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5th Annual Report

Volume 1

COOPERATIVE AGREEMENT #EEC 0540834 / DUE DATE: FEBRUARY 15, 2011

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

University of Minnesota

Georgia Institute of Technology

Milwaukee School of Engineering

North Carolina Agricultural & Technical State University

Purdue University

University of Illinois at Urbana-Champaign

Vanderbilt University

Dr. Kim Stelson, Director

Dr. Perry Li, Deputy Co-Director

Dr. Michael Goldfarb, Deputy Co-Director

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TITLE OF PROPOSED PROJECT Engineering Research Center for Compact and Efficient Fluid Power

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$ 4,000,000	12 months	6/1/2011	

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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), compact rescue robot (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 nineteen education and outreach projects, along with additional related initiatives, through three strategic approaches: partnering with effective and broadly distributed education and outreach networks, focusing on projects that can be replicated and/or adapted by others for audiences outside the Center's reach, and selecting its program menu in such a way that the accomplishments of a given project will bolster the progress and chances of success for another. Informed by the CCEFP's research, the Center's Education and Outreach programs enrich understandings of fluid power technology. But its projects share in a broader goal: to heighten interests in technology and engineering among an increasingly diverse student population.

The CCEFP's 51 corporate members 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 Co-Director	Michael Goldfarb	Mechanical Engineering	Vanderbilt University
Deputy Co-Director	Perry Li	Mechanical Engineering	University of Minnesota
Industrial Liaison Officer	Mike Gust	ERC Staff	University of Minnesota
Education Co-Director	William Durfee	Mechanical Engineering	University of Minnesota
Education Co-Director	Linda Western	ERC Staff	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 Director	Don Haney	ERC Staff	University of Minnesota
Thrust Area 1 Leader	Monika Ivantysynova	Agricult. / Biological Eng.	Purdue University
Thrust Area 2 Leader	Andrew Alleyne	Mechanical Engineering	University of Illinois at UC
Thrust Area 3 Leader	Wayne Book	Mechanical Engineering	Georgia Institute of Technology

THRUST 1: EFFICIENCY

Faculty Researcher	Tom Chase	Mechanical Engineering	University of Minnesota
Researcher	Edat Kaya	Agricult. / Biological Eng.	Purdue University
Faculty Researcher	David Kittleson	Mechanical Engineering	University of Minnesota
Faculty Researcher	Eric Loth	Aerospace Engineering	University of Illinois at UC
Faculty Researcher	John Lumkes	Agricult. / Biological Eng.	Purdue University
Faculty Researcher	Ashlie Martini	Mechanical Engineering	Purdue University
Faculty Researcher	Paul Michael	Fluid Power Institute	Milwaukee School of Engineering
Faculty Researcher	Zongxuan Sun	Mechanical Engineering	University of Minnesota
Faculty Researcher	Thomas Wanke	Fluid Power Institute	Milwaukee School of Engineering

THRUST 2: COMPACTNESS

Faculty Researcher	Eric Barth	Mechanical Engineering	Vanderbilt University
Researcher	Doug Cook	Applied Technology Center	Milwaukee School of Engineering
Faculty Researcher	Jane Davidson	Mechanical Engineering	University of Minnesota
Faculty Researcher	Vito Gervasi	Applied Technology Center	Milwaukee School of Engineering
Faculty Researcher	Michael Goldfarb	Mechanical Engineering	Vanderbilt University
Faculty Researcher	Chris Paredis	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Terry Simon	Mechanical Engineering	University of Minnesota
Faculty Researcher	Robert Webster	Mechanical Engineering	Vanderbilt University

THRUST 3: EFFECTIVENESS

Faculty Researcher	Scott Bair	Mechanical Engineering	Georgia Institute of Technology

Faculty Researcher	Ken Cunefare	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Steven Frankel	Mechanical Engineering	Purdue University
Researcher	J.D. Huggins	Mechanical Engineering	Georgia Institute of Technology
Faculty Researcher	Xiaochun Jiang	Industrial and Systems Eng.	North Carolina A & T
Faculty Researcher	Zongliang Jiang	Industrial and Systems Eng.	North Carolina A & T
Faculty Researcher	Barney Klamecki	Mechanical Engineering	University of Minnesota
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, Test Bed 3	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
Eric Barth	EON Faculty Representative	Mechanical Engineering	Vanderbilt University
Alyssa Burger	Education Outreach Director	ERC Staff	University of Minnesota
Will Durfee	Education Co-Director	Mechanical Engineering	University of Minnesota
Mike Gust	Industrial Liaison Officer	ERC Staff	University of Minnesota
Elizabeth Hsiao-Wecksler	EON Faculty Representative	Mechanical Sci. and Eng.	University of Ilinois at UC
Zongliang Jiang	EON Faculty Representative	Industrial and Systems Eng.	North Carolina A & T
Medhat K. Bahr Khalil	Dir. Prof. Ed. & Rsch. Dev.	Mechanical Engineering	Milwaukee School of Engineering
John Lumkes	Chair, Ed. Outreach Network	Agricult./Biological Eng.	Purdue University
J. Newlin	EON Representative	Physical Sciences & Tech.	Science Museum of Minnesota
Chris Paredis	EON Faculty Representative	Mechanical Engineering	Georgia Institute of Technology
Holly Pellerin	gidaa Program Director	ERC Staff	University of Minnesota
Kim Stelson	Center Director	Mechanical Engineering	University of Minnesota
Andrea Vacca	EON Faculty Representative	Agricult. / Biological Eng.	Purdue University
Linda Western	Education Co-Director	ERC Staff	University of Minnesota

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Dr. Lonnie J. Love	Sr. Research Scientist, Robotics and Energetic Systems	Oak Ridge National Laboratory
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Prof. Jan-Ove Palmberg	Professor, Division of Fluid Power Technology	Linköping University

Prof. Masayoshi Tomizuka	Professor, Dept. of Mech. Engineering	University of California-Berkeley
Prof. Lu Yong Xiang	President	Chinese Academy of Sciences

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R. Edwin Howe	President	Enfield Technologies
Steven Herzog	Global Product Manager	Evonik RohMax USA, Inc.
David GL Holt	Sr. Research Scientist	Exxon Mobil
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G. Scott Lane	Engineering Manager	Linde Hydraulics Corp.
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Richard Baker	Vice President of Engineering	MTS Systems Corp.
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Alain LePrince	Director of Business Development	Poclain Hydraulics
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Eric Cummings	Engineering Manager	Ross Controls
Jeff Herrin	Director of Advanced Programs	Sauer-Danfoss
Allen Carlson	President & CEO	Sun Hydraulics Corp
Larry Castleman	Technical Director of Product Development	Trelleborg Sealing Solutions
P. S. Reddy	Marketing Manager	Veljan Hydrair Private Ltd.

Panel of Education Advisors

Name	Title	Organization
Dr. Stacy Klein-Gardner	Assoc. Professor, Practice of Teaching and Learning; Assoc. Professor, Practice of Biomedical Engineering; Assoc. Professor, Radiology and Radiological Sciences	Vanderbilt University
Mark Gonyea	Teacher of Computer Science	Smyma (TN) High School
Michael McElligot	Director of International Sales	Bimba Manufacturing Co.
Dr. Karl Smith	Professor, Cooperative Learning, Engineering Education	Purdue University

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Volume I Table of Contents — Page

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.

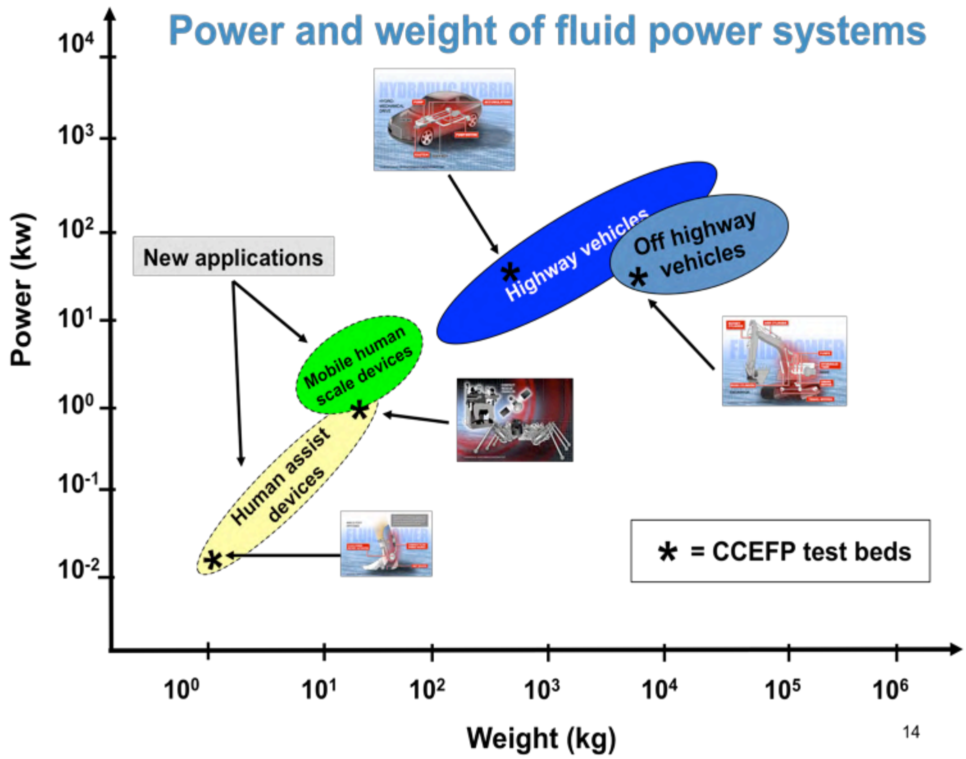
As it completes its fifth year, the CCEFP is already transforming fluid power. The Center has become the catalyst in energizing the Nation's fluid power industry and research community. For the first time in decades, the fluid power industry in the U.S. is undertaking university-industry collaborations 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. CCEFP, the National Fluid Power Association (NFPA) and the Department of Energy (DOE) are conducting a survey to determine the impact of fluid power on our Nation's energy use. This will lead to a national fluid power energy research and development plan that involves partnering among industry, universities and national labs. And, as a direct consequence of a past CCEFP site visit, the fluid power industry has developed a research-technology roadmap, an invaluable reference for guiding future research.

1.1 SYSTEMS VISION

The CCEFP systems vision has been continuously modified and refined over the last five years of operation. 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. Therefore, CCEFP has chosen mobile 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. Four families can be identified, as listed below. The four test beds are representative members of these four families.

1. Mobile Heavy Equipment (50 kW-500 kW): Excavator (Test Bed 1)
2. Highway Vehicles (10 kW-100 kW): Hydraulic Hybrid Passenger Vehicle (Test Bed 3)
3. Mobile Human Scale Equipment (100W-1kW): Compact Rescue Robot (Test Bed 4)
4. Human Assist Devices (10W-100W): Orthosis (Test Bed 6)



CCEFP Testbeds

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

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

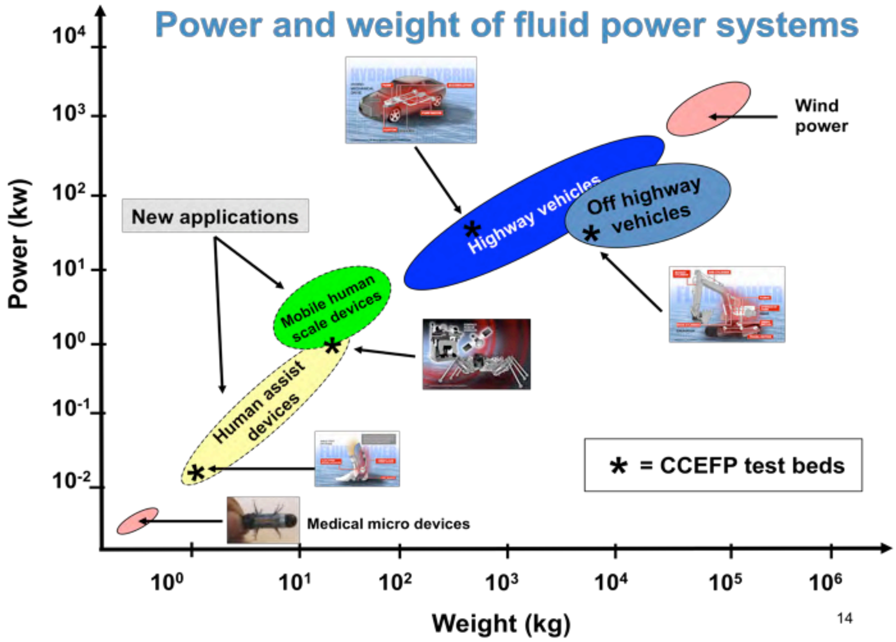
1. Doubling fluid power efficiency in current applications and in new transportation applications.

2. Increasing fluid power energy storage density by an order of magnitude.

3. Developing new miniature fluid power components and systems including power supplies that are one - two orders of magnitude smaller (10 W-1 kW) than anything currently available.

Doubling the efficiency in current off-road applications and future on-road applications would lead to a large reduction in energy consumption. 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 mobile human scale devices and mobile human assist devices.

Associated Test Beds
There are fluid power application opportunities at power and weight levels that are both higher and lower than the four CCEFP test beds. These include wind power at larger scales (500 kW-5 MW) and *in vivo* biomedical devices (100 mW-1 W) at smaller scales. These new opportunities are depicted in the figure below.



CCEFP Associated Testbeds

Current budget limitations prevent the CCEFP from funding added test beds. Therefore, we are seeking other sources of funding to support test beds in higher and lower power and weight ranges. A new $8 million DOE industry-university cooperative wind power research center has been awarded to the University of Minnesota, and hydrostatic transmission of wind power is being investigated as part of this center. Seed funding for this test bed is being provided by the Initiative for Renewable Energy and the Environment (IREE), an internal organization at the University of Minnesota. Further funding is anticipated from a larger IREE grant, industry contributions and the DOE. Hydrostatic power transmission promises to be more reliable and extract more power than existing mechanical gearboxes. The MRI surgery research initiative has been supported by internal funds and infrastructure at Vanderbilt University, with external funds to be sought after preliminary results are available. Unlike electro-mechanical actuation, pneumatics do not interact with the magnetic fields of the MRI, providing the possibility of precision surgical procedures aided by MRI sensing.

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. In the past year, the NFPA has conducted an authoritative energy study funded by DOE that confirmed the importance fluid power in saving energy (see highlights section for more details). Our previous estimate that 4% of the Nation's energy is transmitted through fluid power was confirmed, since the authoritative survey found that the actual figure is between 4.4% and 5.1%. Fluid power system efficiencies range from less than 6% 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 $17B/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 more than $37B/year in energy. Just as important, an aggressive program in energy efficient fluid power can invigorate this industry that is the backbone of U.S. manufacturing and increase U.S. competitiveness in the growing world market. Using fluid power more widely in transportation through the development of hydraulic hybrid vehicles will save an additional $50 billion. More than dollars 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 enable human-scale, untethered systems such as the compact rescue robot and the orthosis.

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, higher forces or torques, and continuously varying transmission. Fluid power also is superior in producing or absorbing high power transients, has a higher control bandwidth for the same power, can hold loads without expending energy, and has flexible routing. 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 factory automation, and large marine and aerospace applications. The manufacturing applications are out of scope because they are stationary. 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. An exception is wind power, a stationary application in early stages of development, where fluid power has the potential to be transformational.

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 twelve, three are transformational.

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

Table 1c: Fluid Power Technical Barriers and Transformational Fluid Power Systems

SWOT Analysis

The weaknesses and threats from last year's site visit report are listed below along with the CCEFP actions taken in response.

SVT: It is unfortunate that the report of the “task force” on systems analysis is not yet available.

CCEFP: In response to the Year 3 NSF Site Visit Team report, two task forces were formed, the Systems Engineering Task Force and the Human Performance and Human-Machine Interface Task Force. The final reports of the task forces are available in Appendix IV of Volume I of this report.

SVT: An effective process for integrating the research projects in the efficiency, compactness and effectiveness thrusts to achieve the energy savings predicted is needed.

