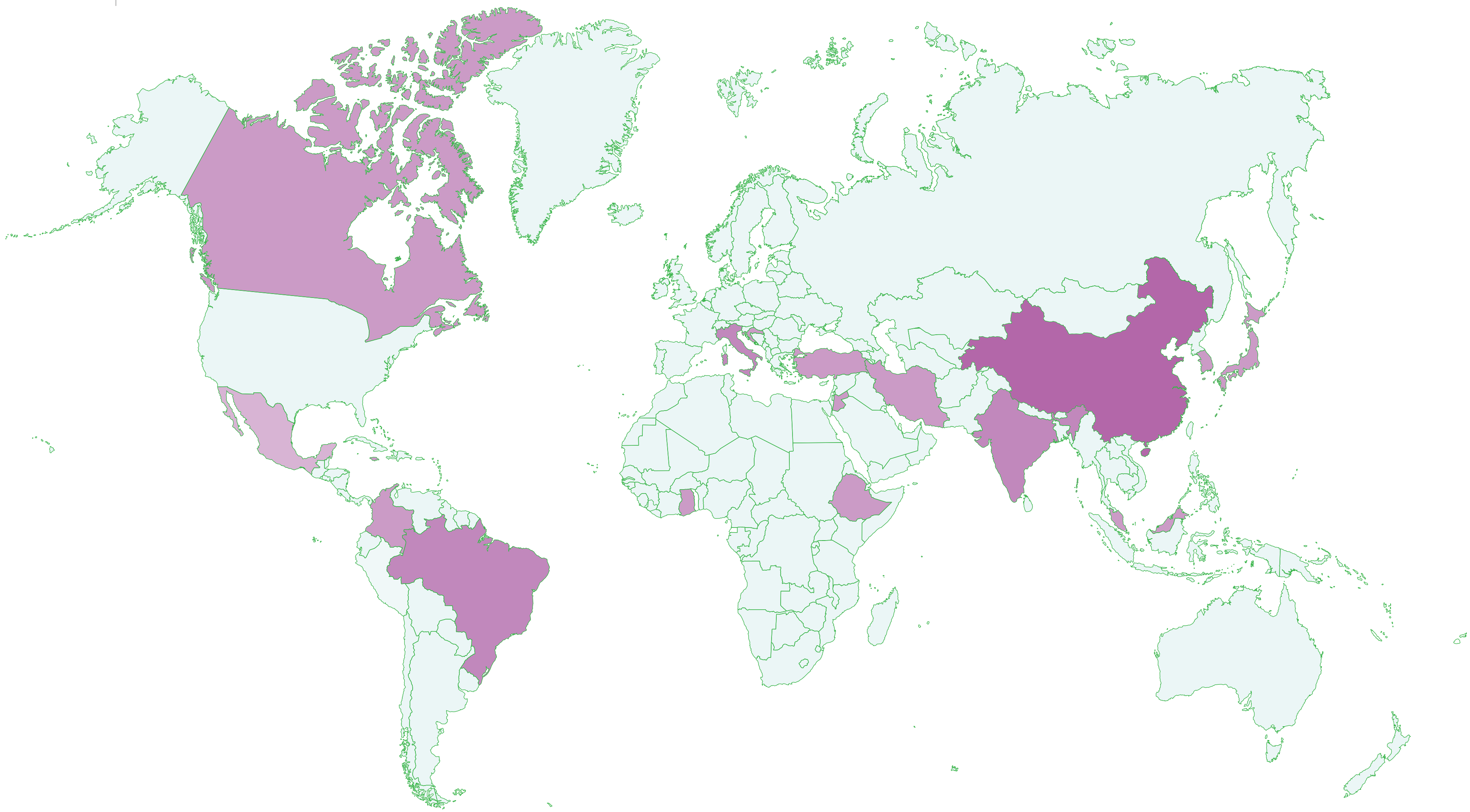
Institutions							Personnel in ERC Activities [1]								
Name and Type	Total	Female Serving	Minority Serving	HBCU	Hispanic Serving	Large Number of URM Students in Engineering	Faculty	Post Docs	Students				Teachers		Young Scholars
									UG Non-REU	REU	Graduate		Non-RET	RET	
											Masters	Doctoral			
University of Maryland, Baltimore, Baltimore, MD							N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A
University of Portland, Portland, OR							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
University of Texas at El Paso, El Paso, TX							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Utah State University, Logan, UT							N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A
Washington State University, Pullman, WA							N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A
Yale University, New Haven, CT							N/A	N/A	N/A	1	N/A	N/A	N/A	N/A	N/A
V. NSF Diversity Program Awardees	**2**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**
Alliances for Graduate Education and the Professoriate (AGEP)	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**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**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**
No CREST institutions were entered.															
Louis Stokes Alliances for Minority Participation (LSAMP)	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**
No LSAMP institutions were entered.															
Tribal Colleges and Universities Program (TCUP)	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**
No TCUP institutions were entered.															
NSF Diversity Program Collaborations (NSF Diversity Program Collaborations)	**2**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**
Northstar STEM Program						✔	0	0	0	0	0	0	N/A	N/A	N/A
SUNY LSAMP			✔				0	0	0	0	0	0	N/A	N/A	N/A
VI. Precollege Partners	**32**	**0**	**9**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**11**	**6**	**0**
Bemidji High School, Bemidji, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Bemidji Middle School, Bemidji, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Brentwood High School, Brentwood, TN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
BugONayGeShig School, Leech Lake, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Burnsville High School, Burnsville, MN							N/A	N/A	N/A	N/A	N/A	N/A	1	0	0
Cass Lake Middle School, Cass Lake, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Circle of Life School, White Earth, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Cloquet High School, Cloquet, MN							N/A	N/A	N/A	N/A	N/A	N/A	1	0	0
Cloquet Middle School, Cloquet, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Deer River School, Deer River, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Gibbon, Fairfax, Winthrop School, Gibbon, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Guilford Middle School, Greensboro, NC							N/A	N/A	N/A	N/A	N/A	N/A	0	1	0
Independence High School, Thompson Station, TN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
KidWind, Saint Paul, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Lafayette Jefferson High School, Lafayette, IN							N/A	N/A	N/A	N/A	N/A	N/A	0	1	0
Mahnomen High School, Mahnomen, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Mahtomedi High School, Mahtomedi, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
McCutcheon High School, Lafayette, IN							N/A	N/A	N/A	N/A	N/A	N/A	0	1	0
Metropolitan Nashville Public School, Nashville, TN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Naytawaush Charter School, Naytawaush, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Ojibwe School, Cloquet, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	2	0	0
Ponemah Elementary School, Ponemah, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Ragsdale High School, Jamestown, NC							N/A	N/A	N/A	N/A	N/A	N/A	0	1	0
Red Lake Middle School, Red Lake, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Robbinsdale Armstrong High School, Robbinsdale, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Rockdale Magnet School for Science and Technology, Conyers, GA							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Smyrna High School, Smyrna, TN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
South Ridge School (formerly Albrook School), Culver, MN			✔				N/A	N/A	N/A	N/A	N/A	N/A	5	0	0
St. Paul Public Schools, St. Paul, MN							N/A	N/A	N/A	N/A	N/A	N/A	2	0	0
Tippecanoe School Corporation, Lafeyette, IN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Walker Alternative School, Walker, MN							N/A	N/A	N/A	N/A	N/A	N/A	0	0	0
Westfield Washington High School, Westfield, IN							N/A	N/A	N/A	N/A	N/A	N/A	0	2	0
VII. Community Colleges	**3**	**0**	**3**	**0**	**0**	**0**	**1**	**0**	**13**	**0**	**0**	**0**	**N/A**	**N/A**	**N/A**
Fond du Lac Tribal and Community College, Cloquet, MN			✔				0	0	0	0	0	0	N/A	N/A	N/A
Lac Courte Oreilles Ojibwa Community College, Hayward, WI			✔				0	0	1	0	0	0	N/A	N/A	N/A
Salish Kootenai College, Pablo, MT			✔				1	0	12	0	0	0	N/A	N/A	N/A
Total	**92**	**1**	**17**	**0**	**2**	**3**	**34**	**2**	**139**	**26**	**24**	**57**	**11**	**6**	**0**

[1] - Only ERC personnel executing the ERC mission are shown in this table.

6a Location of Lead, Core Partner, and All Domestic Collaborating Institutions



6c Country of Citizenship for ERC Foreign Personnel



= Number of ERC personnel from this country

- 1 person
- 2–10 people
- 11+ people

1 person		
Canada	Iran	Malaysia
Colombia	Jamaica	Mexico
Croatia	Japan	South Korea
Ethiopia	Jordan	Turkey
Ghana		

2–10 people	
Brazil	2
India	8
Italy	3

11+ people	
China	15

Country Not Reported	1*

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

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5.2 DIVERSITY EFFORT AND IMPACT

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

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

The Center recognizes opportunities to expand upon the recruitment, retention, and participation of underrepresented students—women, racial and ethnic minorities, persons with disabilities, and recent war veterans—by creating more research and educational opportunities within the Center as these students consider study and career choices in mechanical engineering and fluid power. With successes and lessons learned from Years 1 - 6, the CCEFP continued efforts in Year 7 to engage individuals within each of these underrepresented groups in its programs.

Though there are instances of success, other results require a more dedicated and deliberate effort, in the short term. There is promise that the CCEFP strategy, programs, and activities--new and newly enhanced--will bring long-term improvements given that the early stages of redesign and launch are behind us. 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 specialized membership model includes cooperation between the ERC and the Industry member, who are both academic and corporate members of the National GEM Consortium. The ERC provides the initial funds ($22,500) to recruit and sponsor a GEM Fellow; the research institution provides an additional supplement to sufficiently support the student in full (~$40,000/year), and the Industry member provides the recommended summer graduate internships (~$36,000/year). The GEM Fellow receives over $150,000 of financial support in terms of academic student stipend, tuition remission, and summer intern salary. Often, the Industry member hires the student as an employee following the program. This rich collaboration offers nothing but benefits to the GEM Fellow, the ERC, the Industry member, and the GEM Consortium. To date, the CCEFP has initiated one partnership in this novel interface. Caterpillar, who is a corporate member of the National GEM Consortium, has agreed to co-sponsor a CCEFP-CAT GEM Fellow for the academic years of 2013 - 2014. A faculty member at Georgia Institute of Technology will be advising the GEM Fellow on CCEFP fluid power research.
- The Center has successfully received NSF Graduate Research Diversity Supplement (GRDS) funding for four consecutive years to support two graduate students each year in the field of engineering with an emphasis in fluid power research. Since 2008, the supplement has provided opportunity for five women, four Caucasian, and one African-American, to matriculate through the CCEFP and either earn their Masters Degree or continue pursuing their PhD in an area of fluid power. In 2012, the Center received its fourth year of funding to continue to support a female UIUC PhD student and to fund a new PhD candidate, an African American woman, at Vanderbilt University. The NSF GRDS supplement is now on hold pending other new opportunities for underrepresented students through NSF. For more information, see EO Project C.10.
- In addition to the NSF Graduate Research Diversity Supplement (GRDS) award, the CCEFP has provided an additional $50,000 to further supplement the GRDS grant received 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. The CCEFP is enlisting faculty across the Center as well as local student groups such as SWE (Society for Women Engineers), SHPE (Society for Hispanic Professional Engineers), SACNAS (Society for Advancing Chicanos/Latinos and Native Americans in the Sciences), AISES (American Indians Science and Engineering Society), NSBE (National Society of Black Engineers), NSF LSAMP programs as well as local CCEFP diversity offices to recruit undergraduate students into the Center's research laboratories. To date, the program has sponsored five new students, all women, two of whom are racially or ethnically diverse, to research labs in the CCEFP. Faculty from the University of Minnesota, University of Illinois, Urbana-Champaign, and North Carolina A&T State University submitted proposals to the CCEFP to provide stipends for these academic undergraduate research students. For more information, see EO Project C.9.
- CCEFP's Research Experiences for Undergraduates (REU): This program has traditionally been very successful in recruiting diverse participants, in race, ethnicity, and/or gender. Since revising the CCEFP REU program structure in 2008, 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. (Note: The CCEFP applied for an REU Site award in the recent 2012 solicitation, following very positive feedback and recommendation from the 2010 and 2011 proposals.)

- The CCEFP has recently initiated a formal partnership with Larry Villasmil, a faculty member at Rochester Institute of Technology (RIT), 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. Professor Villasmil will be conducting research at the University of Minnesota in the summer of 2013. The CCEFP will support a number of RIT REUs on CCEFP research during Professor Villasmil's visit.
- The CCEFP's giiwed'anang North Star AISES (American Indian in Science and Engineering Society) Alliance is sponsoring its third First Nations Rocket Launch Competition in cooperation with the Minnesota NASA Space Consortium for the AISES Chapter at the University of Minnesota. In 2012, the CCEFP recruited four engineering students from UMN to AISES and the rocket project. Other AISES engineering students are actively leading fluid power outreach activities.
- CCEFP again took the lead in organizing a joint ERC exhibitor booth at both AISES and SACNAS National Conferences in the fall of 2012. Over 8 ERCs participated: SMART Lighting ERC, FREEDM - Center for Future Renewable Electric Energy Delivery and Management, CIAN - Center for Integrated Access Networks, QoLT - Quality of Life Technology Center, QESST - Quantum Energy and Sustainable Solar Technologies, CBiRC - Center for Biorenewable Chemicals, and CSNE - Center for Sensorimotor Neural Engineering. Also, the contributing ERCs helped to design and create a new ERC Exhibitor Booth. The collaboration is highly successful, reaching over 300 highly motivated students to recruit for ERC undergraduate and graduate research programs. The idea has gained momentum and other ERCs are now making plans to attend NSBE, SHPE, and others, as NSF ERC representatives.

New ERC Exhibitor Booth

2012 SACNAS National Conference Exhibitors

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, so we will focus on those.

Women – Representation is near or above national averages in all categories. It is notable that 28.3% of Undergrad Non-REU students are women as compared to 18.7% nationally. Among REU students the Center percentage of women is 30%. Women were 13.8% of the faculty and 33.3% of the leadership team of the CCEFP.

Racial Minorities – The CCEFP greatly exceeded national averages in nearly all categories. We are particularly pleased with the percentage of Undergrad Non-REU students who are racial minorities, 47.5%, because this number comes from a large pool of 99 students.

Hispanic/Latinos – Numbers of Hispanic/Latinos and persons with disabilities remain small. The Center takes this problem seriously and has taken steps, and put plans in place, to address these issues, as detailed above.

- 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 2012, 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. Underrepresented racial minorities make up 13.8% of CCEFP faculty, 20% of doctoral candidates and 47.5% of undergraduates (non-REU), while 30% of REU students represent racial minorities.
    - The CCEFP has made it a priority to enhance its recruitment of Hispanic/Latino/a participants while increasing Center mentorship opportunities. As a result, there have been some advancements, although the Center has experienced a decrease in the number of Hispanic/Latino/a students in the recent reporting year. 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, URDS, and GRDS 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 Fluid Power Scholars Program holds promise here, too. The CCEFP will continue to recruit underrepresented, diverse students to its database of applicants for this program. Note that industry is ultimately responsible for a given year's demographics since each mentoring company selects its intern(s) from this pool.
- 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, and four in 2012.

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.

<u>At the grass-roots level</u>: 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.

<u>Within the Center network:</u> 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.

Y7 Outcomes:

Research Experiences for Undergraduates	2012	TOTAL (Y2-Y7)
Number of Students	23	130
Male	17	87
Female	6	43
Percentage of students from underrepresented groups 1 racial or ethnic minority 2 gender minority 3 disability	 1) 40% 2) 26% 3) 0%	 1) 33% 2) 33% 3) .01%

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.)

Y7 Outcomes:

Fluid Power Scholars	2012	TOTAL (Y4-Y7)
Number of Students	9	25
Male	8	22
Female	1	3
Percentage of students from underrepresented groups 1 racial or ethnic minority 2 gender minority 3 disability	 1 0% 2 11% 3 11%	 1 88% 2 12% 3 1%

CCEFP Undergraduate and Graduate Research Diversity (URDS and GRDS) 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 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	**2012**	**TOTAL**
Number of Students	7	9
Male	0	0
Female	7	9
Percentage of students from underrepresented groups 1) racial minority 2) gender minority 3) disability	1) 42% 2) 100% 3) 0%	1) 44% 2) 100% 3) 0%

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 six RET teachers at least three CCEFP universities. A special CCEFP RET focus is recruiting teachers from area high schools participating in the PLTW program.

Y7 Outcomes:

Research Experiences for Teachers	**2012**	**TOTAL**
Number of Teachers	6	42*
Male	5	35
Female	1	7
% from underrepresented groups	17%	23%
% PLTW Teachers	67%	47%

**Several repeat participants*

gidaa odaangiina anaangoog (Shooting for the Stars) 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.

Y7 Outcomes:

gidaa odaangiina anaangoog Robotics Program*	2012	TOTAL
Number of Students	60	274
Male	35	158
Female	25	116

**Initiated program in 2009, Y3*

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.

Various outreach efforts throughout the course of the academic year have created the foundation that AISES students need to stay engaged, have a student-body family, have educational support and serve as mentors to others. The giiwed'anang Alliance leverages AISES activities and supports student participation. As participation and interest grows, so does student recruitment and retention.

Since Y2, the giiwed'anang Alliance has reached over 100 undergraduate Native American students in STEM across the state of Minnesota, and beyond. The Alliance has bridged over 10 AISES Chapters in Minnesota to create a highly interwoven region, to the point where Region V (Minnesota, Wisconsin, Dakotas, Iowa, Canada, etc.) earned the "Spirit Stick" by way of popular vote at the 2012 AISES National Conference.

In Y7, CCEFP, with the support of various other sponsoring organizations, funded over 15 students to attend the AISES National Conference in Anchorage, Alaska. The giiwed'anang Alliance also hosted a dinner of over 40 AISES students and chapter advisors during the National Conference. In addition, the CCEFP will support five AISES members to attend the AISES Leadership Conference and 15 AISES members to attend the Region V Meeting at the University of Minnesota-Morris. One AISES member at the University of Minnesota participated in a small research project with the CCEFP on wind turbine efficiency.

Table 7a: Diversity Statistics for ERC Faculty and Students

	US Citizens or Permanent Residents						Foreign (Temporary Visa Holders)						Citizenship Not Reported					
	Leadership Team[4]	Faculty [5]	Doctoral Students	Masters Students	Undergrad Non-REU	REU Students	Leadership Team[4]	Faculty [5]	Doctoral Students	Masters Students	Undergrad Non-REU	REU Students	Leadership Team[4]	Faculty [5]	Doctoral Students	Masters Students	Undergrad Non-REU	REU Students
Center Total	**9**	**29**	**30**	**18**	**99**	**20**	**0**	**3**	**22**	**3**	**14**	**6**	**0**	**1**	**5**	**3**	**24**	**0**
Women																		
Category Total	3	4	6	3	28	6	0	0	2	0	1	1	0	0	0	0	3	0
Center Percent	33.3%	13.8%	20.0%	16.7%	28.3%	30.0%	0	0.0%	9.1%	0.0%	7.1%	16.7%	0	0.0%	0.0%	0.0%	12.5%	0
National Percent [1][2]	N/A	13.8%	23%	20.2%	18.7%	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
Underrepresented Racial Minorities																		
Category Total	1	4	6	1	47	6	0	0	3	0	1	0	0	0	0	0	6	0
Center Percent	11.1%	13.8%	20.0%	5.6%	47.5%	30.0%	0	0.0%	13.6%	0.0%	7.1%	0.0%	0	0.0%	0.0%	0.0%	25.0%	0
National Percent [1][2]	N/A	3%	4.7%	5.8%	6.3%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hispanic/Latinos																		
Category Total	0	1	0	0	5	2	0	0	2	0	2	2	0	0	0	0	0	0
Center Percent	0.0%	3.4%	0.0%	0.0%	5.1%	10.0%	0	0.0%	9.1%	0.0%	14.3%	33.3%	0	0.0%	0.0%	0.0%	0.0%	0
National Percent [1][2]	N/A	3.8%	5.5%	8.6%	10.9%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Persons With Disabilities																		
Category Total	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
Center Percent	0.0%	0.0%	3.3%	0.0%	1.0%	0.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	0	0.0%	0.0%	0.0%	4.2%	0
National Percent [1][2] [3]	N/A	5.3%	3.3%	3.3%	10%	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

[1] The National Percents for Underrepresented Racial Minorities and Hispanic/Latinos are based only on U.S. citizens and permanent residents. The National Percents for Women and Persons With Disabilities disregard citizenship.

[2] National Percents are from the following years: Women - 2011, Underrepresented Racial Minorities - 2011, Hispanic/Latinos - 2011, and Persons with Disabilities - 2008.

[3] The National Percents shown above for Persons with Disabilities for Doctoral Students and Masters Students are from the National Percent for Graduate Students (Masters and Doctoral students combined).

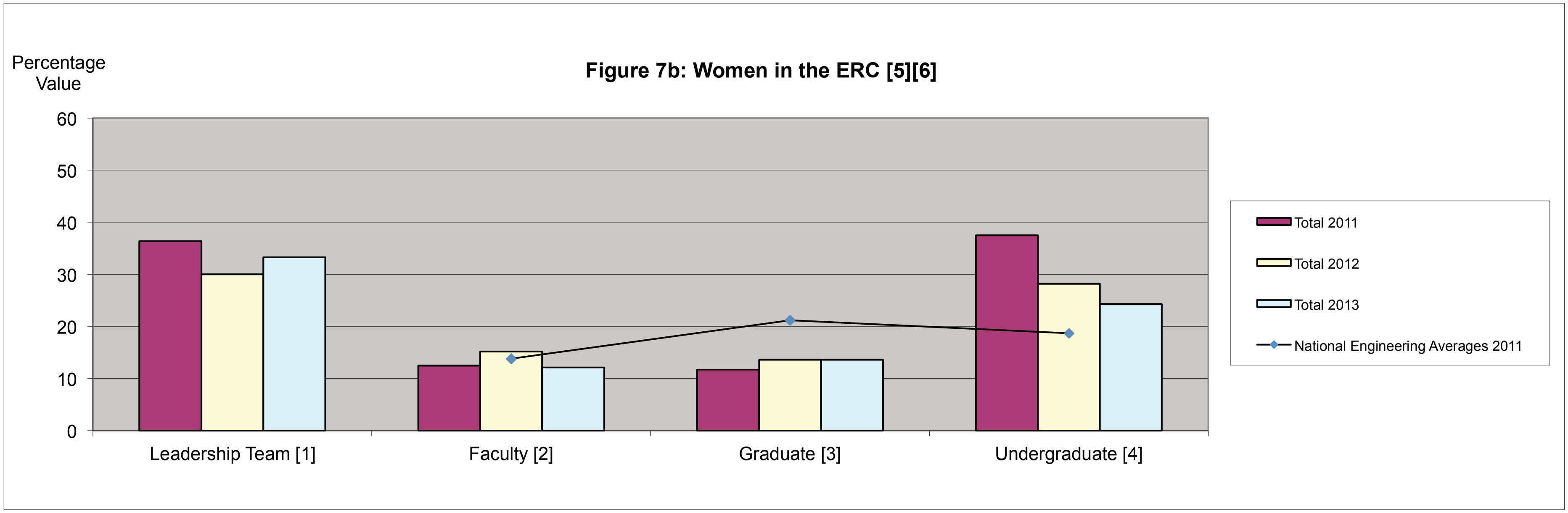
[4] Leadership Team includes Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning.

[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	Post Docs	Students				Teachers		Young Scholars	Other [6]	Total
		UG Non-REU	REU	Graduate		Non-RET	RET			
				Doctoral	Masters					
33	2	137	26	57	24	11	6	0	31	307

[6] Other includes Industrial Liaison Officer, Administrative Director, Research Thrust Management and Strategic Planning, Staff, Research - Industry Researchers, Research - Other Visiting College Students, Research - Research Staff, Curriculum Development and Outreach - Industry Researchers, Curriculum Development and Outreach - Other Visiting College Students and Curriculum Development and Outreach - Staff.



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2011	N/A	13.8%	21.2%	18.7%
All ERC's 2012	32.3%	22.2%	25.7%	34.2%
Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2013	33.3%	12.1%	13.6%	24.3%

[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.

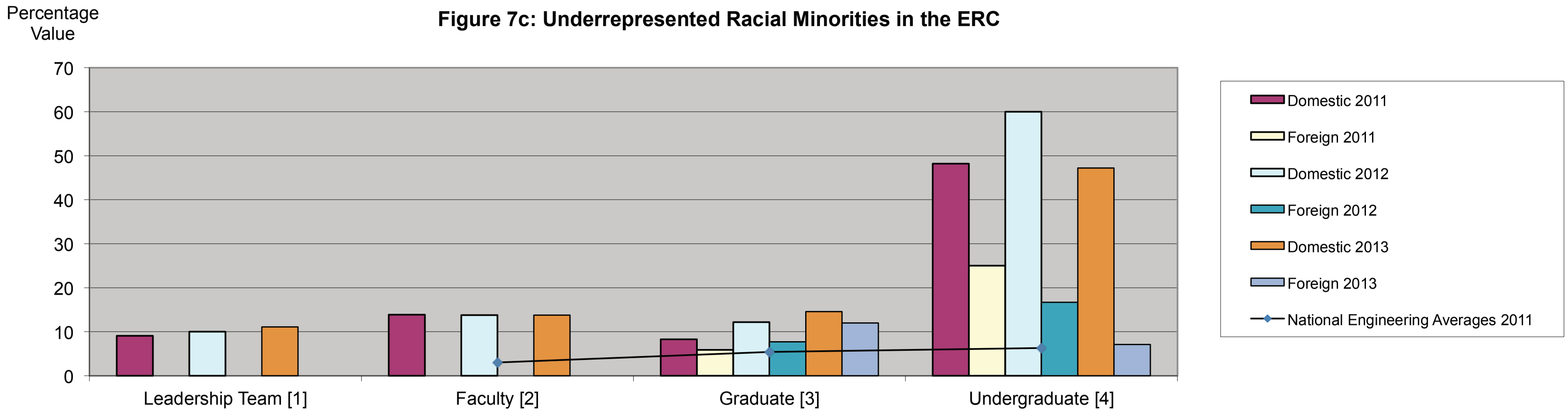
[3] Graduate students include Doctoral and Master's students.