CCEFP: An effective process for demonstrating the predicted energy savings is in place. The deliverables and milestone charts for the plan are listed in the Strategic Research Plan section of this report. The approach is to migrate fundamental research results into enabling technologies for ultimate demonstration on test beds as exemplified by the three-plane diagram. Thrusts are disciplinary in orientation, but the test beds are where the results of overall integration are demonstrated. Considerable progress in fuel savings has already been shown based on modeling and experiments on the excavator and hydraulic hybrid vehicle, and progress is expected to accelerate in the next few years. Further experiments are expected to conclusively demonstrate the energy savings potential for both off-road and on-road use of fluid power. The energy efficiency of smaller systems such as the robot or orthosis will have negligible influence on the Nation’s overall energy use. Nevertheless, the efficiency of these small portable systems is important since it is a major factor in determining system performance.

SVT: Communication and interaction within the CCEFP needs improvement

Because the CCEFP is an extensive network of universities, non-profits and companies, communication, both internal and external, continues to be a challenge. Significant improvements have been made in the last year. Communication has continued to improve through our existing channels that are described in the Communication section of the Management Effort section of the report. Improvements in internal communication have been informed by online surveys, and the timeliness and accuracy of information has improved by communicating directly to students rather than relying on faculty. A center-wide calendar will be introduced soon in response to student requests for a centralized source of information. A completely updated set of project information sheets will be unveiled at IFPE. Based on industry requests these have been structured to convey essential information concisely. The technology readiness level (TRL) system of the Department of Defense (DOD) has been adopted for CCEFP use to effectively communicate the commercialization potential of projects. As part of major center reorganization, a new position, External Relations Coordinator, has been created. The additional position will facilitate communication with our key stakeholders and to free up others to concentrate on internal communication.

SVT: Severe imbalances in underrepresented minority students among the partner institutions, particularly with regard to Hispanic and African American students.

CCEFP: The SVT observation is correct; there are differences in underrepresented group participation among the CCEFP universities. Here is the data:

CCEFP Cumulative Institution Demographic Data:
UMN: 23% women, 20% racial minority, 1% Hispanic
GT: 14% women, 0% racial minority, 3% Hispanic
PU: 9% women, 3% racial minority, 3% Hispanic
UIUC: 11% women, 5% racial minority, 0% Hispanic
VU: 17% women, 8% racial minority, 8% Hispanic
MSOE: 19% women, 5% racial minority, 10% Hispanic
NCAT: 23% women, 54% racial minority, 0% Hispanic

In aggregate, these data compare favorably with national statistics. In 2008, Hispanics received 6.5% and African Americans received 4.7% of all bachelor’s degrees in engineering. Women received 18.0% of all bachelor’s degrees in engineering, but only 11.4% of bachelor’s degrees in mechanical engineering. The overall makeup of the student bodies of individual institutions is little affected by CCEFP presence, however. Thus, increased participation can only be realized by internal recruitment. This we pursue vigorously, and will continue to do so.

On the broader question of increasing overall participation of underrepresented groups, the key to future progress is not recruitment within the finite pool of currently available candidates, but in increasing the available pool. This we are affecting through our outreach programs as described in detail in the Diversity Effort and Impact section of the report.

SVT: Poor representation of underrepresented minorities in the faculty participants

We agree with the SVT observation and are doing what we can to improve faculty participation of underrepresented groups in CCEFP. There are two ways to do this, hiring and internal recruitment. The CCEFP universities have pledged to add twelve professors to their ranks over its lifetime. Of the six hired so far, one is a female. Hiring of additional faculty has slowed due to funding decreases, but all universities remain committed to the goal of hiring six additional professors. CCEFP influence over faculty selection is constrained since departments, not centers, hire faculty, and many factors must be considered in these decisions. Nevertheless, we will strive to increase diversity in these hiring decisions. Internal recruitment will continue at each project renewal cycle, with the call for proposals being broadly circulated within each CCEFP university.

SVT: Even timely, tangible results that lag industry expectations may threaten continued industry involvement and support. Failure to analyze the risks associated with competitive threats to fluid power.

CCEFP: Managing industry expectations is an important element in determining CCEFP success, but this process is complex. A number of CCEFP industry supporters are strong advocates for center research that is pre-competitive. At the same time, industry is hungry for results that can be commercialized. Further, universities can only go so far before partnering or handing off a new idea to industry. And in doing so, a learning process on both sides is required since many of the center's industry supporters have not worked extensively with universities before.. To aid understanding we have developed a technology readiness level (TRL) designation based on an existing system in the DOD. The technology readiness level is described in detail in the Industrial Collaboration and Technology Transfer section of Volume I. CCEFP policy is to only work on ideas up to TRL 4, and to transfer ideas to industry for further refinement and development at this point. The idea is to nurture projects to the point where their potential is clear enough for industry to make a well-informed decision on whether to pursue them. .

All test beds have undergone comparative analysis with competing technologies, mainly approaches based on batteries and motors. These are summarized below:

Test Bed 1: Excavator

Competing approaches include independent metering valves, electro-hydraulic actuators (EHA), a Swedish approach using an open circuit variable displacement pump combined with four two-way valves, and electric hybridization. Simulation and cost analysis were used to compare these alternatives to displacement control (DC). Independent metering valves would only save a third of the energy saved by DC actuators for a similar excavator. EHA requires more costly components and has slower actuator dynamics than DC. The Swedish open center DC approach will give similar savings, but is more complicated and expensive. Electric hybridization is less compact and more costly than DC. A prototype electric hybrid machine nearly the same size as Test Bed 1 was built by Kobelco and measured fuel savings were about 40%, which is the same as what was measured on Test Bed1 using DC actuators.

Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Competing approaches to the hydraulic hybrid passenger car are electric hybrids, plug-in hybrids and pure electric vehicles. We have done extensive modeling and simulation comparing electric and hydraulic hybrid passenger vehicles using open source simulation package, ADVISOR. With current off-the-shelf components, hydraulic hybrid fuel economy is comparable to that of electric hybrids. With improved hydraulic efficiencies of pumps and motors, the hydraulic hybrid passenger vehicle could well surpass the electric hybrid. Because of the superior power density of hydraulics, a hydraulic hybrid passenger vehicle could weigh less and have higher acceleration than an electric hybrid vehicle. A comparison of conventional and plug-in hybrids fleets owned by Google shows no energy-savings advantage to plug-in hybrids if the conversion from hydrocarbon fuel to electricity is included in the analysis. The same can be said of pure electric vehicles. The EPA mileage for a Nissan Leaf, a pure electric vehicle, is 99 miles per gallon. Impressive as this figure is, it is misleading since it assumes that hydrocarbon fuel can be converted to electricity with 100% efficiency. If a more reasonable efficiency, say 30%, is assumed, the Nissan Leaf mileage drops to 30 miles per gallon, less than the Toyota Prius or a future hydraulic hybrid passenger vehicle. The main advantage of electric vehicles is not fuel efficiency; it is energy flexibility since electricity can be generated from many sources.

Hydraulic hybrid vehicles are just coming into production for heavy trucks and busses with hydraulic hybrid systems for refuse trucks being supplied by three major hydraulics companies, Bosch-Rexroth, Eaton and Parker-Hannifin. All three companies are CCEFP members. As this technology matures, it is expected to migrate to vehicles of smaller size. For example, Chrysler has just announced its intention of developing a hydraulic hybrid minivan in cooperation with the Environmental Protection Agency (EPA).

Test Bed 4: Compact Rescue Robot

Current rescue robots do not have sufficient force and power to rescue; they are used for surveillance. Thus there is no currently existing product to compare to. A comparison of potential power sources for the rescue robot has been made. Included in the comparison were electric drives, internal combustion engine powered hydraulics and the two new power sources being developed by CCEFP, the hot-gas vane motor and the free-piston compressor. Comparisons were based on weight, a crucial metric in these systems. It was concluded that the hot-gas vane motor and the free-piston engine compressor would both be lighter than competing electric or internal combustion engine approaches. For a three hour run time, the free piston compressor weighed 50% less than an electrically driven, battery powered unit. For a ten hour run time, the free piston compressor weighed 70% less than an electrically driven, battery powered unit.

Test Bed 6: Orthosis

The orthosis design has proceeded with a structured systematic approach. Electric and fluid power approaches were compared. It was concluded that a pressure exceeding 250 psi (17 bar) would be needed for a fluid power solution to weigh less than an electric drive. This conclusion has caused the test bed to migrate from pneumatic to hydraulic approaches for future designs that will produce higher torque or force output. The best near term approach is a battery-driven pump powering miniature hydraulics. Because of the superior energy density of fuel, a free-piston engine compressor has the potential of being lighter, but requires solving the issues of noise, emissions and heat dissipation.

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 purpose of these test beds are as follows:

- The excavator (TB1) demonstrates efficiency improvements in existing fluid power applications.
- The hydraulic hybrid passenger vehicle (TB3) demonstrates a cost-effective competitive alternative to electric hybrids.
- The rescue robot (TB4) demonstrates a small tele-operated devise capable of performing useful work over an extended duration.
- The orthosis (TB6) demonstrates the practical limits of miniature fluid power systems.

A displacement controlled actuator has been implemented on the excavator test bed. The results indicate that a 40% energy savings is possible compared to the existing design. For multiple actuators, the displacement controlled design allows energy recovery by having one axis feed another directly through the engine shaft. Experiments have revealed new control challenges with displacement control. Approaches to overcome the control problems have been developed. In the future even greater energy savings will be demonstrated by using more efficient fluids, more efficient pumps and motors, better control, better engine management and improved human-machine interface. These are all being pursued in CCEFP projects.

The first generation hydraulic hybrid passenger vehicle (HHPV) has been constructed and tested. Despite the vehicle's deficiencies, these early efforts were extremely valuable learning exercises. The parallel, series and power-split architectures were studied. The power-split architecture was shown to have the best fuel economy. For all architectures fuel economy is very dependent on hydraulic system efficiency. The importance of more efficient pumps, motors and fluids is understood. A three-level control strategy was developed. The top level controls engine on/off function, the middle level causes the engine to operate near its optimal efficiency, and the low level causes tracking of the control commands. It has been shown that operating the engine near its most efficient speed and torque is crucial to realizing efficient operation. Noise is recognized as a future challenge.

Based on the lessons learned from the first generation HHPV, a second generation test bed is being designed and constructed. Because it was a new design, the first generation HHPV was plagued by development and reliability issues. It is being redesigned to overcome these shortcomings and will continue to be used in research. In addition, the second generation vehicle, a Ford F-150 pickup truck, is a proven reliable design. The vehicle will be modified to use a Folsom power-split transmission. CCEFP will hybridize the vehicle, develop and implement controls, and test the vehicle. The second generation vehicle will benefit considerably from the expertise of the industry partners, Ford and Folsom.

Unlike the excavator and the vehicle, no true rescue robot exists. A high-level system study has been conducted to clearly understand the rescue task system requirements and develop a set of specifications to meet these requirements. These requirements overcome barriers in energetic, control and operator interface. The CCEFP has demonstrated two candidate power supplies, a chemofluid powered hydraulic system and a free-piston engine pneumatic system. Gait control has been demonstrated using three approaches: limb-by-limb control, autonomous control and follow-the-leader control. Remote operation of multiple degrees-of-freedom has been demonstrated using a haptic and visual interface.

Like the rescue robot, the orthosis is a novel device and system level requirements based on subject experiments needed to be defined. An untethered pneumatic solution was demonstrated on human subjects. It provided gait assistance but did not meet the weight and duration requirements. A systems analysis has shown that for a fluid power solution to be lighter than a competing electromechanical solution, 250 psi (17 bar) hydraulics are required. The next generation design is underway.

Considerable progress has been made on all test beds in the last year. The excavator has undergone field tests at Caterpillar and the orthosis has been tested on subjects. These results are described as research highlights in the report. Extensive progress has been made on both the Gen-1 and Gen-2 hydraulic hybrid vehicles. The Gen-1 vehicle (Polaris Ranger) has been completely resigned. The new version will be available for field tests within six months. The Gen-2 vehicle (Ford F-150) pickup truck has experienced setbacks from a transmission failure in testing. The transmission has been rebuilt at Ford and is being reassembled at Folsom with delivery to the University of Minnesota expected within six months. The robot test bed is also poised to make rapid progress in the next year with the integration of pneumatic power source in the next version.

Education Outcomes

The CCEFP continues to provide a culture that prepares students to be effective in industry and academia. Undergraduate and graduate students working on research projects learn to approach their problem from a top-down systems level and from a bottom up detail level. Students connect with industry through the project champions program, the webcast series led by the center's Student Leadership Council, the annual meeting and one-on-one interaction. Students become familiar with industry practice through summer internships including the Fluid Power Scholars Program, launched in 2010 with eight participants and seven company sponsors, and by learning about professional topics, such as the importance of intellectual property, in the center's webcast series. The center has hosted 87 REUs over the years including twenty-three during summer 2010. Scheduling the center's 5th Annual Meeting and Site Visit at IFPE 2011 provides CCEFP students with unparalleled opportunities to see the fluid power marketplace first-hand. In turn, the industry audience for learning about the Center's work--through the CCEFP poster session, in presentations at the NCFP Technical Conference, and in discussions prompted by visitors to the CCEFP IFPE booth—is far greater than any number possible without this co-location.

The center is having a growing impact on the undergraduate and graduate education at its seven universities. More and more courses taught by center faculty are incorporating fluid power into the curriculum, including fundamentals as well as the results of CCEFP research, and there are new courses at the graduate level. New efforts to more actively engage industry in fluid power capstone projects began this year. The CCEFP is now playing the role of matchmaker between industry and engineering programs. Every NFPA board members has agreed to sponsor a capstone project. In doing so, these industry leaders are setting examples for all association members, hence we expect the numbers of such projects to increase.

The pre-college outreach program maximizes its impact by leveraging existing networks. Project Lead The Way (PLTW) has incorporated fluid power topics into several of its pre-engineering courses, PLTW teachers have participated in the CCEFP RET program and CCEFP is beginning to develop fluid power training materials for the PLTW summer teacher training workshops. Hands-on fluid power workshops have been developed, including a portable hydraulic excavator demonstrator and a pneumatics training kit. Many hands-on workshops have been conducted for audiences ranging from middle school students to FIRST Robotics teams to RET teachers. The workshops continue to be refined and will be disseminated throughout the center. The general public is learning about fluid power through a new set of interactive floor exhibits developed and built by the Science Museum of Minnesota, which is developing plans for disseminating the exhibits to other venues.

Industrial Collaboration and Tech Transfer Interactions

The industry participation in the CCEFP remains strong and continues to grow. Important equipment donations support our test beds. Bobcat has donated a second excavator to Georgia Tech for HMI studies. Ford has donated an F-150 pickup truck as the next generation HHPV and Folsom has provided the power-split transmission for the test bed. Task forces have significant industry participation with Sauer Danfoss joining the Systems Engineering Task Force, John Deere joining the Human Machine Interface and Performance Task Force and Deltrol, Enfield, Parker-Hannifin and NFPA joining the Sustainability Task Force.

Industry was very active in selecting research projects for years five and six. More than 30 experts from industry reviewed proposals. The IAB representatives on the Executive Committee were active participants in the final selection.

The National Fluid Power Association (NFPA) sponsored the development of a fluid power technology roadmap. CCEFP was invited to participate as part of the road mapping team. The roadmap has three goals: to meet the future needs of customers, to expand fluid power into new markets, and to attract the best and brightest young engineers to fluid power. Six key R&D challenges for fluid power components and systems were identified by the roadmap: increasing energy efficiency; improving reliability; reducing size; building "smart" capabilities; reducing environmental impact; and improving energy storage, recovery and redeployment. These challenges are closely aligned with the CCEFP strategy. More information about the roadmap is available at http://www.nfpa.com/ourindustry/technology_roadmap.asp.

As mentioned above, in the past year, the NFPA has conducted an authoritative energy study funded by DOE that confirmed the importance fluid power in saving energy (see highlights section for more details). Twenty-three fluid power companies participated in the survey.