[4] Undergraduate students include non-REU and REU students.

[5] Total counts include personnel regardless of citizenship status.

[6] The number of personnel for whom gender was not reported are not excluded from the percentage calculations.

Figure 7c: Underrepresented Racial Minorities in the ERC



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2011	N/A	3%	5.4%	6.3%
All ERC's 2012	9.9%	7.7%	9.7%	26.8%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2013	11.1%	13.8%	14.6%	47.2%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2013	0%	0%	12%	7.1%

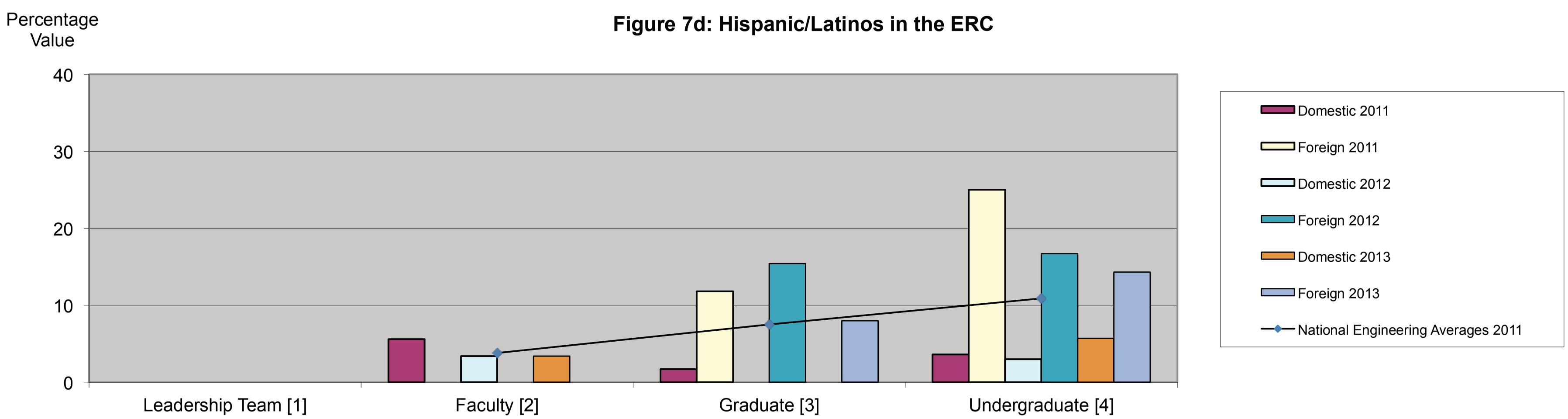
[1] The Leadership Team includes Directors, Thrust Leaders, Industrial Liaison Officer, Education Program Leaders, Administrative Directors, and Research Thrust Management and Strategic Planning.

[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.

Figure 7d: Hispanic/Latinos in the ERC



Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2011	N/A	3.8%	7.5%	10.9%
All ERC's 2012	7.4%	7.5%	10.8%	12.4%
Domestic Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2013	0%	3.4%	0%	5.7%
Foreign Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2013	0%	0%	8%	14.3%

[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.

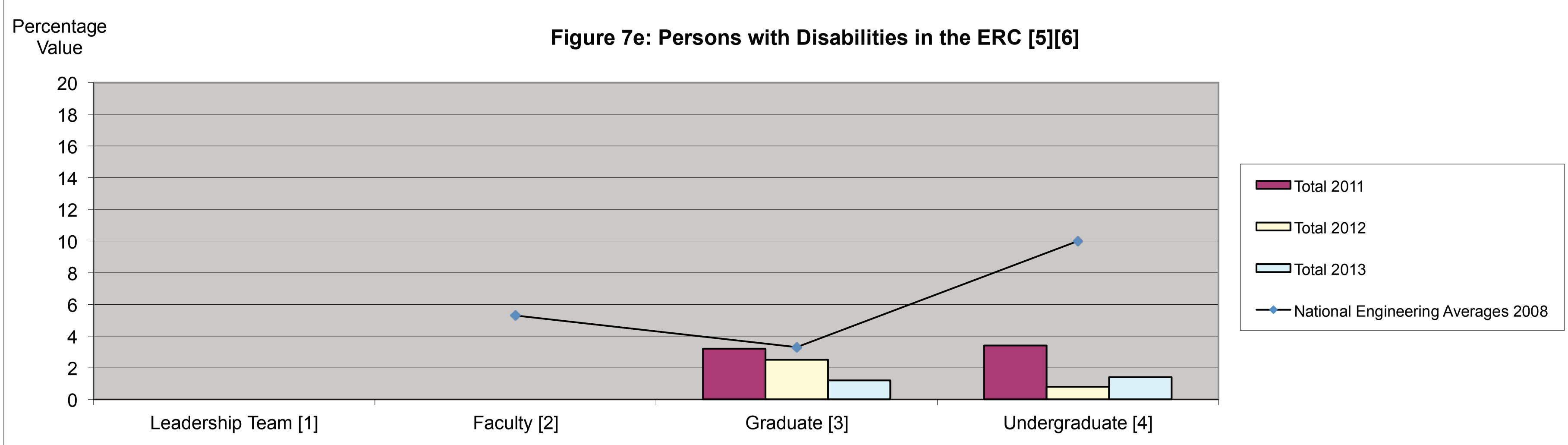


Figure 7e: Persons with Disabilities in the ERC [5][6]

Averages	Leadership Team	Faculty	Graduate	Undergraduate
National Engineering Averages 2008	N/A	5.3%	3.3%	10%
All ERC's 2012	3.1%	1.9%	0.6%	2.2%
Percentage for Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota – Twin Cities 2013	0%	0%	1.2%	1.4%

[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] Total counts include personnel regardless of citizenship status.

[6] 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		Underrepresented Racial Minorities [1] [2]		Hispanics [1] [3]	
	Number	Percent	Number	Percent	Number	Percent
Lead Institution						
University of Minnesota	22	23%	12	19%	4	6%
Core Partners						
Georgia Institute of Technology	3	9%	0	0%	0	0%
Purdue University	2	7%	0	0%	0	0%
University of Illinois at Urbana-Champaign	3	14%	1	7%	0	0%
Vanderbilt University	3	21%	1	10%	1	10%
Collaborating Institutions						
Bemidji State University	1	100%	1	100%	0	0%
Bradley University	1	50%	0	0%	0	0%
Clarkson University	0	0%	0	0%	0	0%
Hennepin Technical College	0	0%	0	0%	0	0%
Illinois Institute of Technology	0	0%	1	50%	0	0%
Iowa State University	0	0%	0	0%	0	0%
Kansas State University	0	0%	0	0%	0	0%
Leech Lake Tribal College	0	0%	4	100%	0	0%
Louisana State University	1	100%	0	0%	0	0%
Michigan Technological University	0	0%	1	100%	0	0%
Milwaukee School of Engineering	2	15%	2	15%	1	8%
National Center for Earth-surface Dynamics	1	100%	0	0%	0	0%
North Carolina Agriculture and Technical State University	4	25%	7	78%	0	0%
Science Museum of Minnesota	1	20%	0	0%	0	0%
St. Cloud State University	2	67%	3	100%	0	0%
University of Minnesota - Duluth	0	0%	0	0%	0	0%
University of Minnesota - Morris	9	56%	13	100%	0	0%
University of Missouri-Columbia	1	50%	0	0%	0	0%
University of North Dakota	1	50%	2	100%	0	0%
Non-ERC Institutions Providing REU Students						
Dartmouth College	1	100%	1	100%	0	0%
Johns Hopkins University	1	100%	0	0%	0	0%
Lehigh University	0	0%	0	0%	0	0%
Stony Brook University	0	0%	1	100%	1	100%
University of Maryland, Baltimore	0	0%	1	100%	0	0%
Utah State University	0	0%	0	0%	0	0%
Yale University	1	100%	0	0%	0	0%
Precollege Partners						
Burnsville High School	1	100%	0	0%	0	0%
Cloquet High 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%
Ojibwe School	1	50%	2	100%	1	50%
Ragsdale High School	1	100%	0	0%	0	0%
South Ridge School (formerly Albrook School)	3	60%	0	0%	0	0%
St. Paul Public Schools	2	100%	0	0%	0	0%
Westfield Washington High School	0	0%	0	0%	0	0%
Community Colleges						
Lac Courte Oreilles Ojibwa Community College	0	0%	1	100%	0	0%
Salish Kootenai College	1	8%	13	100%	0	0%
NSF Diversity Program Collaborations (NSF Diversity Program Collaborations)						
Northstar STEM Program	1	50%	0	0%	0	0%

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

[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.
[3] - Hispanics is a sum of all U.S. Citizens that are indicated to be of hispanic ethnicity.

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 also been with the center since 2006. His role is to provide technology guidance for the center. He owns the strategic plan for technology and oversees the test bed integration. He also provides 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.
- Admin and E&O Assistant – Provides support for operations and E&O projects.
- 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
Tim Deppen - SLC Representative
Vito R. Gervasi - Milwaukee School of Engineering
Steven Herzog – Evonik Oil Additives USA, Inc.
David Holt - ExxonMobil Research Engineering
Monika Ivantysynova - Purdue University
Lew Kasper - Parker Hannifin Corporation
Perry Y. Li - University of Minnesota
Eui Park - North Carolina A&T State University
Joe Pfaff - Husco International
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.
Marcus Royal - Deltrol Fluid Products
Srinivas Patri - Eaton Corp.
Ed Howe - Enfield Technologies
Steven Herzog - Evonik RohMax USA, Inc.
David Holt - ExxonMobil Research and Engineering
Phil Priolo - G.W. Lisk Co., Inc.
Patrick Lee - Gates Corporation
Joe Pfaff - HUSCO International
Scott Lane - Linde Hydraulics Corp.
Shubha Basu - Lubrizol
Eric Lanke - National Fluid Power Association
Dave Moorman - Netshape Technologies
Lew Kasper - Parker Hannifin Corp.
Gilles Lemaire - Poclain Hydraulics
Eric Cummings - Ross Controls
Eric Bretey - Sauer-Danfoss
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
Dr. John Bierlein - Eaton Corporation (Retired)
Prof. Richard Burton - University of Saskatchewan
Dr. Robert J. Cloutier - Stevens Institute of Technology
Prof. Kevin Edge - University of Bath
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
Prof. Masayoshi Tomizuka - University of California-Berkeley
Sohan Uppal – Former Vice President, Technology and Chief Technology Officer for Eaton Fluid Power
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
Jonathan Meyer - Vice President - University of Minnesota
Jon Slightham - Secretary – Milwaukee School of Engineering
Tim Deppen - Treasurer – University of Illinois at Urbana-Champaign

Each institution is allowed a representative on the committee:
Joseph Akyeampong- North Carolina A & T State University
Mark Elton - Georgia Institute of Technology
Sangyoon Lee – University of Minnesota
Kyle Merrill - Purdue University
Hassan Khalid - Milwaukee School of Engineering

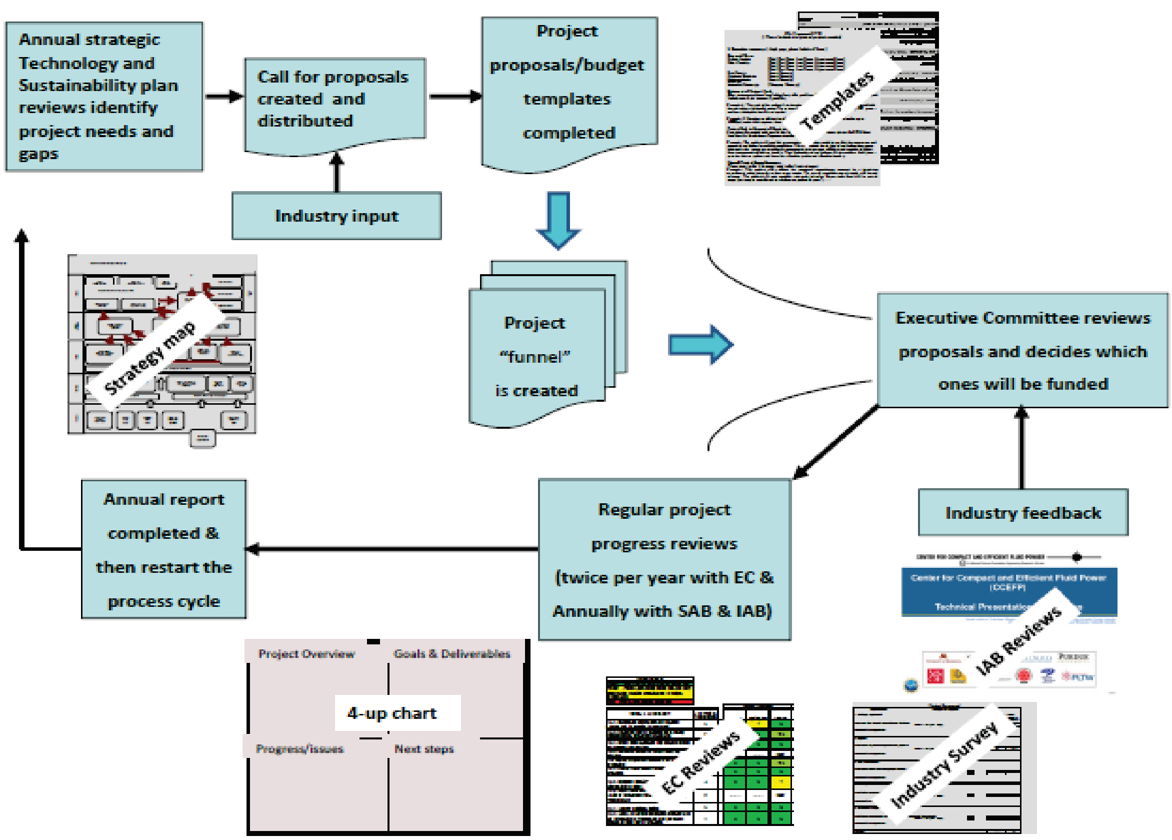
MANAGEMENT OF THE CCEFP

The CCEFP key management activities include strategic planning, budgeting, organizational leadership and control. Long term sustainability planning was added in year seven. 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 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. Feedback from our last site visit questioned whether CCEFP management was selecting projects that best supported overcoming the transformative barriers of the Center's research strategy. Center leadership acknowledges that this criticism is justified. All research projects chosen for funding during the last selection process were important and would surely advance the state of the art of fluid power. However it would have been better if more focus had been placed on addressing the transformative barriers of compact energy storage and compact power supplies. For future project selections the Center will utilize the discipline necessary to ensure these barriers are adequately addressed. If the call for proposals does not result in a sufficient quantity of compelling projects in these areas, Center management will implement a process of identification of projects, project team identification and working with the project teams to create better targeted proposals.



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
A National Science Foundation Engineering Research Center

Year 7-8 Proposal Scorecard

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

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

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

Standardized Proposal Review Template

For the Y7-Y8 funding cycle a total of thirty-two research proposals were received. Budget forecasts allowed for only twenty-one projects to be funded. Of the twenty-four projects underway during the Y5-Y6 funding period, ten were graduated and seven new ones brought into the Center. The 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

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

Twenty three REU students participated in summer 2012, the sixth year of the program: three at the University of Minnesota, eight at Purdue University, one at the University of Illinois Urbana-Champaign, four at Vanderbilt, three 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. Thirteen of the 23 students were recruited from outside the CCEFP's core institutions.

Six teachers participated as RETs in summer 2012, the sixth year of the CCEFP RET program: four at Purdue University and two at North Carolina A&T State University. 42 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.

Two examples of post-doc mentoring activities in CCEFP are:

Farzad Shirazi, University of Minnesota

Farzad, who received his PhD in Mechanical Engineering at the University of Houston, is involved in the NSF EFRI supported associated project titled "Compressed Air Energy Storage for Offshore Wind Turbine". He is the test-bed thrust leader of this project. He is also helping guide graduate students on systems and control topics. He is also leading the effort in exploring the emerging area of integrating our storage concept with electrical grid. Since joining the project in Feb, 2012, Farzad has authored or co-authored 4 conference papers. He will be working on several journal papers and a grant proposal in the coming months.

Dr. Feng Wang, University of Minnesota

Feng did his graduate studies at Zhejiang University and is preparing for an academic career. His time at UMN is focusing on broadening his experience with theoretical and applied studies at both the component and system level. In his first year, Feng collaborated on hydraulics research with Sauer Danfoss (a CCEFP member company). He completed a theoretical study of the influence of viscosity and gap size on the efficiency of hydraulic pumps and motors. He also completed a system level comparison of hydraulic hybrid and electric hybrid vehicles. Feng has spent much of his second year doing research on the use of a hydrostatic transmission for wind power, a CCEFP associated project. He is a key member of the UMN team working with Eaton Corporation and Clipper Windpower on a Department of Energy-funded project focused on developing a hydrostatic drivetrain for offshore wind turbines (6 MW+). Currently in his third year, Feng is continuing to study the use of hydrostatic transmission for mid-wind (100kW-1MW) generators. He meets with Prof. Stelson on a regular basis and has functioned well in opportunities to provide leadership to graduate students. Feng has authored or co-authored a number of papers while here. He plans to use his CCEFP experience to prepare himself for an academic position in the Key State Laboratory for Fluid Power Control at Zhejiang University.

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. Bi-weekly research project webcasts, monthly IAB teleconferences, and a quarterly newsletter are among the efforts targeted at this stakeholder group.

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 and the availability of our fluid power documentary "Discovering Fluid Power" in DVD format.

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

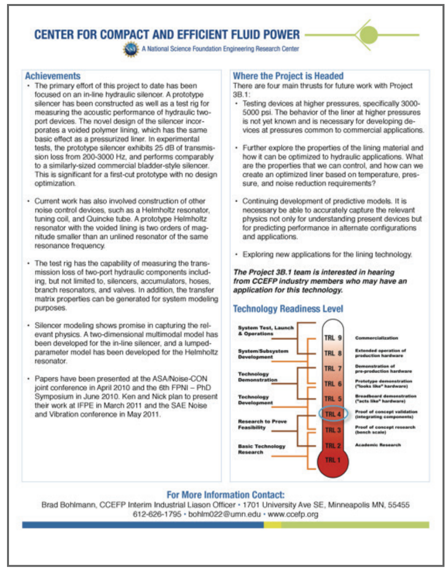
Meetings - The CCEFP has two annual meetings: the NSF Site Visit and the CCEFP Annual Meeting. The primary purpose of the Site Visit is for NSF Center review. The primary purpose of the Annual Meeting is to communicate directly with industry. All past NSF Site Visits have been held at the University of Minnesota. However, this year's site visit will break from tradition and will be held at Purdue University. 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)
2012 – CCEFP Annual Meeting at University of Illinois Urbana Champaign in conjunction with the NFPA Fluid Power Workforce Summit

The 2013 Site Visit will take place at Purdue University and the Annual Meeting will take place in conjunction with the Bath/ASME Symposium on Fluid Power & Motion Control in Sarasota Florida.

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).

The research project overviews will be updated in 2013 to reflect the new project portfolio. Feedback from the SAB indicated that the TRL rating for the projects were likely set over-optimistically. NSF is developing new definitions for TRL ratings more appropriate for ERC projects. These will be implemented as the overviews are updated.



Front

Back

Research Project Overviews

Project Center Database Website – In 2012, CCEFP implemented a new 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.

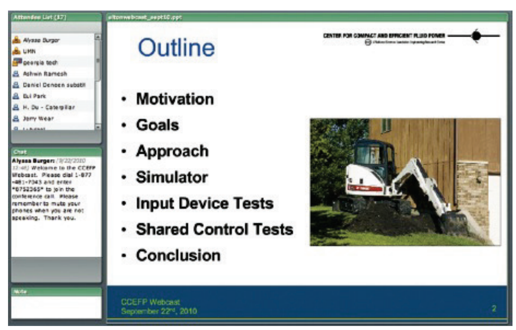
Resources for Effective Presentation Skills – CCEFP provides resources for students to improve their presentation skills. Using the Center's webcast capability, we have made available on our website a video tutorial presented by JoAnn Syverson, Senior Lecturer of the University of Minnesota's Carlson 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.

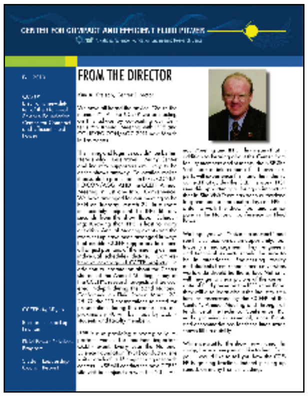
Website - The CCEFP website, www.ccefp.org, continues to be a source for information to the public as well as for our members. The website is a means to communicate information to the widest audience and content is updated regularly. A password-protected member's only section allows industry members, faculty and student access to private information not available to the general public and non-member industry companies.

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.

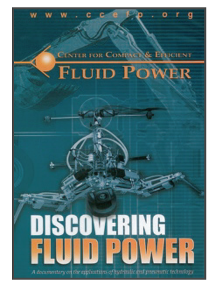




CCe-FP Electronic Newsletter
The CCEFP newsletter is published quarterly to allow for more in-depth content, specifically in the research areas. It is circulated electronically via our comprehensive e-mail lists and reaches subscribers in all stakeholder areas including academia, the trade press, industry, 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 include **Facebook**, **Twitter**, **YouTube** and **TeacherTube**. CCEFP will continue to reach out to various audiences using these and other free, ubiquitous online tools whenever appropriate.

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.

SUSTAINABILITY
Sustainability planning has been ongoing effort of the CCEFP for the last few years, with the intensity growing within the last year. Center sustainability was front and center at the 2012 CCEFP Annual Meeting. It was the main topic of discussion at the IAB and SAB meetings held during the event. The IAB leaders surveyed industry members in advance of the meeting and provided the results. In addition, the Center held its first (but certainly not last) 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 is very strong and many excellent suggestions and insights were gained.

A CCEFP Sustainability Task Force (STF) spanning CCEFP's major stakeholders was formed in 2012. The STF has four members from the Industrial Advisory Board (IAB), three members from the Scientific Advisory Board (SAB) and two Thrust Leaders. It is chaired by the SAB Chairman, Sohan Uppal, retired CTO of Eaton's Fluid Power Group.

The Sustainability Task Force has the following members:

- Dr. Andrew Alleyne, Thrust Leader, University of Illinois, Urbana-Champaign
- David Holt, IAB, Exxon-Mobil
- Dr. Monika Ivantysynova, Thrust Leader, Purdue
- Gary Kassen, IAB, Case New Holland
- Dr. Joseph Kovach, SAB, (retired from Parker-Hannifin)
- Eric Lanke, IAB, National Fluid Power Association
- Dr. Lonnie Love, SAB, Oak Ridge National Laboratory
- Joseph Pfaff, IAB, HUSCO International
- Sohan Uppal, SAB, (retired from Eaton), Chair

The STF held both teleconference and face-to-face meetings. Two sub-committees were formed, one to make recommendations on government funding and the other to make recommendations on pooling industry funding for precompetitive research. Several alternative governance structures for the post-NSF center were proposed and discussed at length.

The Sustainability Task Force recommendations were communicated to the CCEFP Director who assimilated the input and organized the writing of the final report presented here. The STF reviewed the report and suggested changes that were considered for the final version. The Sustainability Task Force will remain an active body to provide advice as the CCEFP makes the transition to the post NSF era.

The executive summary of the sustainability plan is given below. The complete plan can be found in Appendix V. The CCEFP Sustainability Plan was completed in February, 2013, using Year 6 data. The plan will be updated annually.

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 40 industry members, more than 21 of which are on the Industrial Advisory Board. In addition to the $4M in ERC funding from NSF, the Center's FY7 budget includes approximately $800K in matching funds from our core member universities and $577K in industry dues. Center researchers also received more than $2.4M in funding from government and industry sources for associated sponsored research projects in FY6. 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 has been and will continue to be to combine the research, education and transfer of intellectual capital to industry. This facilitates the commercialization of technologies, components and systems that provide benefits to the fluid power industry, its customers and society. Intellectual capital includes assets that a research university can provide to industry such as access to qualified students (graduate and undergraduate) both as university researchers and company employees, as well as access to researchers and research facilities and the potential for licensing and/or creating intellectual property.

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 possible inclusion of additional areas 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:

- 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 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 will be 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 that are 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 Year 7 (NSF-generated Table 8, Figure 8a, Tables 9, 10 and 11 appear at the end of this section.) The research budget shows the following distribution between thrusts and test beds: Efficiency Thrust (36%), Compactness Thrust (24%), Effectiveness Thrust (20%) and Test Beds (20%). The percentage distribution of the functional budget is shown in Figure 8a. The major expense is research, shown at 31% of the budget, with funding for education and outreach activities (including REU and RET) at 5.1%. Anticipated residual funds remaining (31%) are the result of delayed billing and payment of incurred expenses and not actual residuals. Table 11 shows a decrease in member company dues. Industry dues have decreased from $708K to $577K. While the decrease in member dues is undesirable, the dues received are well above the ERC average of $261K. The downward funding trend must be reversed if the CCEFP is to be sustainable.