The CCEFP continued to enhance its communications efforts this past year using its existing approaches including e-news blasts, personal letters from the Director, newsletters, and biweekly webcasts. A completely updated set of project information sheets will be unveiled at IFPE. Based on industry requests these have been structured to convey essential information concisely. The technology readiness level (TRL) system of the DOD has been adopted for CCEFP use to effectively communicate the commercialization potential of projects. As part of major center reorganization, a new position, External Relations Coordinator, has been created. The additional position will facilitate communication with industry.

Team and Diversity

The interdisciplinary makeup of the CCEFP team is appropriate to achieve its vision. As shown in Figure 2a (section 2.1), most of the faculty 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.

In last year's report, women, under-represented minorities, Hispanics, and participants with disabilities all had substantial increases. This year the distribution remained at about the same level.

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. CCEFP conforms to the norms of other centers on funding, research activity metrics and diversity. There were metrics that significantly exceeded norms and are detailed below.

The number of industry members (51) is unchanged from last year with membership fees decreasing only slightly to $601,500 from $616,625. This far exceeds the norm of other ERCs. Given the severity of our current recession, it is remarkable that CCEFP was able to retain its members. We have added three new members, Hoowaki, LLC; the Lubrizol Corporation and Takako Industries. Hoowaki is a small high-tech startup company specializing in fabricating micro-structured surfaces founded by a CCEFP faculty member, William King of the University of Illinois, Urbana-Champaign. Lubrizol is a additive company. Their membership continues the growth of fluid company membership in CCEFP. Takako is a Japanese company specializing in miniature pumps. Takako has also agreed to play an active role in introducing the CCEFP to other Japanese fluid power companies. We have just learned that Case New Holland (CNH) will join the center. CNH is not yet included in the roster. Their membership fees will be $40,000 and they will be a member of the Industrial Advisory Board.

Because of its extensive education and outreach activities, CCEFP exceeds most norms in these categories. These include REU students (27) and K-12 students (3,251). The K-12 students impacted decreased from the number reported last year (4,365). This is because the Youth Science Program and the Science Museum of Minnesota was completed. This program developed fluid power curriculum and displays for the museum, but is now moving on to other topics. More than one thousand K-12 students continue to be exposed to fluid power at the museum every year, but are not included in the survey.

Table 1: Quantifiable Outputs						
Outputs	**Early Cumulative Total [1]**	**December 1, 2007 - January 31, 2008**	**Feb. 1, 2008 - January 31, 2009**	**Feb 01, 2009 - Jan 31, 2010**	**Feb 01, 2010 - Jan 31, 2011**	**All Years**
Publications That Result from Center Support						
In Peer-Reviewed Technical Journals	0	0	12	27	22	**61**
In Peer-Reviewed Conference Proceedings	0	19	57	51	59	**186**
In Trade Journals	0	1	2	23	0	**26**
With Multiple Authors:	0	12	70	101	76	**259**
Co-authored with ERC Students	0	12	51	71	50	**184**
Co-authored with Industry	0	0	2	4	3	**9**
With Authors from Multiple Engineering Disciplines	0	0	4	12	3	**19**
With Authors from Both Engineering and non-Engineering Fields	0	2	9	7	2	**20**
with authors from multiple institutions	0	0	11	7	10	**28**
Publications That Result from Associated Projects in the Strategic Plan						
In Peer-Reviewed Technical Journals	0	6	8	16	6	**36**
In Peer-Reviewed Conference Proceedings	0	18	19	23	7	**67**
Publications Resulting From Sponsored Projects						
In Peer Reviewed Technical Journals	N/A	0	0	6	0	**6**
In Peer Reviewed Conference Proceedings	N/A	0	0	24	0	**24**
Participating Industrial and Practitioner Organizations						
Members	57	57	58	54	54	**280** [2]
Affiliates	0	0	0	0	0	**0** [2]
Contributing Organizations	0	0	0	2	5	**7** [2]
ERC Technology Transfer						
Inventions Disclosed (submitted to agencies by	0	7	8	9	7	**31**
Patent Applications Filed	0	5	5	6	4	**20**
Patents Awarded	0	1	0	0	1	**2**
Licenses Issued	0	0	0	0	2	**2**
Spin-off Companies Started	0	0	0	1	0	**1**
Estimated Number of Spin-off Company Employees	0	0	0	0	0	**0**
Building Codes Impacts	0	0	0	0	0	**0**
Technology Standards Impacts	0	1	1	2	4	**8**
New Surgical and other Medical Procedures Adopted	0	0	0	0	0	**0**
Degrees to ERC Students						
Bachelor's Degrees Granted	0	6	26	44	18	**94**
Master's Degrees Granted	0	9	15	32	14	**70**
Doctoral Degrees Granted	0	2	6	5	9	**22**
ERC Graduates Hired by						
Industry:	0	7	19	12	19	**57**
ERC Member Firms	0	4	3	2	5	**14**
Other U.S. Firms	0	3	16	7	14	**40**
Other Foreign Firms	0	0	0	3	0	**3**
Government	0	0	0	0	2	**2**
Academic Institutions	0	0	2	5	10	**17**
Other	0	0	0	0	3	**3**
Undecided/Still Looking/Unknown	0	0	1	3	6	**10**
ERC Influence on Curriculum						
New courses based on ERC research that have been approved by the curriculum committee and are currently offered [4]	0	1	3	2	8	**14**
Currently offered, on-going courses with ERC content	0	0	15	12	12	**39**
New Textbook Chapter Based on ERC Research	0	0	0	1	0	**1**
New Textbooks Based on ERC Research	0	0	2	1	1	**4**
Free-Standing Course Modules or Instructional CDs	0	0	0	0	0	**0**
New full degree programs based on ERC research	0	0	0	0	0	**0**
New degree minors or minor emphases based on ERC	0	2	0	1	0	**3**
New certificate programs based on ERC research	0	0	0	0	0	**0**
Active Information Dissemination/Educational Outreach						
Workshops, Short Courses, and Webinars [3]	0	8	23	9	9	**49**
Number of participants that attended activity	N/A	N/A	0	86	135	**221**
Innovation-focused Workshops, Short courses, Webinars, and Seminars	N/A	N/A	N/A	N/A	5	**5**
Number of participants that attended activity	N/A	N/A	N/A	N/A	25	**25**
Seminars, Colloquia, Invited Talks, etc.	0	24	44	24	35	**127**
ERC Sponsored Educational Outreach Events for K-12	N/A	N/A	0	14	28	**42**
Number of students that attended activity	0	274	2,575	4,365	3,251	**10465**
Number of teachers that attended activity	0	2	2	26	30	**60**
ERC Sponsored Educational Outreach Events for Community College or Undergraduate students	0	0	0	8	9	**17**
Number of students that attended activity	0	0	0	244	125	**369**
Number of faculty that attended activity	0	0	0	24	9	**33**
Personnel Exchanges						
Student Internships in Industry	0	12	11	4	14	**41**

Outputs	Early Cumulative Total [1]	December 1, 2007 - January 31, 2008	Feb. 1, 2008 - January 31, 2009	Feb 01, 2009 - Jan 31, 2010	Feb 01, 2010 - Jan 31, 2011	All Years
Faculty Working at Member Firm	0	0	0	1	1	**2**
Member Firm Personnel Working at ERC	0	2	2	6	0	**10**

[1] For Centers in operation for more than five years.
[2] Cumulative count of Individual Firms/Organizations may not equal the sum across all years.

[3] For years prior to 2009, the values include 'Workshops and short courses to industry' and 'Workshops and short courses to non-industry groups'

[4] 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.

Table 1a: FY2010 Average Metrics Benchmarked Against All Active ERC's and the Center's Tech Sector					
Metric	Average All Active ERC's FY 2010	Average Energy Sector FY 2010	Average for Class of 2006 - FY 2010	Engineering Research Center for Compact and Efficient Fluid Power Total	Engineering Research Center for Compact and Efficient Fluid Power Total
	(15 ERC's)	(4 ERC's)	(5 ERC's)	FY 2010	FY 2011
Industrial Member Firms	16	25	26	51	51
Small	45%	43%	47%	45%	47%
Medium	11%	15%	15%	24%	24%
Large	45%	41%	38%	31%	29%
Non-Industry Sector Firms	1	1	3	3	3
Total Member Organizations	18	26	29	54	54
Affiliate Organizations	0	0	1	0	0
Contributing Organizations	1	2	1	2	5
Total Membership Fees Received	$244,933.00	$348,837.00	$410,984.00	$616,265.00	$601,500.00
Direct Sources of Support [1]	$5,540,703.00	$6,238,577.00	$5,621,531.00	$5,521,251.00	$5,992,513.00
NSF	66%	61%	74%	68%	72%
Industry	8%	8%	10%	15%	15%
Other Federal	0%	0%	0%	0%	0%
Academic	20%	18%	15%	14%	13%
State	3%	4%	0%	0%	0%
Other	3%	9%	1%	3%	0%
Associated Project Support	$4,306,199.00	$5,243,298.00	$3,957,940.00	$1,847,375.00	$1,885,313.00
ERC Personnel & Educational Participants[2] [3]	2,266	1,726	3,866	4,927	3,726
Leadership Team [7]	16	17	15	10	11
Faculty [2] [4]	43	39	44	35	42
Graduate Students [2]	79	96	70	76	95
Undergraduate Students [2]	42	37	46	59	74
REU Students	15	13	24	27	27
K-12 Teachers [3]	118	50	96	26	30
K-12 Students [3]	1,544	1,310	2,803	4,365	3,251
Faculty that attended ERC Sponsored Educational Outreach Events [3]	52	18	84	24	9
Community College or Undergraduate students that attended ERC Sponsored Educational Outreach Events [3]	327	119	650	244	125
% Women [5] [6]	28%	23%	34%	27%	26%
% Underrepresented Racial Minorities [5] [6]	12%	11%	13%	20%	23%
% Hispanic [5] [6]	10%	6%	8%	5%	4%
Publications	**Average**	**Average**	**Average**	**Total**	**Total**
In Peer Reviewed Technical Journals	32	34	32	27	22
In Peer Reviewed Conference Proceedings	42	48	54	51	59
Multiple Authors: Co-Authored With ERC Students	49	56	57	71	50
Multiple Authors: Co-Authored With Industry	5	4	9	4	3
Intellectual Property	**Average**	**Average**	**Average**	**Total**	**Total**
Invention Disclosures	7	8	4	9	7
Patent Applications	7	5	5	6	4
Patents Awarded	2	1	1	0	1
Licenses (patents, software)	1	0	0	0	2
Education and Outreach Outputs	**Average**	**Average**	**Average**	**Total**	**Total**
New Courses Developed	4	2	10	2	8
Currently offered, on-going courses with ERC content	10	9	10	12	12
New Full Degree Programs	0	0	0	0	0
New degree minors or minor emphases	0	0	0	1	0
New certificate programs based on ERC research	0	0	0	0	0

[1] Includes new support (unrestricted cash, restricted cash, and in-kind donations) from table 9 only. Residual funds carried over from previous years are not included in benchmarking figures.
[2] Includes total ERC Personnel from table 7.
[3] Includes participant values from Table 1 Quantifiable Outputs.
[4] Includes Directors, Education Program Leaders, Thrust Leaders, Senior Faculty, Junior Faculty, and Visiting Faculty from table 7.
[5] These data do not include K-12 Student or Teacher Participants in the percentage calculations. Demographic data are not collected for K-12 Student or Teacher Participants. We only collect the total number of K-12 Student and Teacher Participants.
[6] The percentage calculations are based on the following categories of Personnel only: Faculty, Graduate Students, Undergraduate Students, REU Students, Directors, Thrust Leaders, Research Thrust Management & Strategic Planning, Administrative Director, and Industrial Liasion Officer.
[7] Includes Directors, Thrust Leaders, Education Program Leaders, Research Thrust Management & Strategic Planning, Administrative Director, and Industrial Liasion Officer.

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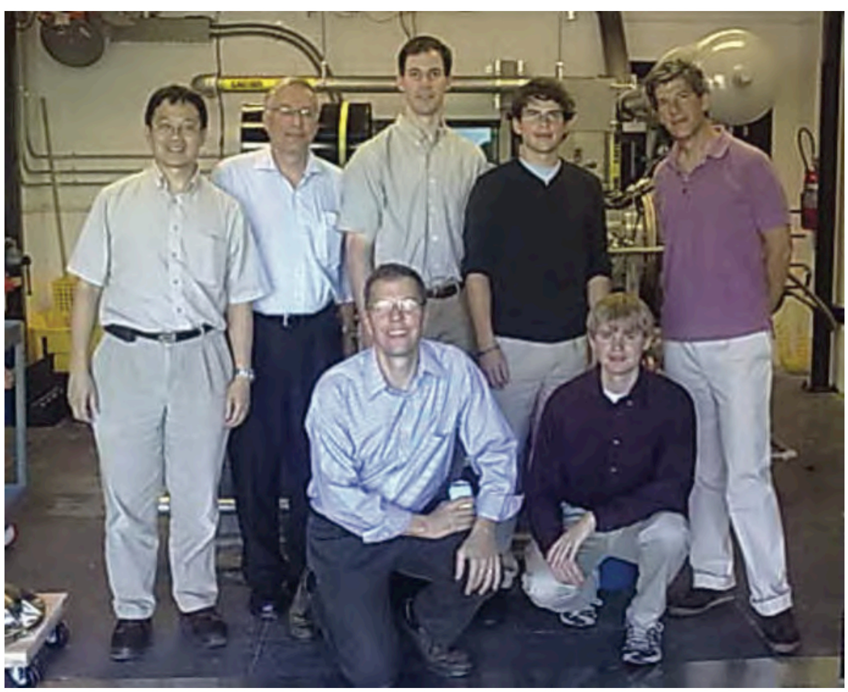
1.3 HIGHLIGHTS OF SIGNIFICANT ACHIEVEMENT AND IMPACT

DISCOVERY HIGHLIGHTS:

Open accumulator for Off-shore Wind Power Energy Storage - Because of the intermittency of wind power, and wind being more abundant during nighttime when demand is low, the ability to store wind power can significantly increase the usefulness and availability of this renewable, clean energy source. For off-shore wind farms where transmission and connections are more costly, storages localized to the wind turbines can also increase the capacity factor of these critical electrical components. However, storing large amount of energy (in the order of several MW-hrs) economically, efficiently and capable at high storage and regeneration rate (at several MW's) is challenging. CCEFP researchers have recently received a 4 year $2 million research grant from the NSF Engineering Frontiers for Research and Innovation (EFRI) program to develop a fluid power based approach to solve the wind energy storage challenge. Specifically, the open accumulator energy storage concept, developed within the CCEFP will be used in the application. The open accumulator concept makes use of high power capability of hydraulics (liquid fluid power) and the high energy density capability of pneumatics (gas fluid power) in a single architecture. Research currently underway involves efficient heat transfer in the compressor/expander design, efficient machine elements and system optimization. The grant is one of four awards made in the renewable energy storage area, a focus topic for the 2010 competition.

Proposed Energy Storage Concept is storing energy locally to the wind turbine.

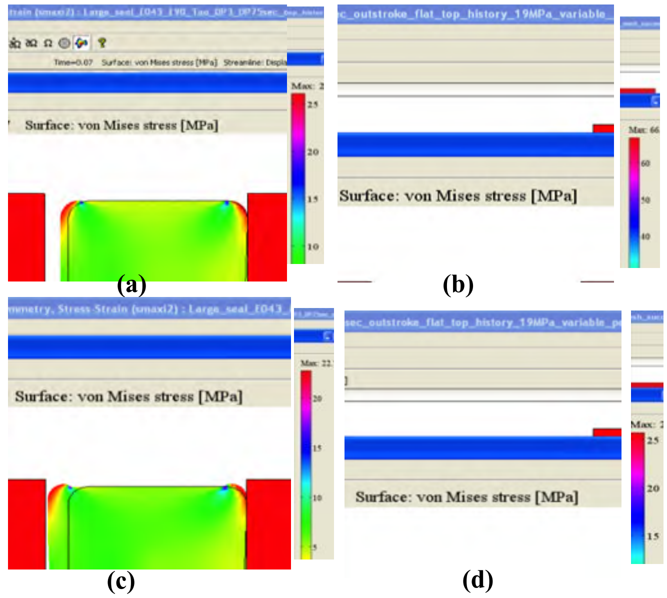


Project team at a kick-off September 2010 meeting in Oakland, CA.