The number of industry members has decreased from 48 to 40, a troubling development, but as described in Sections 1 and 4, the core strategic partners remain in place and efforts to improve engagement are planned. The year-to-year comparison is also somewhat misleading since we have used stricter criteria in deciding who is a continuing or new member. Four of the continuing members are expected to pay their current year dues, but are not listed since they have not yet done so. And four new members have not yet paid their current year dues, but are also expected to do so. These new members are Hitachi Construction Machinery, Idemitsu Kosan, JCB and Pall. In previous years, companies were counted as new members when the signed membership agreement was received even if the first year's dues were not yet paid. 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 8. Membership growth is expected to continue in future years. Associated project funding has continued to grow each year with an increase to $2,428,713 in year 7. As seen in Table 9, associated project funding has continued to grow.

Year 7: $2,428,713 (direct costs only)
Year 6: $2,311,570 (direct costs only)
Year 5: $1,885,000 (direct costs only)

Table 8b below shows the Year 7 budget distribution by university. The largest recipient of direct cash funding and associated project funding is the lead university with 47%. 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	$2,466,688	$499,945	$2,966,633	47%	21%
Georgia Tech	$677,003	$138,834	$815,836	13%	6%
Milwaukee School of Engineering	$196,809	$378,035	$574,844	4%	16%
North Carolina A & T	$205,997	$25,667	$231,664	4%	1%
Purdue University	$879,417	$1,344,565	$2,223,982	17%	55%
UIUC	$358,906	$0	$358,906	7%	0%
Vanderbilt University	$331,596	$41,667	$373,263	6%	2%
Science Museum of Minnesota	$90,000	$0	$90,000	2%	0%
Quality Evaluation Design (QED)	$50,000	$0	N/A	N/A	N/A
FolsomTechnologies International	$0	$0	N/A	N/A	N/A
Grand Total	$5,256,416	$2,428,712	$7,635,128		

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	$0	**$53,321**	$0	**$53,321**
University Education	$77,730	$0	**$77,730**	$0	**$77,730**
Student Leadership Council	$20,000	$0	**$20,000**	$0	**$20,000**
Young Scholars	$5,000	$0	**$5,000**	$0	**$5,000**
REU	$142,450	$0	**$142,450**	$0	**$142,450**
RET	$43,500	$0	**$43,500**	$0	**$43,500**
Assessment	$50,000	$0	**$50,000**	$0	**$50,000**
Community College activities	$9,800	$0	**$9,800**	$0	**$9,800**
Other	$0	$0	**$0**	$0	**$0**
Education Program Total	**$401,801**	**$0**	**$401,801**	**$0**	**$401,801**

Table 9a shows the funding history of the Center and includes funding amounts on the base grant for years 1-7, plus supplements since inception. In year 7, two diversity graduate students received supplemental funding to total $52,000.

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	7 years	$25,480,000	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	In progress	N/A

Table 9 (at the end of this section) shows the sources of support, and Table 9b (next page) includes the cost sharing by institution. In Year 6, all Core Partner universities contributed to meeting the 20% cost-sharing commitment, with the University of Minnesota and University of Illinois Champaign-Urbana, exceeding their annual commitment. CCEFP Core Partners provided $841,710 in cost-sharing cash toward the obligated $800,000.

Table 10 (at the end of this section) shows the annual expenditures and budgets, with Table 10a below showing unexpended residuals. Referring to the residual amounts in Table 10a, the carry-forward amount of $2,479,247 and $0 residuals, shows that all money was either committed or encumbered, at the start of year 7. The residual balance of $0, after committed/encumbered/obligated funds, demonstrates that all funds have been allocated and have been committed. However, in year 8, a stricter billing and payroll process will be implemented as 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 8.

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	$2,479,247	$4,235,091
Committed, Encumbered, Obligated funds	$2,479,247	$4,235,091
Residual Funds Without Specified Use	$0	$0

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

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	$77,249	$124,865	$201,233
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	$200,153	$152,557	$95,526
UIUC	$142,995	$210,852	$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	-	$339,537	-	$2,070,294	
Georgia Tech	$130,232	-	$130,232	-	$1,060,551	
MSOE	$0	-	$0	-	$10,800	
Purdue	$152,557	-	$152,557	-	$1,127,526	
UIUC	$92,093	-	$92,093	-	$899,740	
Vanderbilt	$85,581	-	$85,581	-	$692,630	

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	$898,982	$0	$898,982	$1,912,835	$2,811,817
2: Compactness	$578,869	$0	$578,869	$108,160	$687,029
3: Effectiveness	$481,926	$0	$481,926	$407,718	$889,644
Test beds	$498,217	$0	$498,217	$0	$498,217
Research Total	**$2,457,994**	**$0**	**$2,457,994**	**$2,428,713**	**$4,886,707**
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
Education Program Total	$401,801	$0	$401,801	$0	$401,801
Industrial Collaboration/Innovation Program	$320,000	$0	$320,000	$0	$320,000
Center Related Travel	$220,000	$0	$220,000	$0	$220,000
Residual Funds Remaining	$2,479,247	$0	$2,479,247	N/A	$2,479,247
Indirect Cost	$1,316,162	$0	$1,316,162	N/A	$1,316,162
Total	**$7,916,347**	**$0**	**$7,916,347**	**$2,428,713**	**$10,345,060**

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

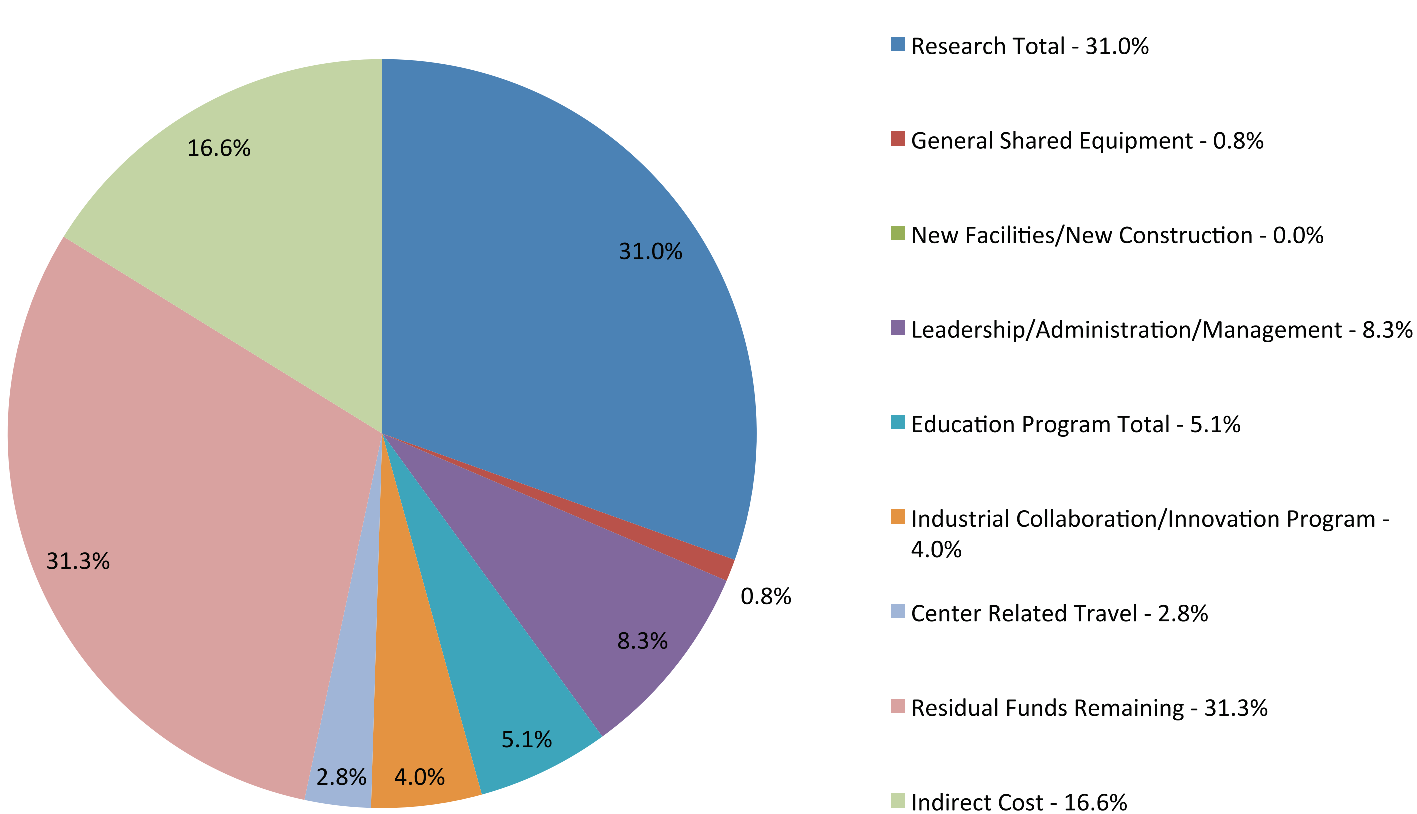


Table 9: Sources of Support

Sources of Support	Early Cumulative Total	Jun 1, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			Cumulative Total [1]
						Received	Promised	Total	
Unrestricted Cash									
Government									
NSF Funding									
NSF ERC Base Award	$5,196,020	$3,500,000	$3,750,000	$4,010,000	$4,000,000	$4,000,000	$0	$4,000,000	$24,456,020
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$5,196,020**	**$3,500,000**	**$3,750,000**	**$4,010,000**	**$4,000,000**	**$4,000,000**	**$0**	**$4,000,000**	**$24,456,020**
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$3,500	$0	$3,500	$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	**$5,196,020**	**$3,500,000**	**$3,750,000**	**$4,010,000**	**$4,000,000**	**$4,003,500**	**$0**	**$4,003,500**	**$24,459,520**
Industry									
U.S. Industry	$683,793	$591,500	$579,415	$517,250	$583,817	$428,100	$72,500	$500,600	$3,456,375
Foreign Industry	$120,000	$141,000	$108,000	$119,000	$112,000	$40,000	$0	$40,000	$640,000
Industrial Association	$0	$0	$0	$51,000	$41,000	$40,000	$1,000	$41,000	$133,000
TOTAL INDUSTRY FUNDING	**$803,793**	**$732,500**	**$687,415**	**$687,250**	**$736,817**	**$508,100**	**$73,500**	**$581,600**	**$4,229,375**
University									
U.S. University	$963,763	$831,646	$913,885	$800,000	$800,000	$800,000	$0	$800,000	$5,109,294
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$963,763**	**$831,646**	**$913,885**	**$800,000**	**$800,000**	**$800,000**	**$0**	**$800,000**	**$5,109,294**
Other									
Private Foundation	$0	$0	$0	$1,000	$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**	**$0**	**$1,000**	**$0**	**$0**	**$0**	**$0**	**$1,000**
Total Unrestricted Cash	**$6,963,576**	**$5,064,146**	**$5,351,300**	**$5,498,250**	**$5,536,817**	**$5,311,600**	**$73,500**	**$5,385,100**	**$33,799,189**
Restricted Cash									
NSF Funding									
NSF ERC Program Special Purpose Awards and Supplements	$65,801	$59,133	$44,814	$281,724	$39,989	$52,000	$0	$52,000	$543,461
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL NSF FUNDING	**$65,801**	**$59,133**	**$44,814**	**$281,724**	**$39,989**	**$52,000**	**$0**	**$52,000**	**$543,461**
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

Sources of Support	Early Cumulative Total	Jun 1, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			Cumulative Total [1]
						Received	Promised	Total	
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 Restricted Cash - Non Translational	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Restricted Cash - Translational									
Government									
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
State Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Local Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Quasi-government research organization	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL GOVERNMENT FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Industry									
U.S. Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
University									
U.S. University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0