Oak Ridge National Laboratory Fluid Power Study - In 2010, Oak Ridge National Laboratory (ORNL) teamed with the National Fluid Power Association and 23 industrial partners to quantify the impact (energy, emissions and economics) that the fluid power industry has on the U.S. energy consumption. Our fundamental hypothesis is that fluid power components and systems (hydraulics and pneumatics), which are an integral part of U.S. manufacturing and transportation, are a large consumer of energy and are typically energy inefficient. This huge industry has had little, if any, R&D since the late 1960s. As a result, there has been little effort to improve energy efficiency. Therefore, there is great potential to impact energy savings in both the industrial and transportation sectors by the development and deployment of energy efficient fluid power components and systems.

Our analysis shows that, in 2008, fluid power systems consumed between 4.446 and 5.127 Quads of energy producing over 300 million metric tons (MMT) of CO_2. To put this in perspective, the U.S. consumes approximately 100 Quads (1 Quad is 1015 Btus) of energy each year. One Quad costs industry and consumers approximately $20B. In terms of efficiency, our study indicates that, across all industries, fluid power system efficiencies range from less than 6% to as high as 40% (depending upon the application), with an average efficiency of 21%. A survey of 23 leading fluid power manufacturers suggests that an average 5% improvement in efficiency is easily achievable with Best Practices within the next 5 years. This near term objective could save close to 0.86 Quads of energy per year, saving consumers and industry over $17B/year in energy costs and reducing emissions by over 60 MMT of CO_2/year. Likewise, a longer term goal, through a strategic R&D program focusing on new controls, manufacturing and materials, can result in a 15% improvement in efficiency over the next 15 years. This aggressive goal can save more than 1.85 Quads of energy per year, saving industry and consumers more than $37B/year in energy costs and reduce emissions by more than 140 MMT of CO_2/year. Just as important, an aggressive program in energy efficient fluid power can invigorate this industry that is the backbone of U.S. manufacturing and increase U.S. competitiveness in the growing world market.

Viscoelastic Seal Modeling - The elastomeric rod seal, which seals the gap between the protruding rod and the housing of a linear hydraulic actuator, is one of the most critical elements in a hydraulic system because it must prevent the leakage of hydraulic fluid directly into the environment. At the CCEFP a numerical viscoelastic model of the rod seal has been developed. It is capable of predicting the key seal performance characteristics, especially seal leakage and friction, and will serve as a design tool. The model simulates the dominant physical processes governing the operation of the seal. It analyzes the behavior of the hydraulic fluid in the interface between the seal and the rod, the contact between asperities on the seal and the rod, and deformation of the seal. Previous models treat the seal material as elastic, reacting instantaneously to changes in the sealed pressure within the actuator. However, the polymeric materials used for seals are viscoelastic and have a delayed reaction to pressure changes. Since they have a memory, the behavior of the seal depends on its past history. Such viscoelastic effects are taken into account in the CCEFP model.



Deformed seal configurations and von Mises stress fields at various times (a) t = 0.07 sec, P_{sealed} = 7.5 MPa (b) t = 0.6 sec, P_{sealed} = 20.7 MPa (c) t = 0.71 sec, P_{sealed} = 7.5 MPa (d) t = 2.21 sec, P_{sealed} = 7.5 MPa

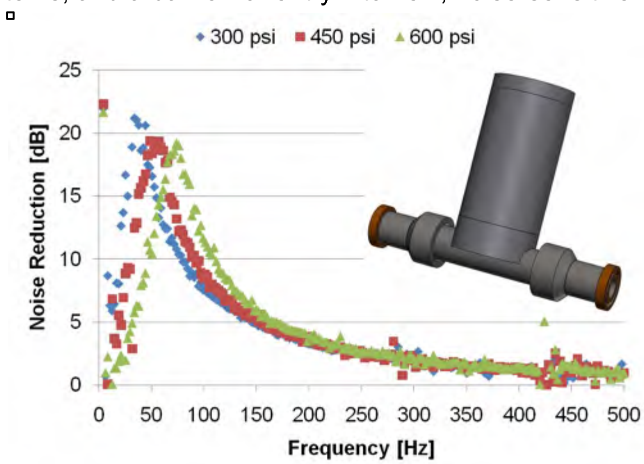
Orthosis Successfully Demonstrated on Impaired Subjects- The development of a lightweight, compact, efficient, powered, un-tethered ankle-foot orthosis has the potential to yield significant advancements in orthotic control mechanisms and new clinical treatment strategies for rehabilitation and daily assistance. One such device being developed in the Center for Compact and Efficient Fluid Power (CCEFP) is the portable powered ankle-foot orthosis. This device uses pneumatic power, provided by compressed CO_2, to move the ankle in the dorsiflexion (toes up) or plantarflexion (toes down) direction.

Recently, the PPAFO's ability to provide functional assistance was successfully demonstrated on two individuals with lower leg weakness. One individual had plantarflexor (calf muscle) weakness due to a spinal injury and could no longer generate torque at the ankle to push his toes down. This impairment affected his ability to propel himself forward while walking - thus making extended walking an exhausting task. The other individual had a form of muscular dystrophy, a disorder that caused weakness in both the calf and shin muscles, i.e., both plantarflexor and dorsiflexor muscles. Dorsiflexor impairment can limit the ability to pull the toes up during swing - thus creating a potential tripping hazard. During testing, the PPAFO was able to provide functional assistance to both subjects. Although the PPAFO was not capable of providing enough power to fully restore normal propulsive torque, it was able to generate modest power for propulsive assistance. For the individual with plantarflexor weakness, this added plantarflexor torque resulted in increased single leg support time on the assisted side and demonstrated a more normal ankle motion. For the individual with dorsiflexor weakness, the PPAFO also successfully controlled the motion of the foot during swing. This assistance eliminated a potential tripping hazard by keeping the toes from contacting the ground.

Generation 2 Portable Powered Ankle-Foot Orthosis (PPAFO)

These experimental results demonstrated that the PPAFO was capable of providing untethered functional assistance for people with walking disabilities. Currently researchers at several CCEFP institutes (University of Illinois, University of Minnesota, Milwaukee School of Engineering, Georgia Institute of Technology, and North Carolina A & T) are working on the development of a next generation AFO that will push the limits of fluid power technology. These innovative projects will lead to the development of a miniature and integrated power supply, actuators, valves, transmission lines and housing, while also addressing specific issues related to the development of novel powered exoskeletons to assist persons with disabilities.

Compliant-lined Helmholtz Resonator for Fluid Power Systems - Noise and vibration is a significant challenge in fluid power systems, and a barrier for entry into new, noise-sensitive environments. The high speed of sound in hydraulic fluid and low fundamental frequencies of pumps means long wavelengths of sound – which typically means impractically large noise control devices. The Georgia Institute of Technology's Integrated Acoustics Laboratory is developing specialized compliant linings for hydraulic noise control devices that effectively lower the speed of sound and result in significantly smaller devices. One such device being developed is a



Helmholtz resonator, which is effectively a filter for sound. A Helmholtz resonator with a compliant lining can be two orders of magnitude smaller than an unlined resonator. The research at the Georgia Institute of Technology may make it possible to have a noise control device that is both effective at the fundamental frequency of pumps, and is also compact enough for practical use.

Displacement Controlled Hydraulic Systems: A Breakthrough in Fuel Savings for Mobile Machines - Mobile machines in construction and agriculture depend on hydraulic cylinders and motors because of their ability to exert large forces and torques relative to their size and weight. However, the energy efficiency of today's hydraulic systems is typically quite low, often less than 25%. Much of the wasted energy is due to hydraulic control valves. An alternative concept called displacement controlled actuation is currently under development in the CCEFP. This technique uses variable displacement pumps to control the actuators, rather than valves. Displacement control reduces power losses and allows energy recovery from gravitational and braking loads.

Displacement controlled excavator uses 40% less fuel!

After four years of development, CCEFP researchers now have a functional prototype for testing displacement controlled actuation. Testbed 1 is a 5 ton compact excavator that has been retrofitted with variable displacement pumps to control the digging arm. Computer simulations have shown energy savings of up to 50% compared to the original machine. Independent testing of the prototype displacement controlled excavator and a standard Bobcat 435 excavator was conducted by Caterpillar, Inc. and the displacement controlled machine was found to consume 40% less fuel than the standard machine while moving the same amount of dirt in a truck loading cycle (see figure). Not only did it consume less fuel, but it did the work faster as well. In fact the prototype machine moved 17% more dirt per hour than the standard machine which results in a 70% machine efficiency improvement defined as dirt moved per fuel consumed. This promises machine owners not only significant savings in fuels costs but will reduce the required man hours for job completion and as a result will save cost per job and increase the number of jobs which can be completed.

The future of the excavator testbed is hydraulic hybrid technology which allows energy storage capabilities and optimal engine controls to minimize fuel consumption and emissions. Early studies have shown that rated engine power of the machine could be reduced by as much as 50% using hybrid displacement controlled technologies without sacrificing the performance of the digging functions of the machine. Support and interest in the excavator prototype from CCEFP member companies has been and continues to be strong as the project moves forward looking at a bright future.

LEARNING HIGHLIGHTS:

NSF ERC Exhibit at SACNAS and AISES - In the Fall of 2010, the CCEFP took the lead in coordinating an "NSF ERC" exhibitor booth for recruiting racially underrepresented students in engineering at the national conferences of SACNAS (Society of Advancing Chicano/Latino and Native Americans in Science) and AISES (American Indians in Science and Engineering Society). The goal of the National Science Foundation's Engineering Research Centers is to promote the advancement of underrepresented students, those being racial minorities, women, and students with disabilities as well as recent war veterans, in engineering. It is absolutely imperative that the engineering workforce reflects the ethnic and gender representation of this country. The CCEFP recognized the need to attract students within the Chicano/Latino and Native American communities and both SACNAS and AISES are highly regarded as worthwhile venues to attend to expose students to engineering disciplines. Furthermore, by leveraging the commitment of other Engineering Research Centers to participate in the exhibitor booth, the financial burden of attending the conferences was significantly reduced by splitting the cost among eight ERCs. The NSF ERC family will continue to partner together by coordinating efforts to attend recruiting events for underrepresented students in the STEM fields.

The CCEFP goes to IFPE - Through its participation in IFPE, 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 will have unprecedented opportunities to share its research findings with engineers working in the fluid power industry and its end use markets. The size of the show is just one measure of the potential audience. Scheduled for March 2011 in Las Vegas, Nevada, IFPE will host 30,000 attendees who have come to see the more than 500 exhibitors utilizing 128,500 square feet on the trade show floor. Attendees will also be able to select from among the presentations offered at the prestigious 52nd National Conference on Fluid Power (NCFP), held in conjunction with IFPE.

The CCEFP has played a central role in planning this triennial event, expanding the offerings of the NCFP and organizing four short courses on topics of specific interest to CCEFP's industry supporters. Forty of the NCFP's 120 papers will be presented by CCEFP faculty and students, and another 20 will be made by international fluid power experts, recruited by Center faculty. The CCEFP will also be an exhibitor; its booth will feature printed highlights as well as hands-on displays drawn from several of its research projects. In addition, the Center will hold its 5th Annual Meeting at IFPE along with its annual NSF site visit. Further, a special poster show and reception, highlighting the CCEFP's progress on its research projects and test beds, will be open to the Center's industry supporters and invited guests. Some of these guests will include exhibitors and attendees at CONEXPO-CON/AGG. This trade show, which is co-located with IFPE, is the largest trade show in the western hemisphere. Together, the two shows bring 144,600 to the five-day event.

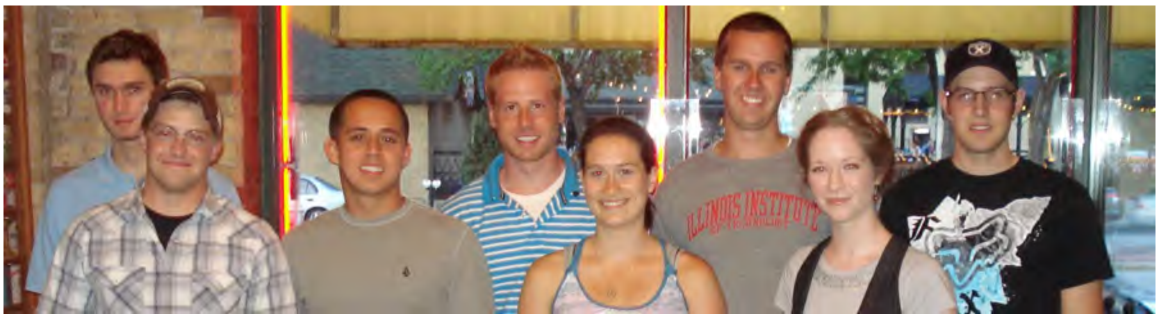
Fluid Power Scholars Program - "I gained an immeasurable amount of experience—nothing you can read from a textbook or learn in a class. The internship experience really opened up my eyes to the amount of work, resources and right people it takes to take a design from concept to product. " "A great understanding of how the engineering process works—from the initial idea, through the research and development states, to the testing of the component." "The biggest thing I gained was a full-time job! I was happy to find out that (the company that sponsored me) wanted to hire me full time at the end of the summer!"

These are among the responses to the 2010 CCEFP Fluid Power Scholars Program post-experience survey question, "What did you gain from your internship experiences?" While heartening in themselves, they also are representative of a broadly positive assessment of the program—start to finish—from students and industry mentors alike. Because the first year of this CCEFP program was a success in so many ways, it has laid a firm foundation for the program as it develops in the years ahead. Key elements and outcomes include:

- The program itself was designed jointly by a team of CCEFP staff and members of the Center's Industrial Advisory Board. Based on this plan, supporting companies of the CCEFP volunteer to provide summer-long engineering internships in their companies to undergraduate engineering students. They also provide stipends for room and board during an intensive orientation to fluid power at the Milwaukee School of Engineering before the internships begin. And, while CCEFP staff recruit student applicants, it is the companies themselves that make their scholar/intern selections based on students' on-line application materials and subsequent interviews.
- The fluid power orientation draws on the teaching expertise of MSOE, one in the CCEFP's network of seven schools. All eight of the selected scholars/interns in 2010 pointed to the strength of this three-day program in their evaluations; several asked that it be longer! For their part, companies noted that with this experience at the outset, students arrived at their internships, ready to "hit the decks running."
- The number of applicants was greater than expected for a first-year program (40+) and pointed to the long-reach of the CCEFP—the applicant pool stretched far beyond the CCEFP's seven schools. Of the eight scholar/interns selected in 2010, six came from schools outside of the Center network.

- And, among the strongest indications of program success, each of the seven companies sponsoring 2010 scholar/interns has indicated strong interest in participating in the 2011 program.

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—first with CCEFP staff and then with their selected students—in creating environments where scholar/interns could effectively apply what they had learned about fluid power in the classroom to hands-on, real-world applications.