Sources of Support	Early Cumulative Total	Jun 1, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			Cumulative Total [1]
						Received	Promised	Total	
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	**$65,801**	**$59,133**	**$44,814**	**$281,724**	**$39,989**	**$52,000**	**$0**	**$52,000**	**$543,461**
Residual Funds carried over from prior years [2]									
Government									
NSF Funding									
NSF ERC Base Award	$1,303,280	$696,322	$316,642	$316,643	$589,405	$1,896,501	N/A	$1,896,501	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	**$1,352,936**	**$696,322**	**$316,642**	**$316,643**	**$589,405**	**$1,896,501**	**N/A**	**$1,896,501**	**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	**$1,352,936**	**$696,322**	**$316,642**	**$316,643**	**$589,405**	**$1,896,501**	**N/A**	**$1,896,501**	**N/A**
Industry									
U.S. Industry	$1,186,869	$484,959	$297,485	$297,485	$464,648	$491,549	N/A	$491,549	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	**$1,186,869**	**$484,959**	**$297,485**	**$297,485**	**$464,648**	**$491,549**	**N/A**	**$491,549**	**N/A**
University									
U.S. University	$425,941	$281,567	$232,525	$232,757	$184,201	$91,197	N/A	$91,197	N/A
Foreign University	$0	$0	$0	$0	$0	$0	N/A	$0	N/A
TOTAL UNIVERSITY Residual Funds from Prior Years	**$425,941**	**$281,567**	**$232,525**	**$232,757**	**$184,201**	**$91,197**	**N/A**	**$91,197**	**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]	**$2,965,746**	**$1,462,848**	**$846,652**	**$846,885**	**$1,238,254**	**$2,479,247**	**N/A**	**$2,479,247**	**N/A**
Associated Projects [3]									
NSF Funding									
NSF ERC Program	$0	$0	$0	$640,109	$0	$0	$0	$0	$640,109
Other NSF (Not ERC Program)	$142,166	$99,326	$99,051	$640,749	$591,183	$508,500	$0	$508,500	$2,080,975
TOTAL NSF FUNDING	**$142,166**	**$99,326**	**$99,051**	**$1,280,858**	**$591,183**	**$508,500**	**$0**	**$508,500**	**$2,721,084**

Sources of Support	Early Cumulative Total	Jun 1, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			Cumulative Total [1]
						Received	Promised	Total	
Associated Projects - Non Translational [3]									
Government									
Other U.S. Government (Not NSF)	$803,318	$734,017	$527,447	$181,654	$13,320	$69,707	$0	$69,707	$2,329,463
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	$57,276	$0	$0	$0	$0	$57,276
TOTAL GOVERNMENT FUNDING	**$803,318**	**$734,017**	**$527,447**	**$238,930**	**$13,320**	**$69,707**	**$0**	**$69,707**	**$2,386,739**
Industry									
U.S. Industry	$1,077,864	$663,806	$1,098,877	$350,123	$0	$1,974	$0	$1,974	$3,192,644
Foreign Industry	$0	$0	$0	$52,865	$78,000	$70,417	$0	$70,417	$201,282
Industrial Association	$0	$0	$0	$71,067	$0	$0	$0	$0	$71,067
TOTAL INDUSTRY FUNDING	**$1,077,864**	**$663,806**	**$1,098,877**	**$474,055**	**$78,000**	**$72,391**	**$0**	**$72,391**	**$3,464,993**
University									
U.S. University	$0	$0	$0	$0	$128,550	$5,826	$0	$5,826	$134,376
Foreign University	$0	$0	$0	$32,000	$13,714	$3,077	$0	$3,077	$48,791
TOTAL UNIVERSITY FUNDING	**$0**	**$0**	**$0**	**$32,000**	**$142,264**	**$8,903**	**$0**	**$8,903**	**$183,167**
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	$25,000	$141,620	$0	$527,388	$1,099,920	$1,549,850	$0	$1,549,850	$3,343,778
TOTAL OTHER FUNDING	**$25,000**	**$141,620**	**$0**	**$527,388**	**$1,099,920**	**$1,549,850**	**$0**	**$1,549,850**	**$3,343,778**
Total Associated Projects - Non Translational	**$1,906,182**	**$1,539,443**	**$1,626,324**	**$1,272,373**	**$1,333,504**	**$1,700,851**	**$0**	**$1,700,851**	**$9,378,677**
Associated Projects - Translational [3]									
Government									
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$187,208	$60,667	$0	$60,667	$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**	**$0**	**$187,208**	**$60,667**	**$0**	**$60,667**	**$247,875**
Industry									
U.S. Industry	$0	$0	$0	$0	$115,701	$76,362	$0	$76,362	$192,063
Foreign Industry	$0	$0	$0	$5,000	$83,974	$37,583	$0	$37,583	$126,557
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$5,000**	**$199,675**	**$113,945**	**$0**	**$113,945**	**$318,620**
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**

Sources of Support	Early Cumulative Total	Jun 1, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			Cumulative Total [1]
						Received	Promised	Total	
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$44,750	$0	$44,750	$44,750
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$44,750**	**$0**	**$44,750**	**$44,750**
Total Associated Projects - Translational	**$0**	**$0**	**$0**	**$5,000**	**$386,883**	**$219,362**	**$0**	**$219,362**	**$611,245**
Total Associated Projects	**$2,048,348**	**$1,638,769**	**$1,725,375**	**$2,558,231**	**$2,311,570**	**$2,428,713**	**$0**	**$2,428,713**	**$12,711,006**
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, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			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	$234,000	$350,402	$0	$0	$39,253	$11,957	$0	$11,957	$635,612
Foreign Industry	$0	$0	$0	$0	$500	$2,300	$0	$2,300	$2,800
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$234,000**	**$350,402**	**$0**	**$0**	**$39,753**	**$14,257**	**$0**	**$14,257**	**$638,412**
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 Equipment	**$234,000**	**$350,402**	**$0**	**$0**	**$39,753**	**$14,257**	**$0**	**$14,257**	**$638,412**
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

Sources of Support	Early Cumulative Total	Jun 1, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			Cumulative Total [1]
						Received	Promised	Total	
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
University									
U.S. University	$250,591	$375,000	$0	$0	$0	$0	$0	$0	$625,591
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL UNIVERSITY FUNDING	**$250,591**	**$375,000**	**$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	**$250,591**	**$375,000**	**$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	$0	$22,500	$0	$0	$0	$0	$0	$0	$22,500
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**	**$22,500**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$22,500**
University									
U.S. University	$0	$16,200	$0	$0	$8,000	$0	$0	$0	$24,200
Foreign University	$49,500	$10,000	$0	$0	$0	$0	$0	$0	$59,500
TOTAL UNIVERSITY FUNDING	**$49,500**	**$26,200**	**$0**	**$0**	**$8,000**	**$0**	**$0**	**$0**	**$83,700**
Other									
Private Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0
Medical Facility	$0	$0	$0	$0	$0	$0	$0	$0	$0
Non Profit	$0	$0	$0	$0	$0	$0	$0	$0	$0
Venture Capitalist	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL OTHER FUNDING	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Total Value of Visting Personnel	**$49,500**	**$48,700**	**$0**	**$0**	**$8,000**	**$0**	**$0**	**$0**	**$106,200**

Sources of Support	Early Cumulative Total	Jun 1, 2008 - May 31, 2009	Jun 1, 2009 - May 31, 2010	Jun 1, 2010 - May 31, 2011	Jun 1, 2011 - May 31, 2012	Jun 1, 2012 - May 31, 2013			Cumulative Total [1]
						Received	Promised	Total	
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	$0	$219,621	$106,408	$0	$0	$0	$326,029
Foreign Industry	$0	$0	$0	$9,000	$62,308	$0	$0	$0	$71,308
Industrial Association	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL INDUSTRY FUNDING	**$0**	**$0**	**$0**	**$228,621**	**$168,716**	**$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	$0	$169,032	$0	$0	$0	$0	$0	$169,032
TOTAL OTHER FUNDING	**$0**	**$0**	**$169,032**	**$0**	**$0**	**$0**	**$0**	**$0**	**$169,032**
Total Value of Other Assets	**$0**	**$0**	**$169,032**	**$228,621**	**$168,716**	**$0**	**$0**	**$0**	**$566,369**
Total In-Kind Support, All Sources	**$534,091**	**$774,102**	**$169,032**	**$228,621**	**$216,469**	**$14,257**	**$0**	**$14,257**	**$1,936,572**
Total Cash Support, All Sources [2]	**$9,995,123**	**$6,586,127**	**$6,242,766**	**$6,626,859**	**$6,815,060**	**$7,842,847**	**$73,500**	**$7,916,347**	**$34,342,650**
Percent Non-ERC Program Cash	**34%**	**35%**	**34%**	**30%**	**32%**	**24%**	**100%**	**25%**	**27%**
Total Cash + In-Kind	**$10,529,214**	**$7,360,229**	**$6,411,798**	**$6,855,480**	**$7,031,529**	**$7,857,104**	**$73,500**	**$7,930,604**	**$36,279,222**
Grand Total (Cash + In-Kind + Associated Projects)	**$12,577,562**	**$8,998,998**	**$8,137,173**	**$9,413,711**	**$9,343,099**	**$10,285,817**	**$73,500**	**$10,359,317**	**$48,990,228**

[1] - No Residual amounts are included in the Cumulative Total column because the funds are by definition included in the year in which they were received.

[2] - Cash Total = The sum of Unrestricted Cash, Restricted Cash, and Residual Funds for a particular NSF Award Year, but NOT Support for Associated Projects. This cash amount in Table 9 is also the total for the 'Expenditure' column pertaining to the same Award Year in Table 10: Annual Expenditures and Budgets.

[3] - Associated project support is the sum of the received and promised amounts from the prior year. Actual amounts are not collected for associated project support.

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

Table 10: Annual Expenditures and Budgets

Total Direct Center Cash Support	Early Cumulative Total [1]	Jun-01-2008 - May 31-2009	Jun-01-2009 - May 31-2010	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Next Award Year
Direct Cash Support (All Sources)	**$7,029,377**	**$5,123,279**	**$5,396,114**	**$5,779,974**	**$5,576,806**	**$5,437,100**	**N/A**
Residual Funds from Prior Year (All Sources)	**$2,965,746**	**$1,462,848**	**$846,652**	**$846,885**	**$1,238,254**	**$2,479,247**	**N/A**
Total Direct Center Cash Support	**$9,995,123**	**$6,586,127**	**$6,242,766**	**$6,626,859**	**$6,815,060**	**$7,916,347**	**N/A**

Expenses Proposed and Residual Budget	Early Cumulative Total [1]	Jun-01-2008 - May 31-2009	Jun-01-2009 - May 31-2010	Jun-01-2010 - May 31-2011	Jun-01-2011 - May 31-2012	Jun-01-2012 - May 31-2013	Proposed Budget Next Award Year
Salaries & Benefits							
A. Senior Personnel: PI/PD, Co-PIs, Faculty and Other Senior Associates	$576,702	$477,455	$484,549	$505,207	$741,340	$759,854	$759,854
B. Other Personnel:	$2,807,340	$1,592,092	$1,919,364	$1,853,739	$1,133,600	$1,342,618	$1,342,618
Postdoctoral associates	$302,645	$115,001	$67,797	$19,180	$0	$79,098	$79,098
Other professionals (technician, programmer, etc.)	$266,141	$121,572	$232,601	$113,991	$112,105	$47,208	$47,208
Graduate Students	$1,196,644	$710,796	$892,055	$1,117,358	$799,764	$1,005,113	$1,005,113
Undergraduate students	$211,173	$125,435	$157,422	$59,537	$43,105	$55,510	$55,510
Secretarial - clerical	N/A	N/A	N/A	$188,104	$143,463	$30,000	$30,000
Other	$830,737	$519,288	$569,489	$355,569	$35,163	$125,689	$125,689
C. Fringe Benefits	$717,849	$541,702	$591,497	$587,333	$562,251	$608,511	$608,511
Total Salaries & Benefits (A+B+C)	**$4,101,891**	**$2,611,249**	**$2,995,410**	**$2,946,279**	**$2,437,191**	**$2,710,983**	**$2,710,983**
Other Expenses							
D. Equipment	$549,273	$187,609	$95,831	$147,311	$83,508	$64,349	$64,349
E. Travel	N/A	N/A	N/A	$253,621	$175,231	$302,434	$302,434
F. Participant Support	N/A	N/A	N/A	$161,046	$111,808	$370,407	$370,407
G. Other Direct Costs	$1,393,668	$752,196	$811,591	$629,139	$396,298	$823,691	$791,676
H. Direct Costs Total (A through G):	**$6,044,832**	**$3,551,054**	**$3,902,832**	**$4,137,396**	**$3,204,036**	**$4,271,864**	**$4,239,849**
I. Indirect Costs	**$1,811,905**	**$1,080,129**	**$1,262,004**	**$1,251,209**	**$993,916**	**$1,165,236**	**$1,165,236**
J. Direct and Indirect Costs Total (A through I):	**$7,856,737**	**$4,631,183**	**$5,164,836**	**$5,388,605**	**$4,197,952**	**$5,437,100**	**$5,405,085**
K. Residual Funds Remaining	**$2,965,746**	**$1,312,927**	**$0**	**$1,238,254**	**$262,725**	**$2,479,247**	**$0**
TOTAL Expenditures and Budgets (J+K)	**$10,822,483**	**$5,944,110**	**$5,164,836**	**$6,626,859**	**$4,460,677**	**$7,916,347**	**$5,405,085**
Current Year Support	**$9,995,123**	**$6,586,127**	**$6,242,766**	**$6,626,859**	**$6,815,060**	**$7,916,347**	**N/A**
Prior Award Year Residual Funds spent in Current Award Year							
ERC Program	$1,023,980	$279,300	$279,300	$316,643	$589,405	$2,479,247	$0
Other NSF	$0	$0	$0	$0	$0	$0	$0
Other Federal	$0	$0	$0	$0	$0	$0	$0
Industry	$587,207	$1,250,042	$1,250,042	$297,485	$464,648	$0	$0
Other	$297,496	$756,115	$0	$232,757	$184,201	$0	$0
Prior Award Year Residual Funds spent in Current Award Year	**$1,908,683**	**$2,285,457**	**$1,529,342**	**$846,885**	**$1,238,254**	**$2,479,247**	**$0**

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

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

Organization	Jun 1, 2011 - May 31, 2012						Jun 1, 2012 - May 31, 2013						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	$1,000	$0	$0	$0	$0	$0	$2,000	$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	$1,974	$59,615	$0	$0	$0	$0	$0	$800	$0
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	$17,231	$0	$40,000	$0	$0	$0	$0	$0	$0
Concentric AB/Haldex	$6,000	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0
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	$0	$0	$0
Eaton Corporation	$50,000	$0	$0	$0	$64,225	$14,232	$50,000	$0	$0	$0	$76,362	$0	$0
Enfield Technologies	$5,000	$0	$0	$0	$0	$1,000	$5,000	$0	$0	$0	$0	$0	$0
Evonik Industries	$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
G.W. Lisk Company	$15,000	$0	$0	$0	$0	$0	$0	$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
High Country Tek, Inc.	$1,000	$0	$0	$0	$0	$0	$0	$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
Linde Hydraulics Corp.	$5,000	$0	$0	$0	$0	$0	$5,000	$0	$0	$0	$0	$0	$0
Main Manufacturing Products, Inc.	$1,000	$0	$0	$0	$0	$0	$2,000	$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	$15,000	$0	$0	$0	$0	$0	$0
MTS Systems Corporation	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
National Fluid Power Association	$40,000	$0	$0	$0	$0	$0	$40,000	$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	$11,250	$0	$0	$0	$0	$0	$7,500	$0	$0	$0	$0	$0	$7,500
Nexen Group, Inc.	$1,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
Nitta Corporation	$1,000	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
Parker Hannifin Corporation	$50,000	$0	$0	$0	$0	$7,765	$0	$0	$0	$0	$0	$700	$50,000
PIAB Vacuum Products	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
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	$1,000	$0	$0	$0	$0	$0	$0
Racine Federated Inc. (formerly Hedland Flow Meters)	$1,000	$0	$0	$0	$1,974	$0	$0	$0	$0	$0	$0	$0	$0
Ross Controls	$5,000	$0	$0	$0	$0	$0	$5,000	$0	$0	$0	$0	$0	$0
Sauer-Danfoss	$50,000	$0	$0	$0	$1,974	$6,345	$50,000	$0	$0	$0	$0	$10,757	$0
Shell Global Solutions	$12,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
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	$1,000	$0	$0	$0	$0	$0	$0
Sun Hydraulics	$6,000	$0	$0	$0	$0	$500	$6,000	$0	$0	$0	$0	$0	$0
Takako Industries	$1,000	$0	$0	$0	$0	$2,693	$1,000	$0	$0	$0	$0	$0	$0
Tennant	$12,000	$0	$0	$0	$0	$0	$12,000	$0	$0	$0	$0	$0	$0
The Lubrizol Corporation	$5,000	$0	$0	$0	$7,917	$0	$5,000	$0	$0	$1,974	$0	$0	$0

Organization	Jun 1, 2011 - May 31, 2012						Jun 1, 2012 - May 31, 2013						
		Sponsored Projects		Associated Projects				Sponsored Projects		Associated Projects			
	Fees and Contributions	Non-translational	Translational	Non-translational	Translational	In-Kind Support	Fees and Contributions	Non-translational	Translational	Non-translational	Translational	In-Kind Support	Promised Support
Trelleborg Sealing Solutions	$15,000	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0
Walvoil Fluid Power	$6,000	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0
Woodward, Inc.	$62,567	$0	$0	$0	$0	$0	$16,600	$0	$0	$0	$0	$0	$0
Total Members	**$707,817**	**$0**	**$0**	**$0**	**$95,295**	**$92,150**	**$506,100**	**$0**	**$0**	**$1,974**	**$76,362**	**$12,257**	**$72,500**
Non-Member Organizations: Funders of Sponsored Projects, Funders of Associated Projects, and Contributing Organizations													
Bimba Manufacturing Company	$0	$0	$0	$0	$0	$2,319	$0	$0	$0	$0	$0	$0	$0
Casappa S.p.A.	$0	$0	$0	$0	$82,000	$0	$0	$0	$0	$55,417	$37,583	$0	$0
Confidential Organization (optional use for associated or sponsored projects only)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,549,850	$44,750	$0	$0
Daman Products Co., Inc.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
DARPA	$0	$0	$0	$0	$182,000	$0	$0	$0	$0	$0	$60,667	$0	$0
Deere and Company	$15,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Festo Corporation	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0	$1,500	$0
Fluid Power Educational Foundation	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Hydac Corporation	$0	$0	$0	$0	$0	$7,500	$0	$0	$0	$0	$0	$0	$0
International Fluid Power Society	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,000
MGI Coutier	$0	$0	$0	$58,000	$0	$0	$0	$0	$0	$0	$0	$0	$0
Mico, Inc.	$1,000	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$0	$0
National Defense Science and Engineering Fellowship Grant (NDSEG)	$0	$0	$0	$13,320	$0	$0	$0	$0	$0	$69,707	$0	$0	$0
National Institutes of Health (NIH)	$0	$0	$0	$0	$5,208	$0	$0	$0	$0	$0	$0	$0	$0
No Magic, Inc.	$0	$0	$0	$0	$0	$6,000	$0	$0	$0	$0	$0	$0	$0
NorthStar STEM Alliance	$0	$0	$0	$0	$0	$0	$3,500	$0	$0	$0	$0	$0	$0
Phoenix Integration	$0	$0	$0	$0	$0	$100,000	$0	$0	$0	$0	$0	$0	$0
Precision Associates	$0	$0	$0	$0	$0	$0	$500	$0	$0	$0	$0	$500	$0
The Martin Company	$0	$0	$0	$0	$12,692	$0	$0	$0	$0	$0	$0	$0	$0
The Toro Company	$12,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Tol-O-matic	$0	$0	$0	$0	$0	$0	$1,000	$0	$0	$0	$0	$0	$0
Total Oil Company	$0	$0	$0	$20,000	$0	$0	$0	$0	$0	$15,000	$0	$0	$0
United Technologies Research Center	$0	$0	$0	$0	$9,688	$0	$0	$0	$0	$0	$0	$0	$0
Total Non-Members	**$29,000**	**$0**	**$0**	**$91,320**	**$291,588**	**$116,319**	**$5,500**	**$0**	**$0**	**$1,689,974**	**$143,000**	**$2,000**	**$1,000**
Total	**$736,817**	**$0**	**$0**	**$91,320**	**$386,883**	**$208,469**	**$511,600**	**$0**	**$0**	**$1,691,948**	**$219,362**	**$14,257**	**$73,500**

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 ten faculty members: Randy Ewoldt (UIUC), Zongliang Jiang (NCAT), 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). CCEFP is well positioned to fulfill its commitment to hire a total of twelve faculty members by adding two new faculty members in the future. Although not yet public, it is planned to announce the hiring of a new senior faculty member at the Year 7 Site Visit.

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 Site Visit, the first sustainability workshop with the Deans was held. The second sustainability workshop will be held during the Year 7 Site Visit. 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.

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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APPENDIX I

Glossary of Acronyms and Special Terms

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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
CAREI …………	Center for Applied Research and Educational Improvement
CCEFP …………	Center of Compact and Efficient Fluid Power
CFD ……………	Computational Fluid Dynamics
CNT ……………	carbon nano-tubes
DC ……………...	direct current
DOHF ………….	Design Optimization and Hybrid Fabrication
E & O …………	Education and Outreach
EAB ……………	Education Advisory Board
EC ……………...	Executive Committee
EON ……………	Education and Outreach Network
ERC ……………	Engineering Research Center
ESEM ………….	Environmental Scanning Electron Microscope
FDLTCC ……….	Fon du Lac Tribal and Community College
FIRST ………….	For Inspiration and Recognition of Science and Technology
FLUENT ®……..	Commercial Computational Fluid Dynamics Code
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
HuMVIIS ……….	Human-Machine Virtualization Interaction & Integration Systems Laboratory
IAB …………….	Industrial Advisory Board
IFPE……………	International Fluid Power Expo
IC ………………	internal combustion
kW ……………..	kilowatt
LSAMP ………..	Louis Stokes Alliance for Minority Participation
ME ……………..	Mechanical Engineering
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
NSF …………….	National Science Foundation
OMG SysML …..	modeling language for OMG technology
PC ……………...	Project Champion
PFPD…………..	Portable Fluid Power Demonstration
PIV ……………..	particle image velocimetry
PLTW ………….	Project Lead The Way
PWM …………..	pulse width modulation
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
SAM …………...	strategic action mapping
SLC …………….	Student Leadership Council
SMM …………..	Science Museum of Minnesota
STF…………….	Sustainability Task Force
STEM ………….	Science Technology Engineering and Mathematics
SURE ………….	Summer Undergraduate Research in Engineering/Science
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
VaNTH…………	Multidisciplinary ERC consisting of Vanderbilt, Northwestern and Texas-Harvard/MIT
W ………………	watt

APPENDIX III

Table 7: Personnel

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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 All Institutions																	
Total [2]	307	193	68	46	49	0	15	131	15	2	14	43	38	8	4	0	5
Leadership/Administration																	
Directors	2	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	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	11	6	4	1	0	0	1	7	0	0	2	0	1	0	0	0	0
Subtotal	**20**	**12**	**7**	**1**	**0**	**0**	**1**	**14**	**1**	**1**	**2**	**0**	**1**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																	
Senior Faculty	21	18	3	0	2	0	1	13	3	1	1	0	0	1	0	0	0
Junior Faculty	10	8	1	1	0	0	0	4	1	0	1	3	1	0	0	0	0
Research Staff	6	6	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0
Industry Researchers	2	2	0	0	0	0	0	1	0	0	0	0	1	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	57	43	8	6	3	0	3	20	2	0	2	22	5	0	2	0	1
Total Master's Students	23	17	2	4	1	0	0	13	2	0	1	3	3	0	0	0	0
Total Undergraduate Students	109	52	28	29	40	0	3	29	4	1	4	8	20	4	0	0	1
Subtotal	**230**	**147**	**42**	**41**	**46**	**0**	**7**	**86**	**12**	**2**	**9**	**37**	**31**	**5**	**2**	**0**	**2**
Curriculum Development and Outreach																	
Senior Faculty	8	6	2	0	0	0	0	5	2	0	1	0	0	0	0	0	0
Junior Faculty	6	5	1	0	0	0	0	4	1	0	0	1	0	0	0	0	0
Research Staff	14	6	7	1	1	0	0	10	0	0	2	0	1	0	0	0	2
Industry Researchers	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Doctoral Students	15	11	4	0	1	0	1	8	1	0	1	3	0	0	2	0	1
Total Master's Students	3	2	1	0	0	0	0	1	0	0	0	2	0	0	0	0	0
Total Undergraduate Students	59	42	12	5	6	0	5	23	6	0	2	9	8	2	2	0	2
Subtotal	**106**	**73**	**27**	**6**	**8**	**0**	**6**	**51**	**10**	**0**	**6**	**15**	**10**	**2**	**4**	**0**	**5**
ERC REU Students																	
ERC's Own REU Students	26	19	7	0	0	0	6	10	3	0	1	6	0	2	2	0	0
Subtotal	**26**	**19**	**7**	**0**	**0**	**0**	**6**	**10**	**3**	**0**	**1**	**6**	**0**	**2**	**2**	**0**	**0**
Precollege (K-12)																	
Teachers (non-RET)	11	4	7	0	2	0	0	8	0	0	1	0	0	1	0	0	0
Teachers (RET)	6	4	2	0	0	0	1	3	0	0	1	0	1	0	0	0	0
Subtotal	**17**	**8**	**9**	**0**	**2**	**0**	**1**	**11**	**0**	**0**	**2**	**0**	**1**	**1**	**0**	**0**	**0**
University of Minnesota - Lead Institution																	
Total [2]	96	61	22	13	10	0	2	42	3	0	5	20	14	4	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	10	5	4	1	0	0	1	6	0	0	2	0	1	0	0	0	0
Subtotal	**16**	**9**	**6**	**1**	**0**	**0**	**1**	**11**	**1**	**0**	**2**	**0**	**1**	**0**	**0**	**0**	**0**
Research Under Strategic Research Plan																	
Senior Faculty	6	5	1	0	0	0	0	5	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	1	1	0	0	0	0	0	1	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 Postdocs	2	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0
Total Doctoral Students	18	15	1	2	1	0	0	3	1	0	0	12	1	0	0	0	0
Total Master's Students	9	7	0	2	0	0	0	5	0	0	1	2	1	0	0	0	0
Total Undergraduate Students	32	19	9	4	8	0	1	11	0	0	2	4	6	3	0	0	0
Subtotal	**72**	**51**	**12**	**9**	**9**	**0**	**1**	**28**	**3**	**0**	**3**	**19**	**9**	**3**	**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	5	1	1	0	0	4	0	0	1	0	1	0	0	0	1
Total Doctoral Students	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Total Master's Students	2	1	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Total Undergraduate Students	19	12	5	2	4	0	1	6	0	0	1	3	4	2	0	0	0