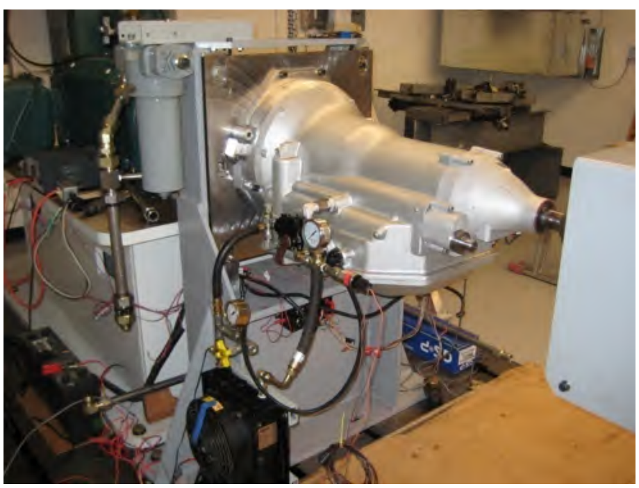


INFRASTRUCTURE HIGHLIGHTS:

Vanderbilt Imaging Institute MRI Scanners - The Vanderbilt Imaging Institute is a unique facility with several dedicated research MRI scanners, which are now available to the CCEFP through the newly funded project "Fluid-Powered Surgery & Rehabilitation via Compact, Integrated Systems". The institute has both a 3 Tesla, and a state of the art 7 Tesla human scanner (as well as access to standard 1.5 Tesla clinical scanners at the Vanderbilt University Medical Center). These scanners are a new resource to the CCEFP and are useful for testing many small-scale fluid power devices, including surgical robots, rehabilitation robots, and orthoses. These small-scale devices must work directly with humans and it is desirable to use the exquisite images provided by the MRI scanner in real time to adapt therapy mediated by fluid powered devices on a patient-specific basis. This represents a tremendous and rare resource for the CCEFP, since MRI scanners are typically used clinically 24 hours per day at most hospitals, and getting research time on them is either difficult or impossible. Furthermore, only a few 7 Tesla human scanners exist in the world, making this a particularly valuable resource. It is also a maintenance-free testbed for the center, since the scanners are already maintained by the Vanderbilt Imaging Institute.

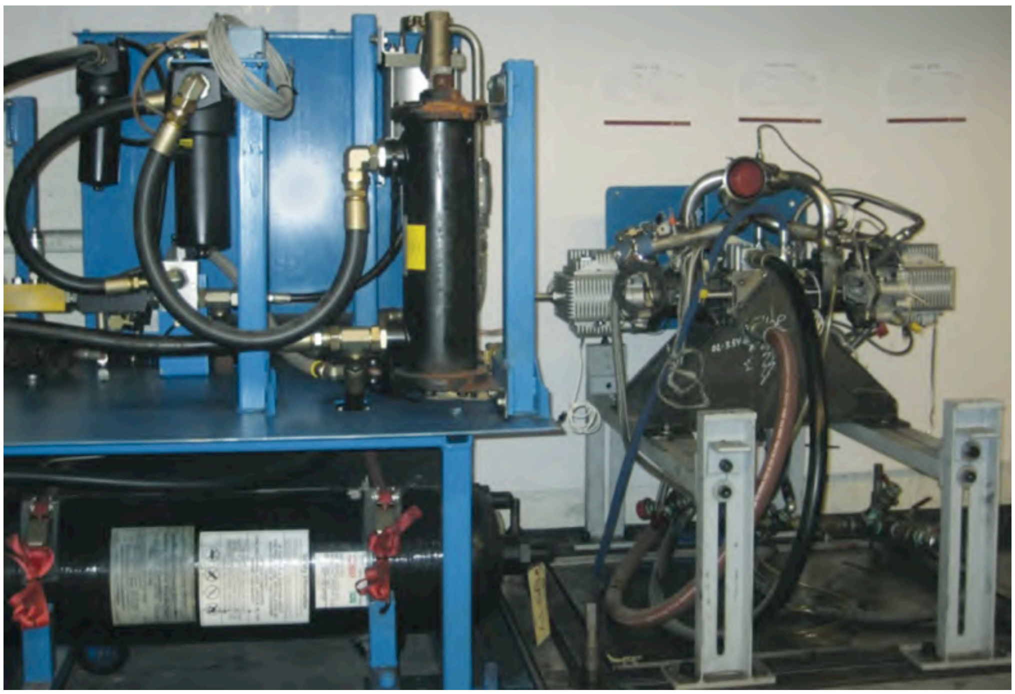
Ford F-150 with A Hydraulic Hybrid Drive-train - In a collaboration between Ford Motor Company, Folsom Technologies International (FTI), and the Center for Compact and Efficient Fluid Power (CCEFP), the drive-train of a Ford F-150 pick-up truck is being replaced by a hybridized Hydro-Mechanical transmission (HMT). This second generation hydraulic hybrid vehicle testbed is to demonstrate the capability of hydraulic hybrid drive-trains to significantly increase fuel economy with high performance and rugged operation. The HMT, developed by FTI, is a specialized output-coupled power-split continuously variable transmission (CVT) with efficient hydraulic pump/motors integrated into the design. While the CVT alone without energy storage can improve engine efficiency and fuel economy to some extent, hybridizing it with hydraulic accumulators as energy storage, allows braking energy to be captured and reused and enables the engine to be operated at high efficiency regardless of instantaneous output demand (by storing or supplementing power in/from storage). Analysis shows that with efficient components and controls, fuel economy can potentially be increased from below 20mpg for a conventional transmission to over 50mpg with a hybridized HMT drive-train. The transmission is currently being characterized and control algorithms are being developed. The vehicle with the modified drive-train will eventually be tested under typical EPA driving cycles.

Ford F-150 pick-up truck with a 4.6L gasoline engine.



Integrated HMT on a dynamometer test-stand (left) and hydraulic accumulators to be used as energy storage elements.

Ford Free Piston Engine Pump - Ford Motor Company has donated a hydraulic free piston engine (HFPE) to the University of Minnesota to support research work sponsored by the CCEFP. The HFPE is an opposed cylinder opposed piston engine with a linear hydraulic pump. Contrary to the conventional crankshaft based internal combustion engine (ICE) driven rotational pump, this system can produce fluid power in real-time with linear motion and with much improved efficiency and reduced emissions. There are two opposed combustion cylinders in this engine. Combustion in one cylinder will compress gas in the other cylinder and pump high-pressure fluid at the same time. Alternating firing in the two cylinders will move the pump back and forth to produce fluid power in real-time. There are three key advantages of the HFPE. First, the energy conversion efficiency is greatly improved from the conventional ICE enabled by the variable compression ratio, advanced combustion such as homogeneous charge compression ignition (HCCI), and lower friction. Second, the linear hydraulic pump/motor offers higher efficiency due to a simpler design. Third, the output power can be adjusted quickly in real-time due to the flexibilities of the engine and the high power density of the fluid. This system is critical for research to provide compact and efficient fluid power sources (10-500kw) for mobile applications including both on-highway vehicles and off-highway heavy equipment.



The Ford Hydraulic Free Piston Engine (right) installed at the University of Minnesota.

2. STRATEGIC RESEARCH PLAN AND OVERALL RESEARCH PROGRAM

The CCEFP research plan was strategically derived from the Center vision and major goals. The four major goals are:

1. Increase efficiency in existing fluid power applications.
2. Expand fluid power use in transportation to reduce fuel consumption.
3. Create portable, un-tethered human-scale fluid power applications.
4. Making fluid power ubiquitous, meaning that fluid power is safe, quiet, clean and easy to use so that it can be used anywhere.

The test beds represent systems that were carefully selected to align with the goals. The heavy equipment test bed was chosen to address efficiency of existing systems. The transportation test bed was chosen to expand fluid power use in transportation. The human-scale equipment and the human-assist device test beds were chosen as examples of future portable human-scale fluid power applications. The ubiquity issues apply to all test beds.

The technical barriers to realizing the test beds' vision can be described using nine important attributes of future fluid power systems. The four test beds and their contribution to the nine important fluid power attributes are shown in the chart below.

	Technical Barriers								
	Efficient Components	Efficient Systems	Control and Energy Management	Compact Power Supply	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet
Test Beds									
TB-1 Mobile Heavy Equipment	•	•	•				•	•	
TB-3 Highway Vehicles	•	•	•		•		•	•	•
TB-4 Human-scale Mobile Equipment	•			•	•	•	•	•	
TB-6 Human Assist Devices	•			•	•	•	•	•	•
Associated TB - Wind Power	•	•	•		•			•	
Associated TB - Biomedical devices	•	•	•	•	•	•	•	•	•

During the latest project selection funding for five existing projects was discontinued and four new projects were initiated. The discontinued, or "graduated", projects listed below had either reached their goals, encountered large technical difficulties or were unable to fit into the test beds.

1. Improved Seal Design Based on Adaptive Materials
2. Passivity Based Safe Human-Machine Interaction of Fluid Powered Systems with Cyclic Tasks and Delayed Response
3. LES of Cavitation in Hydraulic Components
4. Nanoscale Additives for Pump Performance - a Computational Study of Carbon Nanotube Rheology
5. Heat Transfer Enhancement in the Open Accumulator System

The four new projects funded for the year 5/6 budget cycle are listed below. These projects are closely aligned with overcoming the important technical barriers, supporting test bed integration and meeting industry needs.

1. Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor
2. MEMS Proportional Pneumatic Valve
3. Fluid-Powered Surgery & Rehabilitation via Compact, Integrated Systems
4. Free Piston Engine Hydraulic Pump

The helical ring pump/motor is a promising new high efficiency component concept that could be used on the excavator or HHPV test beds. The MEMS proportional pneumatic valve is a new miniature fluid power component that could be used in the orthosis test bed. The fluid power surgery project supports the new associated biomedical test bed. The free piston engine hydraulic pump is a potentially more compact and efficient power supply that could be used in either the excavator or HHPV test beds.

2.1 STRATEGIC RESEARCH PLAN

The strategic research plan for the Center takes a systems-based approach using test beds of associated projects that support the Center goals. For each test bed, a description of the goals and alignment with the Center goals, the research activities completed, in process, and planned, significant milestones, and demonstrated and potential benefits to the fluid power industry as described below.

Test Bed 1: Heavy Mobile Equipment – Excavator

Off-road mobile equipment is one of the largest users of hydraulic systems and components. Off-road mobile equipment is used in industries such as agriculture, construction, mining, and forestry. Some examples of off-road mobile equipment include wheel loaders, excavators, tractors, combines, and many others. Fluid power is widely used in this equipment for propulsion, steering, and performing the work the vehicle is designed to do. The inherently high power density of fluid power makes it a critical technology in accomplishing these functions. Fluid power components and systems have historically been designed for maximum productivity with low emphasis on efficiency. The recent increases in energy prices coupled with the soon to be implemented off-road engine emissions regulations have caused industry to look for ways to improve the efficiency of all vehicle components and systems, including the hydraulics.

CCEFP has selected an excavator as the primary vehicle for test bed 1. It is one of the most common multi-actuator mobile machines in use today. The excavator will be used to demonstrate the improvements in hydraulic system operation made possible by integrating the advanced component and system designs by CCEFP research.

1. Statement of Project Goals
The goal of this test bed has been to study new system concepts based on throttle-less actuator technology and to demonstrate fuel savings (target of 40%) and improved performance and compactness applying this technology to an excavator which represents the large vehicle sector of construction, agricultural and forestry equipment market. The excavator is also be used to study and demonstrate

effective control strategies for complex multi actuator systems and robot like machine functions. This includes new human/machine interfaces, including those that provide haptic feedback.

With the extension of project funding into years 5 and 6, the project's focus will be to develop a multi-actuator mobile machine (an excavator in this case) with dramatically improved fuel economy and a significant reduction in engine size that uses displacement controlled hydraulics and hybrid technologies. The machine should be capable of equaling or exceeding the performance capability of the standard version of the machine while providing these benefits.

The test bed's goals include:

- Reducing fuel consumption to 50% of standard excavator
- Reducing engine size by 50% of standard excavator
- Meeting current emission standards
- Maintaining standard machine performance

2. Test Bed Role in Support of Strategic Plan

This test bed supports the center goal of increasing the efficiency of existing fluid power components and systems. The test bed will be used to demonstrate fuel savings by more efficient fluid power actuator technology and effective machine power management, especially for large and high power equipment. The new actuator technology will open new applications in both large scale heavy duty machinery and robots and in human scaled applications like surgery robots or other portable devices where efficient and compact actuator technology is necessary.

3. Project Description

A. Description and explanation of research approach

Test Bed 1, the excavator, was selected to primarily to demonstrate potential energy savings which could be achieved for multi-actuator mobile machines through innovative system designs and advanced control strategies. However, the system is also very suitable for demonstrating the capabilities and performances of individual components developed by projects throughout the CCEFP. Thus, while the focus of the test bed research is to improve the energy efficiency and performance of multi-actuator mobile hydraulic machines, the scope of the test bed activities also includes demonstrations of individual components and evaluations of their effect on system performance.

The core of the test bed will be based upon the results from project 1A2 although technologies developed by several projects throughout the CCEFP will be integrated onto the test bed for demonstration. All contributing project leaders have been contacted and agreed to the timeline for the milestones and deliverables listed in the previous section. The contributions are as follows:

Project 1A2:
- Controls for optimal power management of multi-actuator DC hydraulic system
- Controls for energy based trajectory optimization
- Design and installation of hybrid hydraulic system and downsizing of excavator engine
- Reduction of hydraulic cooling power due to improved system efficiency
- Design and installation of smart pump with integrated electronic pump controls

Project 1B1:
- Development of next generation of highly efficient and smart variable displacement pumps

Project 1E2:
- Development of virtual variable displacement pump for the excavator low pressure hydraulic system using high speed on-off valves

Project 1E3:
- High efficiency, high bandwidth, actively controlled variable displacement pump/motor

Project 1G1:
- Testing of energy efficient hydraulic fluids

Project 3A1:
- Tele-operation of the test bed using haptic controls and the Phantom controller

Project 3D3:
- Improved seal design based on adaptive materials

B. Achievements:

Productivity and Fuel Test

The productivity and fuel test for test bed 1 with DC hydraulics was conducted in cooperation with Caterpillar, Inc. who is a member company of the CCEFP. Two mini excavators were tested: Tested 1 with DC actuators and a standard excavator of the same model. The test site is shown in Figure 1. Measured quantities included the mass of soil loaded, fuel mass consumed, and cycle times. The excavator loaded soil into a 6-ton dump truck, after which the truck was weighed to determine the soil mass. Fuel measurements were obtained by weighing an external fuel tank with a precision scale (5 g resolution). Data was acquired on the DC excavator from all onboard sensors. The standard excavator was not instrumented. All testing was conducted at the same location with the same professional operator on the same day. Identical fuel was used for all tests.

Tables 1 and 2 summarize the results of the test and it can be seen that test bed 1 consumed 40% less fuel on average than the standard machine while moving the same amount of dirt. This shows that the goal of reducing the energy consumption of the system by 40% was achieved. The results not only show that the fuel consumption was reduced, but the productivity of the machine was increased. On average, the test bed with DC actuators was able to move 16.6% more tons of dirt per hour.

Figure 1: Productivity test site

Machine	Soil loaded (metric ton)	Fuel consumed (kg)	Cycle time (s)
Standard LS	6.85 ±0.43	0.529 ±0.046	11.86 ±0.67
Prototype DC	6.97 ±0.47	0.319 ±0.037	10.32 ±1.09
Difference	+1.73%	-39.7%	-12.9%

Table 1: Excavator productivity test results

Machine	Fuel consumption rate (kg/h)	Productivity (ton/h)	Fuel Efficiency (ton/kg)
Standard LS	8.04	104.3	13.0
Prototype DC	5.57	121.7	21.9
Difference	-30.8%	+16.6%	+68.7%

Table 2: Excavator performance comparison

Machine Power Management

A fuel efficiency test was conducted to evaluate the proposed optimal power management algorithm from Project 1A2. The duty cycle consisted of moving a 250 kg mass suspended from the bucket on a chain. Targets were placed on either side of the excavator. While rotating the cabin 180°, the weight was raised from one target and then lowered onto the other. Each trial consisted of 20 repetitions, after which an external fuel tank was weighed to determine the fuel mass consumed. Five trials each were conducted with and without power management. In the latter case, the engine speed was set to high idle (~2700 rev/min).

Figure 2: Power management fuel test setup

Results are tabulated in Table 3. Mean values are listed along with 95% confidence intervals based on a two sided t-distribution.

	Fuel consumed (g)	Cycle time (s)	Fuel rate (kg/h)
Constant engine speed	270 ±14	15.9 ±0.3	3.030 ±0.116
Power management	118 ±16	15.3 ±1.0	1.383 ±0.114
Difference	-56.4%	-3.5%	-54.4%

Table 3: Power management test results, average of five trials

Using power management, the engine operates at a lower speed and the pumps operate at higher displacement. In this way, the same actuator motion is attained more efficiently. The measured duty cycle was intentionally selected because it requires slow, careful motions to prevent the weight from swinging. The cycle is comparable to pipe laying or other realistic tasks for an excavator. In a more demanding cycle, there would be less opportunity for reducing engine speed and fuel consumption.