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	
Subtotal	**37**	**21**	**13**	**3**	**5**	**0**	**1**	**17**	**2**	**0**	**2**	**5**	**5**	**2**	**0**	**0**	**1**
ERC REU Students																	
ERC's Own REU Students	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Georgia Institute of Technology - Core Partner																	
Total [2]	35	23	3	9	0	0	0	20	1	0	1	4	9	0	0	0	0
Leadership/Administration																	
Thrust 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**
Research Under Strategic Research Plan																	
Senior Faculty	5	5	0	0	0	0	0	5	0	0	0	0	0	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	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Total Doctoral Students	11	8	2	1	0	0	0	8	0	0	1	1	1	0	0	0	0
Total Master's Students	3	1	1	1	0	0	0	2	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	11	5	0	6	0	0	0	3	0	0	0	2	6	0	0	0	0
Subtotal	**34**	**22**	**3**	**9**	**0**	**0**	**0**	**20**	**0**	**0**	**1**	**4**	**9**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Senior Faculty	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Total Doctoral Students	3	2	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Subtotal	**6**	**5**	**1**	**0**	**0**	**0**	**0**	**5**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																	
ERC's Own REU 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**
Purdue University - Core Partner																	
Total [2]	28	25	2	1	0	0	0	13	3	0	1	9	2	0	1	0	0
Leadership/Administration																	
Thrust Leaders	1	0	1	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**	**1**	**1**	**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	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Industry Researchers	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Doctoral Students	12	11	0	1	0	0	0	4	0	0	1	6	1	0	1	0	0
Total Master's Students	2	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	2	1	0	0	0	0	1	2	0	0	0	0	0	0	0	0
Subtotal	**21**	**18**	**2**	**1**	**0**	**0**	**0**	**8**	**3**	**0**	**1**	**7**	**2**	**0**	**1**	**0**	**0**
Curriculum Development and Outreach																	
Junior Faculty	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Industry Researchers	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Doctoral Students	3	3	0	0	0	0	0	1	0	0	1	1	0	0	1	0	0
Total Undergraduate Students	8	8	0	0	0	0	0	5	1	0	0	2	0	0	0	0	0
Subtotal	**14**	**14**	**0**	**0**	**0**	**0**	**0**	**7**	**1**	**0**	**1**	**4**	**1**	**0**	**1**	**0**	**0**
ERC REU Students																	
ERC's Own REU Students	7	7	0	0	0	0	0	4	1	0	0	2	0	0	0	0	0
Subtotal	**7**	**7**	**0**	**0**	**0**	**0**	**0**	**4**	**1**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
University of Illinois at Urbana-Champaign - Core Partner																	
Total [2]	21	16	3	2	0	0	0	8	4	1	2	2	4	0	0	0	2
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	3	2	1	0	0	0	0	1	1	1	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Total Doctoral Students	4	2	1	1	0	0	0	2	1	0	0	0	1	0	0	0	1
Total Master's Students	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Total Undergraduate Students	5	5	0	0	0	0	0	2	0	0	0	1	2	0	0	0	0

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	
Subtotal	**15**	**12**	**2**	**1**	**0**	**0**	**0**	**6**	**2**	**1**	**1**	**2**	**3**	**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
Total Doctoral Students	2	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1
Total Master's Students	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Total Undergraduate Students	10	8	1	1	0	0	0	4	2	0	1	0	3	0	0	0	1
Subtotal	**14**	**11**	**2**	**1**	**0**	**0**	**0**	**5**	**4**	**0**	**1**	**1**	**3**	**0**	**0**	**0**	**2**
ERC REU Students																	
ERC's Own REU Students	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Vanderbilt University - Core Partner																	
Total [2]	14	10	3	1	0	0	1	9	0	0	0	3	1	1	1	0	0
Research Under Strategic Research Plan																	
Senior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Total Doctoral Students	5	2	3	0	0	0	1	3	0	0	0	1	0	0	1	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	3	2	0	1	0	0	0	1	0	0	0	1	1	1	0	0	0
Subtotal	**11**	**7**	**3**	**1**	**0**	**0**	**1**	**7**	**0**	**0**	**0**	**2**	**1**	**1**	**1**	**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	1	3	0	0	0	1	2	0	0	0	1	0	0	1	0	0
Total Undergraduate Students	4	3	0	1	0	0	0	1	0	0	0	2	1	0	0	0	0
Subtotal	**9**	**5**	**3**	**1**	**0**	**0**	**1**	**4**	**0**	**0**	**0**	**3**	**1**	**0**	**1**	**0**	**0**
ERC REU Students																	
ERC's Own REU Students	3	3	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0
Subtotal	**3**	**3**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
Bemidji State University - Collaborating Institution																	
Total [2]	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Bradley University - Collaborating Institution																	
Total [2]	2	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	2	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Total Undergraduate Students	2	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Clarkson University - 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																	
Total Undergraduate Students	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]	4	4	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	4	4	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0
Subtotal	**4**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**2**	**0**	**0**	**0**	**0**
Illinois Institute of Technology - Collaborating Institution																	
Total [2]	2	2	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	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																	
Total Undergraduate Students	2	2	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

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	
Iowa State University - Collaborating Institution																	
Total [2]	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	2	2	0	0	0	0	0	2	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**
Curriculum Development and Outreach																	
Total Undergraduate Students	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**
Kansas State University - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Research Under Strategic Research Plan																	
Total Undergraduate Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
Curriculum Development and Outreach																	
Total Undergraduate Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
Leech Lake Tribal College - Collaborating Institution																	
Total [2]	4	1	0	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Senior Faculty	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**4**	**1**	**0**	**3**	**4**	**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**
Louisana State University - Collaborating Institution																	
Total [2]	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate 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**
Michigan Technological University - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	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**
Milwaukee School of Engineering - Collaborating Institution																	
Total [2]	13	11	2	0	0	0	2	9	2	0	0	0	0	1	0	0	0
Research Under Strategic Research Plan																	
Senior Faculty	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Research Staff	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
Total Master's Students	4	3	1	0	0	0	0	3	1	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	2	1	0	0	0	0	2	1	0	0	0	0	0	0	0	0
Subtotal	**11**	**9**	**2**	**0**	**0**	**0**	**1**	**8**	**2**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Research Staff	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	1	0	1	0	0	0	0	0	0	0	0
Subtotal	**3**	**3**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																	
ERC's Own REU Students	2	2	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**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**
North Carolina Agriculture and Technical State University - Collaborating Institution																	
Total [2]	16	10	4	2	2	0	5	0	1	0	1	5	2	0	2	0	0

Personnel Type	Total [1]	Gender: Male	Gender: Female	Gender: Gender Not Reported	Citizenship Status: Race—U.S. citizens and permanent residents only: AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	Race Not Reported	Citizenship Foreign/ Temp Visa	Citizenship Not Reported	Ethnicity: Hispanic: U.S. Citizen/ Perm Resident	Citizenship Foreign/ Temp Visa	Citizenship Not Reported	Disability
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	7	5	1	1	2	0	2	0	0	0	0	2	1	0	0	0	0
Total Master's Students	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Undergraduate Students	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**12**	**8**	**2**	**2**	**2**	**0**	**3**	**0**	**1**	**0**	**1**	**3**	**2**	**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	1	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	5	2	3	0	0	0	3	0	0	0	0	2	0	0	2	0	0
Subtotal	**7**	**4**	**3**	**0**	**1**	**0**	**3**	**0**	**0**	**0**	**1**	**2**	**0**	**0**	**2**	**0**	**0**
ERC REU Students																	
ERC's Own REU Students	4	2	2	0	0	0	2	0	0	0	0	2	0	0	2	0	0
Subtotal	**4**	**2**	**2**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**2**	**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**
St. Cloud State University - Collaborating Institution																	
Total [2]	3	0	2	1	3	0	0	0	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	3	0	2	1	3	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**3**	**0**	**2**	**1**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of Minnesota - Duluth - Collaborating Institution																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Curriculum Development and Outreach																	
Total Undergraduate Students	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**
University of Minnesota - Morris - Collaborating Institution																	
Total [2]	16	1	9	6	13	0	0	0	0	0	0	0	3	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	16	1	9	6	13	0	0	0	0	0	0	0	3	0	0	0	0
Subtotal	**16**	**1**	**9**	**6**	**13**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																	
Total Undergraduate Students	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of Missouri-Columbia - Collaborating Institution																	
Total [2]	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate 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**
Curriculum Development and Outreach																	
Total Undergraduate 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**
University of North Dakota - Collaborating Institution																	
Total [2]	2	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Master's Students	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Dartmouth College - Non-ERC Institution Providing REU Students																	
Total [2]	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
ERC REU Students																	
ERC's Own REU Students	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Johns Hopkins University - Non-ERC Institution Providing REU Students																	

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	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
ERC REU Students																	
ERC's Own REU 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**
Lehigh University - Non-ERC Institution Providing REU Students																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
ERC REU Students																	
ERC's Own REU Students	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**
Stony Brook University - Non-ERC Institution Providing REU Students																	
Total [2]	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
ERC REU Students																	
ERC's Own REU Students	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
University of Maryland, Baltimore - 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																	
ERC's Own REU 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**
Utah State University - Non-ERC Institution Providing REU Students																	
Total [2]	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
ERC REU Students																	
ERC's Own REU Students	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**
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																	
ERC's Own REU 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**
Lac Courte Oreilles Ojibwa Community College - Community College																	
Total [2]	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Total Undergraduate Students	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Salish Kootenai College - Community College																	
Total [2]	13	4	1	8	13	0	0	0	0	0	0	0	0	0	0	0	0
Research Under Strategic Research Plan																	
Senior Faculty	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	12	3	1	8	12	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**13**	**4**	**1**	**8**	**13**	**0**	**0**	**0**	**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**
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**
Guilford Middle School - Pre-college Partner																	
Total [2]	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (RET)	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**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

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	
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**
Ojibwe School - Pre-college Partner																	
Total [2]	2	1	1	0	2	0	0	0	0	0	0	0	0	1	0	0	0
Precollege (K-12)																	
Teachers (non-RET)	2	1	1	0	2	0	0	0	0	0	0	0	0	1	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Ragsdale High School - Pre-college Partner																	
Total [2]	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (RET)	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
South Ridge School (formerly Albrook School) - Pre-college Partner																	
Total [2]	5	2	3	0	0	0	0	5	0	0	0	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (non-RET)	5	2	3	0	0	0	0	5	0	0	0	0	0	0	0	0	0
Subtotal	**5**	**2**	**3**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
St. Paul Public Schools - Pre-college Partner																	
Total [2]	2	0	2	0	0	0	0	1	0	0	1	0	0	0	0	0	0
Precollege (K-12)																	
Teachers (non-RET)	2	0	2	0	0	0	0	1	0	0	1	0	0	0	0	0	0
Subtotal	**2**	**0**	**2**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
Westfield Washington High School - Pre-college Partner																	
Total [2]	2	2	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
Precollege (K-12)																	
Teachers (RET)	2	2	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
Subtotal	**2**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**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**

[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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APPENDIX IV

Center Diversity Strategic 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.

<u>The objectives</u> 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:

- Develop 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.
- Develop an award program following the NSF Graduate Research Diversity Supplement model: CCEFP Undergraduate Research Diversity Supplement (URDS) award for CCEFP faculty who recruit and retain underrepresented students in engineering. In addition, CCEFP Graduate Diversity Supplement (GRDS) award for faculty who recruit and retain underrepresented graduate students in engineering.
- Through 2012, the CCEFP leveraged funding and support from the NSF Graduate Research Diversity Supplement proposal. This supplement is now on hold while NSF intends on designing other funding opportunities to support graduate level students who are diverse.
- 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.
- Develop a dynamic Fluid Power Scholars Program to bring highly qualified underrepresented students from across the country to CCEFP industrial members for summer internships.
- 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, and four in 2012.

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 Undergraduate and Graduate Research Diversity (URDS and GRDS) 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 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.

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 six 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 odaangiina anaangoog (Shooting for the Stars) 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.

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.