DC Hydraulic Hybrid Feasibility Study

Through project 1A2 a feasibility study was done for a DC hydraulic hybrid system on TB1. The simulation model previously created for the DC excavator test bed was modified to include an additional pump/motor (18 cc/rev) and accumulator (5 L) to create a parallel hybrid system. Measurements from the productivity study where an expert operator was performing a truck loading cycle as fast as possible were used to generate actuator trajectories and loads for the cycle. This cycle was selected because it is very aggressive representing the extremes of the power requirements for the DC actuators. As previously stated one of the project goals is to be able to reduce the required engine power of the machine by 50%. To check the feasibility of this goal the simulation was controlled to limit the engine power output to be 50% of the current test bed engine power where power requirements of the cycle above that level would be met by the hydraulic accumulator and the additional pump/motor.

Simulations were completed to investigate engine power for the non-hybrid and the hybrid DC hydraulic systems during the digging cycle. The results indicate that the hybrid system power was able to be limited to be 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.

Future work:

- Modification of machine control for haptics tele-operation (from project 3A1). Deliverables include:
    - Installation of controller hardware [06/01/2011]
    - Demonstration of haptics tele-operation [07/01/2011]
- Design, modeling, and simulation of hybrid excavator system. Deliverables include:

  - Hydraulic schematic and component sizing (accumulator, pump/motor, etc.) for displacement controlled hybrid machine [01/01/2011]
  - Dynamic and energy simulation model in Simulink of hybrid system and energy/fuel consumption predictions [03/01/2011]
  - Thermal model of test bed hydraulic system [06/01/2011]
- Conduct on-vehicle experiments. Deliverables include:
  - Thermal measurements of hydraulic system and experimental evaluation of reduction in cooling requirements [06/01/2011]
  - Installation of hybrid hydraulics and smaller engine [04/01/2012]
  - Measurements of fuel and performance of hybrid system [06/01/2012]
- Demonstration of technologies from associated projects. Deliverables include:
  - Installation of next generation smart pump and demonstration of control of a single actuator [2012]
  - 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 [2012]
  - Comparison of energy consumption of the test bed using standard hydraulic oil and energy efficient fluids developed in project 1G1 [2012]
  - Integration of next generation of efficient pumps for control of a single actuator [2013]
  - Demonstration of adaptive material for seals from project 3D3
  - Demonstration and energy measurements for digital pump control of a single actuator using a prototype high efficiency, high bandwidth, actively controlled variable displacement pump/motor (from project 1E3) [2013-2014]

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

- Test bed 1 provides a usable displacement controlled actuator prototype that can be evaluated and tested by industry members. This saves them much time and money compared to building prototypes to evaluate the potential of displacement controlled actuation hydraulic systems.
- The results of this test bed have shown that up to 40% fuel savings can be achieved which would clearly be a benefit to OEM companies within the Center.
- The improved efficiencies and potential for reduced engine power requirements made possible by the technologies being developed in this project will help OEMs meet upcoming off-road emission regulations.

Test Bed 3: Hydraulic Hybrid Passenger Vehicle

1. Statement of Project Goals
The overall goal of this project is to realize a hydraulic hybrid power-train with drastic improvement in fuel economy and good performance that is competitive with other technologies such as electric hybrid, for the passenger vehicle segment. As a test bed project, it also drives and integrates associated projects by identifying the technological barriers to achieving that goal. The design specifications for the vehicle include: fuel economy of 70 mpg under the federal drive cycles; an acceleration rate of 0-60 mph in 8 seconds; the ability to climb a continuous road elevation of 8%; emissions meeting California standards; and size, weight, noise, vibration and harshness comparable to similar passenger vehicles on the market.

2. Project Role in Support of Strategic Plan
Test Bed 3 directly supports goal 2: improving the efficiency of transportation. Efficiency is obtained by utilizing fluid power to create novel hybrid powertrains for passenger vehicles. The powertrains integrate high efficiency components (goal 1), compact energy storage (goal 2) and methodologies for achieving quiet operation (goal 4) from related CCEFP projects.

3. Project Description
A. Description and explanation of research approach
The high power density of hydraulics makes it an attractive technology for hybrid vehicles, since they should be able to provide both high mileage and high performance. Hydraulic hybrid systems 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 realize their potential for small vehicles, hydraulic hybrid drive trains 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.

Three possible architectures for hybrid drive trains 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 sends a high percentage of wheel power 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 are the less studied hydraulic hybrid architectures. Power-splits combine the positive aspects of the series and parallel drive train. All architectures can regenerate braking energy.

This test bed is currently developing two hydraulic hybrid passenger vehicles, each of which offers unique research benefits. The “Generation 1” vehicle was built using the platform of an off-road all terrain vehicle (ATV). The vehicle has been outfitted with a modular power train that enables testing 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.

The “Generation 2” vehicle is being developed in partnership with Ford and Folsom Technologies International (FTI). It is built on the platform of a F150 pickup truck, which has refined vehicle dynamics capable of highway speeds. The power-train is attractive in that it is built as a compact, highly integrated, self-contained package. However, the integrated package prevents changing the hydraulic pump/motors. Also, since it is not originally designed for hybrid operation, the transmission not necessarily optimally sized and presents some control restrictions when operating in hybrid modes. Therefore, the “Generation 1” vehicle is being continued despite the pending availability of the roadworthy “Generation 2” vehicle.

Our ultimate goal will be a “Generation 3” vehicle with a true passenger vehicle chassis. We expect this development to begin in 2012.

B. Achievements

Achievements and Plans Applicable to Both Vehicles

Three achievements apply to both vehicles: replacement of the controls firmware, a study of input and output coupled hybrid transmission architectures, and a comparison of hydraulic and electric hybrid architectures. These studies utilize the 3 level hierarchical control/analysis approach that was developed in previous years. They are described in order as follows.

Controls firmware upgrades: The Generation 1 vehicle has previously used “xPC Target” firmware to interface the controller with the powertrain. We are now converting to firmware that is popular for automotive systems, “Micro-Autobox”, to improve both the hardware and software robustness. In addition, the standard system will simplify migration of the controller to the Generation 2 vehicle.

Input vs. Output Coupled Study: Power split transmissions can be classified as “input coupled”, “output coupled” and compound. An input coupled transmission utilizes a fixed gear ratio between the engine and one pump/motor, while the second pump/motor is coupled to the wheels with a planetary gear train[1]. An output coupled transmission utilizes a fixed gear ratio between the wheels and one pump/motor, while the second is coupled to the engine with a planetary gear train[2]. A compound transmission is one in which both pump/motors are coupled with planetary gear trains.

[1] The transmission of the rebuilt Generation 1 vehicle is input coupled.
[2] The transmission in the Generation 2 vehicle is output coupled.

Architecture	Input coupled
Matrix G	$\begin{pmatrix} 1.0175 & 0 \\ 2.0660 & -8.3570 \end{pmatrix}$
P/Ms' size	P/M-T=27.7cc P/M-S=28.8cc
City	78.6 [mpg]
Highway	56.1 [mpg]
Combined	64.2 [mpg]
Architecture	Output coupled
Matrix G	$\begin{pmatrix} 1.2768 & -4.0424 \\ 0 & 4.7239 \end{pmatrix}$
P/Ms' size	P/M-S=23.9cc P/M-T=39.1cc
City	72.7 [mpg]
Highway	54.9 [mpg]
Combined	61.2 [mpg]
Architecture	Compound
Matrix G	$\begin{pmatrix} 0.981 & 0.64 \\ 2.0573 & -8.3764 \end{pmatrix}$
P/Ms' size	P/M-1=24.5cc P/M-2=24.7cc
City	79.5 [mpg]
Highway	56.1 [mpg]
Combined	64.5 [mpg]

Table 1: Preliminary results of the architecture comparison

A study to determine the most efficient powertrain configuration was performed. This was achieved by defining and optimizing a generalized expression that relates the kinematics of the engine, wheels, and pump/motor units. This expression is referred to as Matrix G.

The elements of Matrix G were optimized for a prescribed drive cycle using all three potential architectures. This approach maximizes the opportunity for improving fuel economy. The optimal size of the hydraulic pump/motors is generated as part of the process.

Preliminary results are shown in Table 1. The fuel economy of the various architectures appears fairly similar: the optimized results are within about ±5%. The component sizing varies slightly, with the compound architecture requiring the overall smallest pump/motors. However, the input and output architectures are competitive. Refined results will be obtained in 2011.

Hydraulic/Electric Hybrid Comparison: A comparison of the efficiency of hydraulic and electric hybrid vehicles was performed in 2010.The initial results indicate that for the light (1000kg) vehicle that was studied, electric and hydraulic hybrids have comparable fuel economy under standard EPA driving cycle without additional acceleration requirements. It is expected with heavier vehicles, more stringent acceleration requirements, and more efficient pump/motor, the advantages of hydraulic hybrids will be accentuated. Improved analysis will be performed to refine this comparison in 2011.

<u>Achievements and Plans for Generation 1 Vehicle</u>

Drive Train Redesign: The original Generation 1 vehicle drive train suffered from several limitations which restricted its usefulness. The drive train is complicated and it includes several belts and chains. The vehicle's frame would flex enough during driving that the chains would sometimes skip teeth. In addition, the planetary gear trains, which combine power from hydraulic pump/motors with engine power at the rear wheels, were undersized, so they were not capable of carrying the full wheel torque specification.

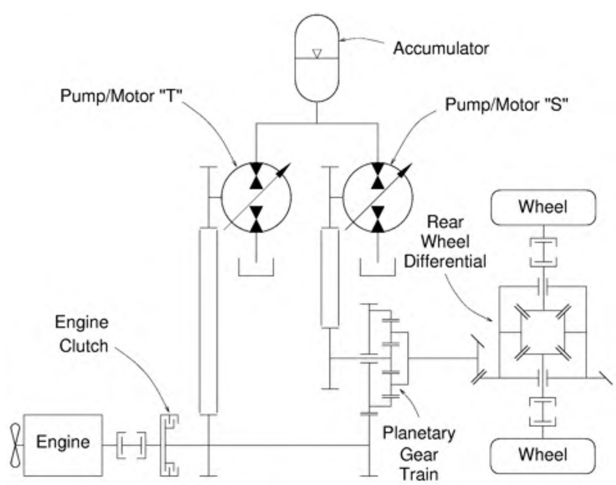


Figure 1: Schematic representation of redesigned Generation 1 HHPV powertrain

The drive train was completely redesigned in 2010. A schematic of the revised system is provided in Figure 1. All of the problems caused by the belts, chains and frame flexion have been eliminated by using gears. The drive train has been simplified by replacing dual rear wheel pump/motors and planetary gear trains with single units driving a stock automotive rear wheel differential. The original axial piston type pump/motors have been replaced with high efficiency bent axis piston units. Gear ratios and pump/motor sizes are chosen to optimize fuel economy under EPA driving cycles and to satisfy the acceleration requirement.

The redesigned drivetrain can operate in four different modes. The first is hydromechanical transmission ("HMT") mode. The second is parallel mode. The last two modes are similar to a series transmission where only the motor is operating and powered only by the accumulator charge.

Transmission components are currently in the machining and assembly stages. A fully assembled transmission expected to be ready for testing in March 2011.

In addition to providing a more robust drivetrain on the vehicle, the transmission is also designed to be operated as a stand-alone unit. With this new capability, it will be possible to test the transmission on a dynamometer, facilitating efficiency mapping and control development of the vehicle.

Finally, the modular architecture of the redesigned transmission enables the pump/motors to be changed out. We plan on replacing the bent axis pump/motor used as pump/motor "S" with a pulse width modulated fixed displacement pump/motor designed in Project 1E.1 during 2011. The purpose of this test is to compare the efficiencies of the two approaches. This test will provide demonstration of a real world application for the pulse width modulated pump/motor also.

Low level Control Refinement: System identification experiments have been performed on the existing Generation 1 vehicle. This together with experimentally derived pump/motor maps in provide improved information for refining the low level control algorithm design.

Fuel Sensor: An accurate engine efficiency map is crucial to developing controllers capable of minimizing fuel consumption of a hybrid vehicle. Simulations of the Generation 1 vehicle performed to date have utilized a Willans' line approximated engine efficiency map; the engine in the vehicle may deviate substantially from this approximate map. A fuel flow sensor was calibrated and installed on the Generation 1 vehicle, utilizing its original drive train, during 2010 to enable creating an accurate map.

Additional Plans for Generation 1 Vehicle During 2011: Experiments will be performed to operate the Generation 1 transmission as a continuously variable transmission (CVT) rather than 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 limit for comparing full hydraulic hybrid modes.

<u>Achievements and Plans for Generation 2 Vehicle</u>

Returning FTI Transmission to Service: Collaboration with Ford Motor Company and FTI was started in spring 2009. Ford donated an F150 truck to the CCEFP. Testing of the FTI hydro-mechanical transmission was initiated in early winter 2009. The FTI transmission is shown mounted to a 400 HP dynamometer available at the FTI facility in Figure 2.

Figure 2: Hydromechanical transmission on the dynamometer test stand at FTI

Problems with the controls on the FTI dynamometer in early 2010 resulted in the transmission being driven at high speed in reverse. Because no lubricant is supplied in this configuration, extensive damage occurred to both mechanical and hydraulic components in the transmission. Ford agreed to fabricate many parts to replace the damaged hydraulic components and new planetary gear sets were procured and modified for the transmission rebuild.

Testing resumed in early autumn 2010 and performance problems, particularly poor efficiency and the inability to generate sufficient torque, were noted immediately. Ford once again supplied the machining to modify the hardware to eliminate the problems. The transmission is currently being reassembled and is scheduled for resumption of testing in January 2011.

The F150 is expected to be delivered to the University of Minnesota with the FTI transmission installed in Spring 2011.

Efficiency Map Test Plan: FTI has provided a simulated efficiency map with their transmission. However, the transmission was originally intended to be run as a continuously variable transmission rather than a hydraulic hybrid transmission. Therefore, dynamometer tests are being planned to obtain the efficiency map corresponding to hydraulic hybrid operation. This is essential for fuel economy predication and the design the control and energy management system. The test plan, developed by CCEFP researchers, will be implemented on the dynamometer available at the FTI site prior to shipping the transmission to Minnesota.

The tests must be designed to overcome two unique circumstances. First, the two pump/motors in the FTI transmission are intrinsically coupled; therefore, the mechanical and volumetric efficiency of each pump/motor cannot be obtained individually. Second, a hydraulic power supply cannot be utilized for the dynamometer tests at the FTI site.

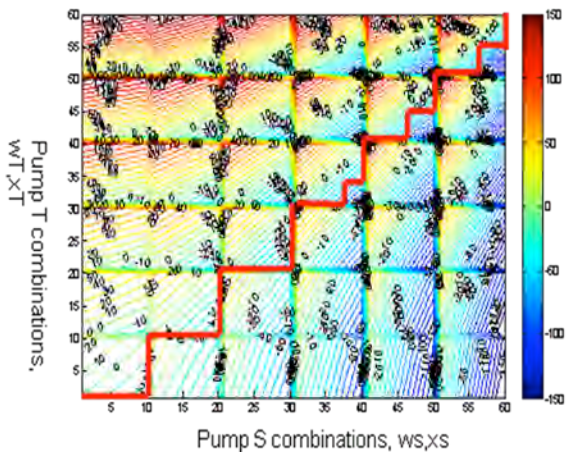


Figure 3: Combinations of test conditions for FTI transmission. Contours represent flow rate through the relief valve.

Both restrictions have been overcome by developing a procedure where flow is measured through a relief valve connected between the high and low pressure ports of the pump/motors. Figure 3 illustrates all combinations in which the combinations of the two pump/motors could operate. Ordinarily, approximately 3600 data points would be required to fully define all portions of this map. However, many of these combinations are not feasible with the restriction of the test facility. If the assumption that both pump/motor units have similar characteristics is used, we have devised a means for approximating the entire map by obtaining only 240 data points, which are represented by the stepped red profile Figure 3. This approach also reduces the risk of operating the relief valve beyond its capacity. Furthermore, regenerative braking scenarios can also be simulated. Data for creating the FTI transmission efficiency map is expected to become available by March 2011.

Development of Enhanced Simulations: Analysis of the FTI transmission utilized in the Generation 2 vehicle was initiated by adapting the "backward facing" simulation tools developed for the Generation 1 vehicle. "Backward facing" means that the drive cycle is known in advance and the transmission components are optimized to provide the prescribed wheel torque while consuming the minimum amount of fuel. Mechanical restrictions imposed by the Generation 2 transmission architecture increase the complexity of the controls strategy development. However, the restrictions appear to have only minor impact on the fuel economy using the backward facing simulation.

In order to further investigate this issue, a "forward facing" dynamic model is being developed and refined. The forward facing model takes driver commands as the input. This model takes advantage of a MATLAB Simulink model provided by Ford, which includes details of the engine dynamics, auxiliary losses of the vehicle, aerodynamics, temperature variation, and the like. We have enhanced the Ford model by replacing a model of a conventional automatic transmission with that of the FTI transmission and adding a model of an accumulator. In addition, the model is being re-structured so that the designed controllers can be directly implemented onto the actual vehicle controls hardware. The forward facing model is expected to predict the fuel economy more accurately due to controlling energy management in real time.

Expected Milestones and Deliverables

- Efficiency map of FTI transmission completed – February 2011
- Redesign of powertrain installed in Generation 1 vehicle – March 2011
- Project 1E.1 virtually variable displacement pump/motor installed as Pump/Motor “S” in Generation 1 vehicle – August 2011
- Controller demonstrated in Generation 2 vehicle – October 2011

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 4: Compact Rescue Robot

1. Statement of Project Goals

The goal of this test bed is to demonstrate a compact rescue robot, as an example of a portable, un-tethered human scale fluid power application. Current rescue robots are electric and can navigate and observe, but do not have the needed force or power to perform rescue operations. Our goal is to develop a mobile fluid-power robot that can operate for a reasonable length of time (2 hours minimum), navigate in difficult terrain (urban disaster site), produce a required force (500 lbs of lift) with precision control and resulting dexterity (sufficient to apply medical test and treatment devices) and transport a specified weight (250 lbs.).

2. Project Role in Support of Strategic Plan

The Compact Rescue Robot occupies the power range from 100W to 1KW in the Center’s efforts to apply to the full power range of applications. This range is poorly addressed by fluid power today due to several barriers, including a lack of compact power supplies, lack of miniature components and difficulty in tele-operation and control. Thus, this test bed focuses on all three thrust areas. Efficient operation is needed to achieve the operating time goal, compact is needed to achieve the mobility and weight goals, and effectiveness is need to be able to operate the robot remotely.

3. Project Description

A. Description and explanation of research approach

The existing applications at human scale are simple one degree-of-freedom devices and generally dependent on large external power supplies. Examples are log splitters and the “jaws of life” for extracting victims of accidents. While the technology is very successful and indicates the potential of fluid power, their applications are limited. Expansion to more degrees of freedom will require untethered power, miniaturized components and remote or autonomous operation. Addressing these issues in the context of fluid power requires an imaginative leap into devices with this collection of requirements. Rescue in disaster scenarios is the leap we have taken. Advances will be relevant to scenarios in the military, construction, agriculture, personal service and assistance to the handicapped and aged. The state of the art in rescue robots has been reviewed by NIST in its periodic examination published in the Rescue Robotics Handbook. All entries are electrically powered, although a few extremely heavy ones have hydraulic manipulators attached. Some have been exercised on a few disaster sites, but have not been capable of an actual rescue. The military (DARPA) is pursuing rescue on the battlefield (BEAR) robot and legged field transportation (Big Dog), both employing hydraulics. Neither would meet the demanding specifications for TB4.

TB4 resides on the top level of the three plane chart and will demand inputs from several projects to be successful. Possible new compact power supplies being developed under other CCEFP projects include a free piston engine compressor or pump and a hot gas vane motor. Safe and intuitive tele-operation will be accomplished through multi-modal haptic user interfaces. The current embodiment of TB4 uses a monopropellant producing 300 psi gas and is the only source of power in an appropriate package for compact, untethered operation at this time.

B. Achievements

TB4 has advanced most through the development of two separate platforms. At Vanderbilt, a four-legged crawler actuated by custom miniature high-pressure valves coupled with a Bimba cylinder and linear damper, has been designed and constructed (Figure 1). The robot is controlled via CANbus communication to local microcontrollers at the three joints on each leg. In the past year, the Vanderbilt hardware has been pre-programmed with several low-level gaits for motion across relatively predictable surfaces, including a crawl, a walk, and a trot. The Vanderbilt technology has been intended for use with hardware designed at Georgia Tech: An operator workstation that uses two Sensable Phantom™ haptic joysticks together with an A/V headset to provide feedback to the operator (Figure 2). The workstation maps the two joysticks to the four legs of the robot, granting the operator intuitive control of gait and manipulation motions. Georgia Tech has also developed a two-legged platform for manipulation testing and interim functionality. These platforms are interfaced using xPC Target real-time software.

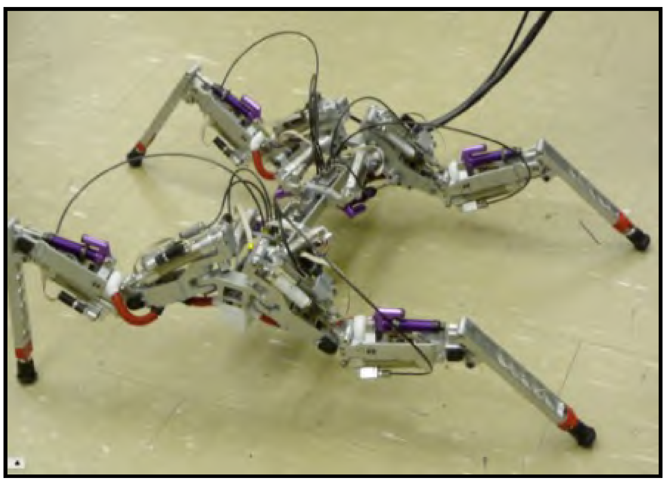


Figure 1: Four-legged crawler

Figure 2: Operator Workstation

<u>Quantifiable Performance Advantages</u>: A study, undertaken at Vanderbilt, used the mass and performance of the TB4 hardware in combination with properties of Center-developed power sources to point out the substantial improvements in energy efficiency that TB4 can bring to mobile human-scale platforms capable of significant manipulation. These studies, shown in Table 1, demonstrate that using fluid-power can greatly reduce the mass of the system, especially as higher and higher run-times are expected. This reduction in weight in turn allows the system to carry larger loads and last for longer periods of time on less energy, thereby validating many of the efforts of TB4 and associate CCEFP projects.

System	Run Time (hours)	Mass (kg)	Extra Mass (relative to lightest version)
Electric	3	21	10.9
IC Engine Hydraulic	3	23.1	13
HGVP Hydraulic	3	17.7	7.6
Free Piston Compressor	3	10.1	0
Electric	10	36.5	24
IC Engine Hydraulic	10	25.9	13.4
HGVP Hydraulic	10	25.2	12.7
Free Piston Compressor	10	12.5	0

Table 1: Quantitative Analysis of Rescue Robot Mass for Fluid Power and Electric (Battery) Energy Sources

Hardware Advances: In the past year, the Vanderbilt crawler has been completed, revised for functionality, documented, and brought to Georgia Tech. It had originally been developed in a non-real time environment, so changes were needed to ensure that the hardware functioned with the operator interface created at Georgia Tech. An undergraduate researcher, Michael Baker, successfully converted several programs developed by Keith Wait at Vanderbilt. Thus, several of the key components needed for control of the motions have been converted and work is ongoing to apply these to the pre-programmed gait software that had been developed at Vanderbilt.

Georgia Tech has also improved the two-legged test bed, which is used as simulation verification and as a platform for actuator control improvements. Whereas the four-legged test bed couples a damper with a cylinder to make control of the position control joints simpler on a mechanical level, the two-legged test bed employs pressure sensors and Bimba™ cylinders with position feedback. This allows testing of alternate control strategies, such as passive control. In the last year, substantial improvements have been made to this platform. Control was achieved via the operator workstation, using commands from the haptic joysticks to direct motion of the legs. Electronics were reconfigured for a cleaner, more effective, and robust design. The previous custom cylinders were replaced with new hardware, as noted above, actuated by Festo proportional directional valves. An undergraduate researcher, Michael Valente, redesigned the legs to accommodate the different, more compact cylinders. He also enhanced the range of motion of the platform, using increased stroke length and improved design to substantially increase the range of motion of the legs, making them more capable of the desired lifting and motion tasks that the test bed aims to provide. The revised design is also somewhat sleeker and lighter, yet maintains the kinematics used in all previous iterations of the robot (both at GT and at Vanderbilt). This revised design is currently in construction and is expected to be complete by the end of the calendar year.

In the future, the Georgia Tech revised design will be completed and implemented with the new cylinders and improved range of motion. This will be used to test control techniques targeted at precise movement of large loads by pneumatically actuated manipulators.
The Vanderbilt hardware will be completely integrated into the Georgia Tech platform, allowing usage of both the low-level, pre-programmed gaits and the semi-autonomous operator-guided gaits to control the robot. Control techniques similar to the ones used on the two-legged Georgia Tech test bed will be implemented here, too. The robot will also be further equipped with A/V feedback using a pan-and-tilt camera that moves together with operator motions of an associated headset, previously developed at Georgia Tech on the interim test bed.

Testing Environment: While the low-level gaits used on the four-legged crawler have been tested in several outdoor environments, a necessary component to proving the versatility of the designed hardware is the usage of standardized “challenging” terrains. Using NIST environments as a guide, a modular terrain block was created that can be configured to illustrate several difficult scenarios.

Future plans for this terrain include its use as a way of verifying the capabilities of the robot and simulation.

Advances in Simulation: Another key component of TB4 is the hardware simulation. The simulation was created in 2008/09, and uses an open source robotics library, courtesy of Seoul National University, known as SrLib. This library lets the user select from a variety of joints and links to create kinematic representations of the desired hardware. These are then placed in a simulated dynamic environment, where joints can be controlled either by actuated forces (representative of the actual hardware), or desired positions (representative of the ideal circumstance). This serves several key functions: First, it enables the testing of higher level control and operator interface features that would otherwise not be possible without a complete and functional robot, control scheme, and environment. Similarly, it allows design of the operator interface in parallel with robot design, which can be tested within the safe and efficient bounds of the simulation.

A third feature of simulation is the result primarily of advances throughout the past year: it provides a better understanding of joint dynamics and allows simulated testing of new control techniques. This is made possible by coupling the dynamic simulation of the robot with a low-level model of an actuator, consisting of the valve, cylinder, and associated controller. This model, which has been discussed in two papers published/accepted for publication this year, has been designed in Simulink and uses a simple proportional valve model, internal cylinder dynamics, and a friction model to generate a force output. The model has been verified within Simulink to show near equivalent position and pressure behavior as physical systems, using a simple test setup as a measurable comparison. These models have also been implemented together with the simulation, where they have demonstrated similar behavior and drawn conclusions on the effect of naturally occurring time delays in multi-platform simulations on the behavior of pneumatic models.

In the future, the dynamic actuator models will be applied to each of the joints and improved upon to ensure equivalence not only in single-platform simulations, but also when combining multiple software tools for a comprehensive dynamic simulation. The model developed here will be used as a basis for advanced controls approaches, starting with establish pneumatic control techniques such as sliding mode control and LQR-derived control. The simulation itself will continue to be used as a guide for interface design and operator control strategies.

Operator Interface and Robot Control: The final key component of the TB4 platform is the operator interface. This interface uses two Phantom haptic joysticks to control the legs of the robot, using a strategy known as the Follow-the-Leader gait to map the user to the robot for gait motions. This strategy allows the user to place the front legs, while to computer decides where to place the rear ones based on knowledge of variables such as stability, safe footholds, and desired direction. Several changes have been made in this interface in the past year. Haptic guidance has been enabled, granting the user a better sense of telepresence through feedback from the joysticks. The interface has also been redefined on a software level, using several modes of operation and internal state machines to provide clarity and ease of use to both the operator and the designer. Several new gaits were added, including haptically guided ones developed at Georgia Tech and the pre-programmed low level gaits provided by Vanderbilt.

The operator interface has also benefited from a higher level controller developed at GT that places a penalty on stability (with respect to balance, not actuator performance) of the robot and relates it back to the user in the form of haptic feedback. Thus, the user is guided to move in such a way that the stability of the robot is never compromised. This operator-in-the-loop controller results in more effective overall motion without impeding too heavily on the user’s level and sense of control.

Future plans for the operator interface are primarily focused on applying it to the four-legged crawler and ensuring complete functionality. This entails coupling higher level control approaches that related robot balance and user desired motion with lower level actuator motion control to ensure that the user is able to effectively guide the robot across difficult terrain, as well as move the legs to lift items when necessary.

Education and Outreach: TB4 has consistently provided an array of opportunities for impact and outreach, and continued to do so over the past year. Because of its interactive set of components, TB4 is ideally situated to provide hands-on demonstrations to audiences from a wide range of backgrounds. This past year, such demonstrations have been given to Atlanta city students visiting campus as part of National Robotics Week, FIRST students from across the country competing in the annual championship in downtown Atlanta, and visitors from a variety of other universities. Additionally, the robot was featured as an example of the future of fluid power at a teaching enhancement session for Atlanta area FIRST students on fluid power, organized in conjunction with Georgia Tech's RoboJackets organization.

TB4 has also supported several undergraduate researchers, as noted throughout the summary of achievements. This past summer, an REU, Allison Byrum, contributed towards control and dynamic modeling of the two-legged test bed. In the fall, REU Michael Baker and undergraduate researcher Michael Valente both worked on TB4, integrating the Vanderbilt model with the Georgia Tech system, constructing terrain obstacles, and designing and constructing a revised manipulator design for the two-legged platform working with the newly acquired Bimba cylinders.

Finally, work on TB4 has resulted in several papers on modeling, simulation, and interfaces of fluid-powered technologies, presented or accepted to be presented at conferences both within and outside the fluid power community.

In the future, TB4 will continue to provide compelling demonstrations that benefit from advances in fluid power research and natural appeal among varied audiences. Because of its broad range of components, it will keep serving as an optimal source of research experiences for undergraduates and graduates alike, and will continue to result in publications across the industry.

Upcoming Milestones: To recap, most of the efforts in the upcoming year are targeted at improved performance capabilities of the test bed and associated simulation. Combining such functionalities with fluid-powered energy sources being developed in the associated center projects would truly allow TB4 to showcase the advances it provides to mobile-human scale platforms.

These milestones, as defined by the most recently submitted TB4 proposal, include:

- Robust hardware and software platform for physical testing [January 2011]
- Installation of visual indicators to display state of robot [January 2011]
- Experimental Results regarding FTL effectiveness when combined with stability margins and haptic sensory substitution [March 2011]
- Case II (if alternative design to legged version is decided preferable by end of January) : Experimental results regarding effectiveness of sensory feedback and operator workstation in providing improved mobility and manipulative ability when combined with a fluid-powered system [April 2011]

  Paper submission [January 2011]
- Results: Validation of focus on haptics or proof of other more critical sensory modality [May 2011]
- Results regarding mobility and manipulative ability on medium difficulty terrain and with respect to isolated challenges [August 2011]
- Experimental results of improved user interface [March 2012]
- Paper Submission [April 2012]

C. Member company benefits

Festo, Bimba, and Enfield are the companies most closely related to TB4 in its present incarnation. Hydraulics component and fluid companies stand to gain from future advances. The end users and integrators for this power range of devices do not generally exist, but could include John Deere, Toro, Caterpillar and Bobcat.

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

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

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

3. Project 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 AFO. 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.

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.

B. Achievements

In 2010, we continued to advance our first generation portable, powered, ankle-foot orthosis (PPAFO). The Gen1 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. A U.S. patent application covering the technology embodied by the Gen1 PPAFO was filed. In the current reporting year, a description of the PPAFO system hardware, a characterization of system performance and preliminary results from both healthy and impaired walkers were formally detailed. Subject testing with two impaired individuals demonstrated the PPAFO's ability to provide functional assistance. These subjects were examined because their deficits span the space of impairments that the PPAFO is capable of assisting.

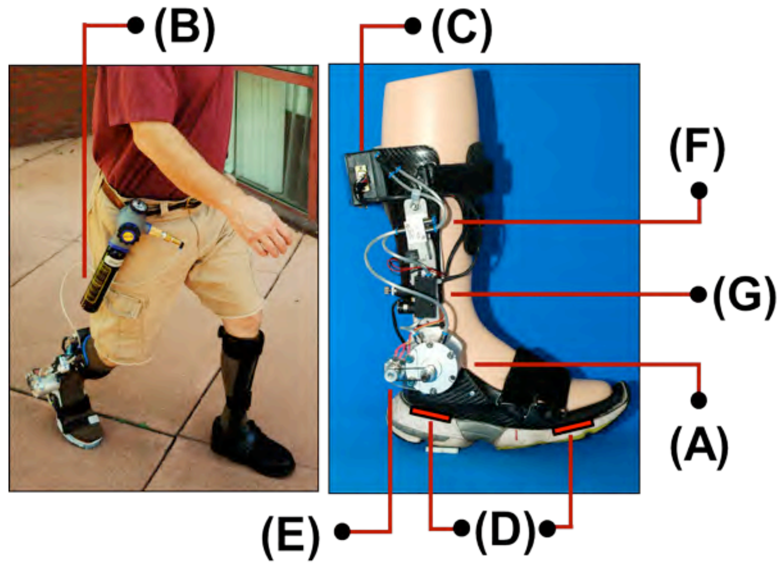


Figure 1: The Gen1 portable powered ankle foot orthosis (PPAFO) shown assisting an impaired walker (Left). The rotary actuator (A) is powered using a compressed CO_2 bottle (B) worn by the subject on the waist. Onboard electronics (C), force sensors (D), and an angle sensor (E) are used to control the solenoid valves (F). A second pressure regulator (G) is used to modulate the magnitude of the dorsiflexor assistance.

We analyzed the performance and the efficiency of the Gen1 PPAFO system. The initial low energy efficiency limited the performance of the Gen1 system. Currently, the can run continuously for about 40 min at 30 psig for both plantarflexor and dorsiflexor assistance, falling short of the more than 1 hr of use requirement. To analyze system efficiency, the problem was divided into two parts: component efficiency and operational efficiency. Component efficiency analysis identified energy loss due to the pressure drop across different components (e.g., line loss, valve loss) as well as backpressure. The operational efficiency analysis identified the energy loss due to how the system was used (e.g., currently energy is wasted when compressed gas is exhausted after an actuation cycle). An overall system efficiency of 19% was calculated from the product of the two efficiencies (component: 50% and operational: 39%). Solutions to improve the overall system efficiency have been proposed and will be investigated in 2011. These include recycling the compressed exhaust gas, eliminating system backpressure and improving the efficiency of the valving. Preliminary analysis indicates that the proposed solutions could raise overall system efficiency to 45%.

We also improved the control of the system. The control problem was divided into two parts: (1) the detection of the gait events during the cycle that determine AFO control objectives, and (2) the implementation of the control. To address the first part of the control problem, we proposed a new cross-correlation based algorithm to accurately estimate events during gait Gait event detection is essential to the control of the PPAFO because the timing of gait events (heel strike, foot flat and toe off) is used to determine the assistance required by the user. The Gen1 PPAFO uses embedded force sensors with thresholds to identify gait events, but this method lacks the desired accuracy and robustness for the system due to the use of pneumatic power. Experimental results from five healthy subjects walking with the PPAFO were used to verify the performance and highlight the advantages of the cross-correlation algorithm.

We addressed the second part of the control problem through model-based system analysis to facilitate improved control design. The model included the associated pneumatic components of the PPAFO (rotary actuator and valves), and a simplified rigid body model of the human leg (shank and foot). The model was used to evaluate the simulated performance of control schemes and hardware. The results from this work led to adding a proportional valve to the Gen1 system to addresses performance and efficiency limitations of the original binary valves.

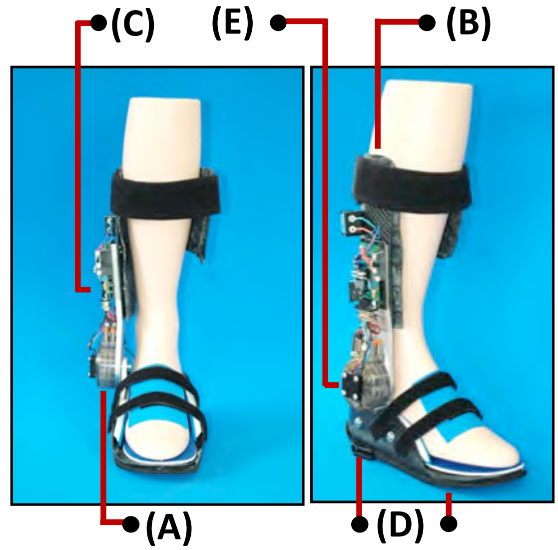


Figure 2: The Gen2 portable powered ankle foot orthosis. A new rotary actuator that was designed by MSOE students and faculty (A) has been integrated into the AFO structure (B) to greatly increase the compactness of the design. Improved onboard electronics (C), along with force sensors (D) and a more compact angle sensor (E) are used to control the solenoid valves that are now integrated into the actuator.

Work continued on developing the Gen2 PPAFO. Several CCEFP projects are contributing to the testbed to improve subsystem performance given target specifications. For the Gen2 design, work at MSOE (Project 2D) resulted in significant compactness and performance gains in the actuator and valve subsystem. The MSOE actuator was bench tested and integrated into the Gen2 PPAFO structure (Figure 2). The compactness of the new actuator was enhanced by integrating the valves, silencers, and sensors directly into the actuator housing and including the actuator directly into the structural subassembly. Additionally, center technologies are being used to address other subsystem limitations, including an integrated shell with vibration and noise abatement (Project 2D), a miniature HCCI air compressor power supply (Project 2B2), passive noise control (Project 3B1), improved human-machine interface (Project 3A3), and a new class of pneumatic MEMS valves to improve compactness (Project 2F).

Last year we identified high pressure hydraulics as a promising technology path for tiny fluid power systems suitable for applications such as the untethered AFO. During the past year theoretical analysis of tiny hydraulic systems was conducted to understand their limits. For example, to understand small-scale hydraulic cylinder efficiency, four configurations of including or omitting seals were analyzed. The key result is shown in Figure 3, which indicates that removing the piston seal improves cylinder efficiency if the clearance between piston and cylinder wall is small. The improvement becomes significant as cylinder bore becomes smaller.

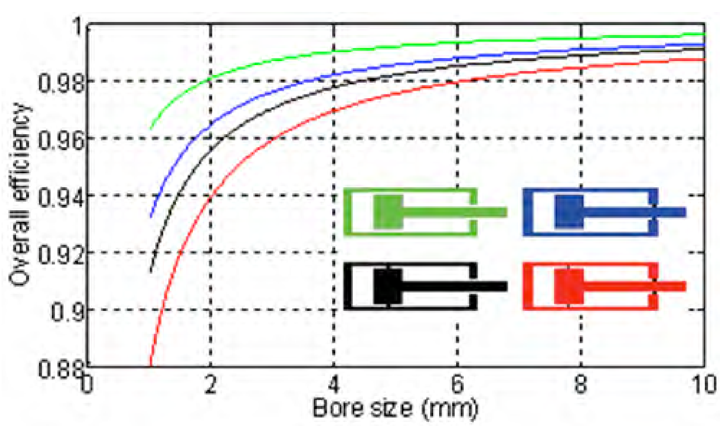


Figure 3: Cylinder efficiency versus bore size

A compact fluid power EHA 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. The Oildyne pump is the smallest commercially available pump and can output more than 300 Watts of power, more than required for the orthosis. For the custom system we are developing, the vane pump was selected because it is the most compact among all pump types for a given displacement. Preliminary analysis of vane pumps showed that a smaller rotor results in higher pump efficiency. The results also showed that high efficiency is theoretically achievable for small-scale pumps. We will continue this path with further analysis and prototype hardware next year.

During 2010, the TB6 team held a 2-day workshop to discuss systems engineering ideas and the SysML tool (MagicDraw). The workshop was led by Prof. Chris Paredis and his students from Georgia Tech. Participants were students and faculty from UIUC, UMN, and MSOE who work on projects affiliated with TB6. The workshop output included modeling the requirements and some system architectures for the PPAFO designs, which will be used to guide further PPAFO development.

Plans, Milestones and Deliverables for Next Year

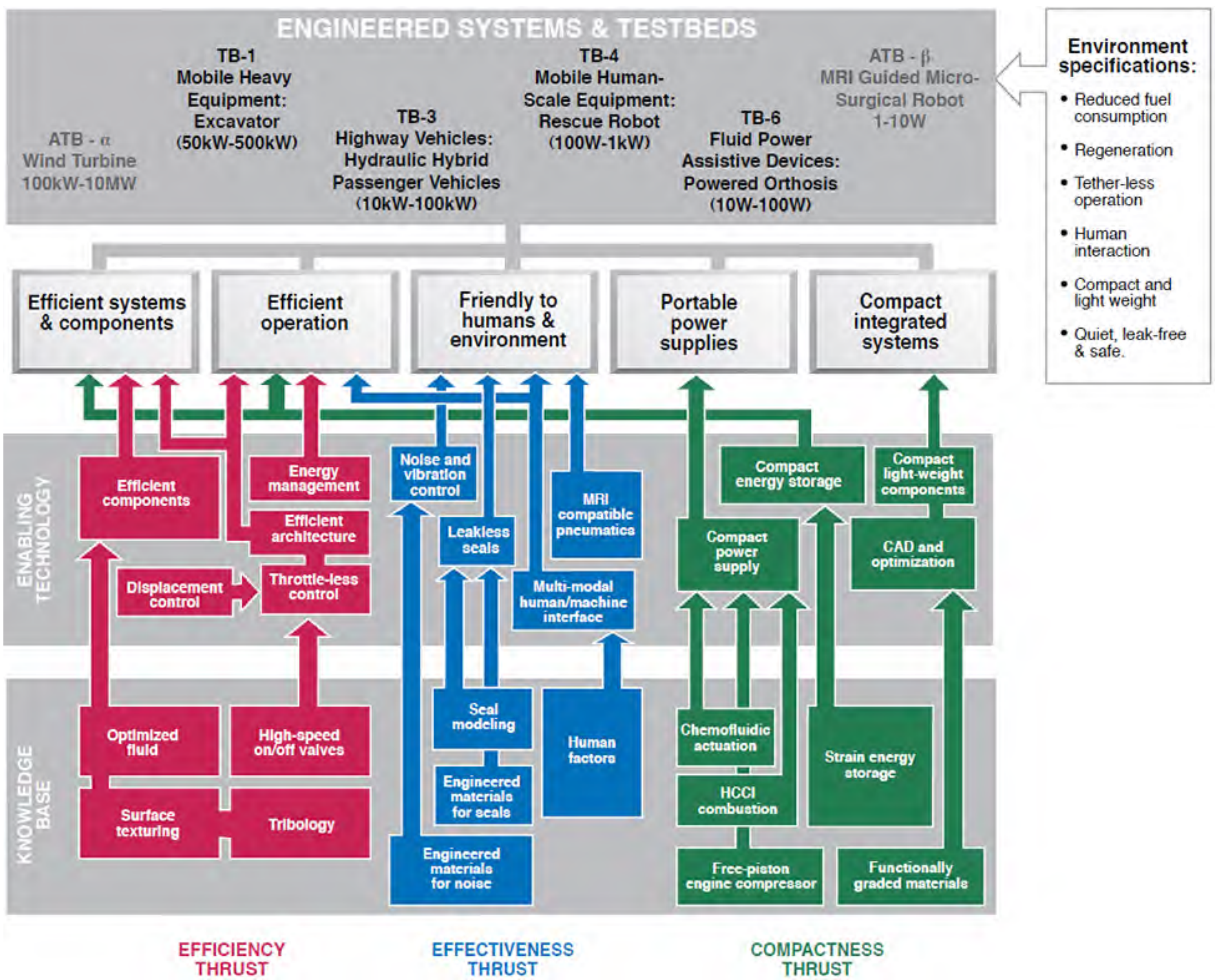
- Experimental validation of PPAFO system models (February 2011)
- Implementation of proposed efficiency improvements (March 2011)
- Integration of improved valve technology (proportional) with PPAFO Gen1 (March 2011)
- Construction and bench testing of custom, tiny hydraulic systems (Spring-Fall 2011)
- Gen 2 PPAFO subject testing (Summer-Fall 2011)
- Integration of HCCI engine prototype into the PPAFO (Summer 2011)
- Improved PPAFO control algorithms for different locomotion modes (standing, ramp walking, stairs) (Fall 2011)

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.

Three-Plane Research Chart

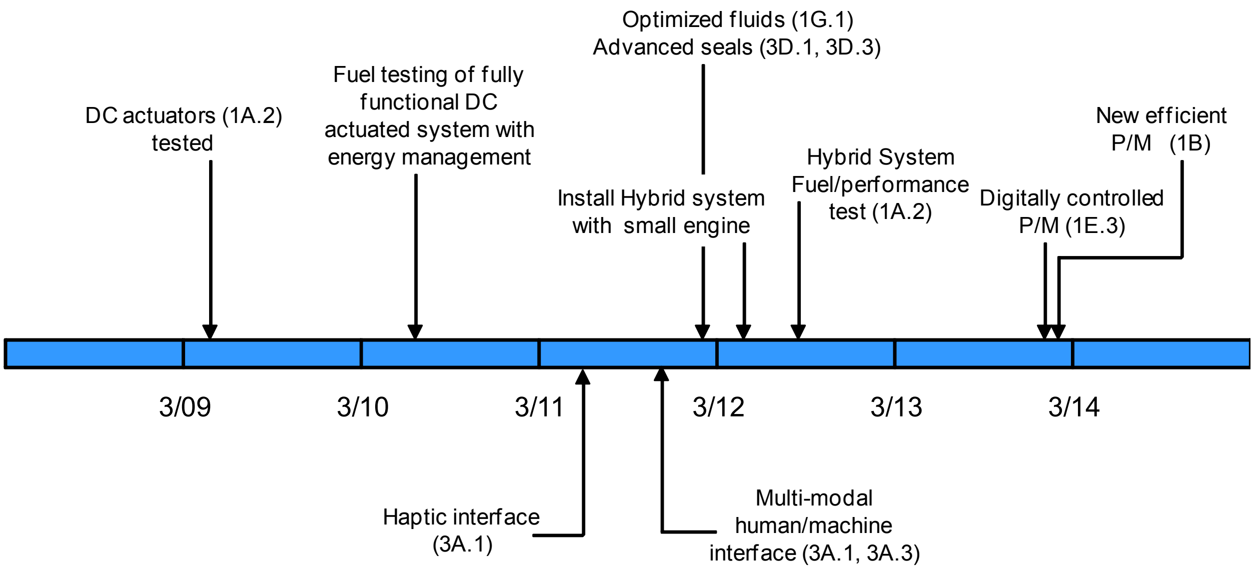
The three-plane chart of the CCEFP shown below has been modified over the past year to reflect changes in research strategy and research portfolio. Most significant of all, two associated test beds (ATB) (these are not funded by direct center funding) have been added. They are ATB-alpha: Wind Turbine at the University of Minnesota, and ATB-beta: MRI guided micro-surgical robot at Vanderbilt University. These reflect new applications of fluid power at the highest power level (100kW-10MW) and at the lowest level (1-10W). Other changes to the three-plane diagram include the elimination of the "open accumulator" in the compactness thrust as a strategy for energy storage for mobile applications, and the focus on "safety oriented control" and "cavitation and noise prediction" in the effectiveness thrust. Added to the effectiveness thrust is the focus to develop MRI compatible pneumatics to address the need of the new associated test bed.



CCEFP Three-Plane Research Chart

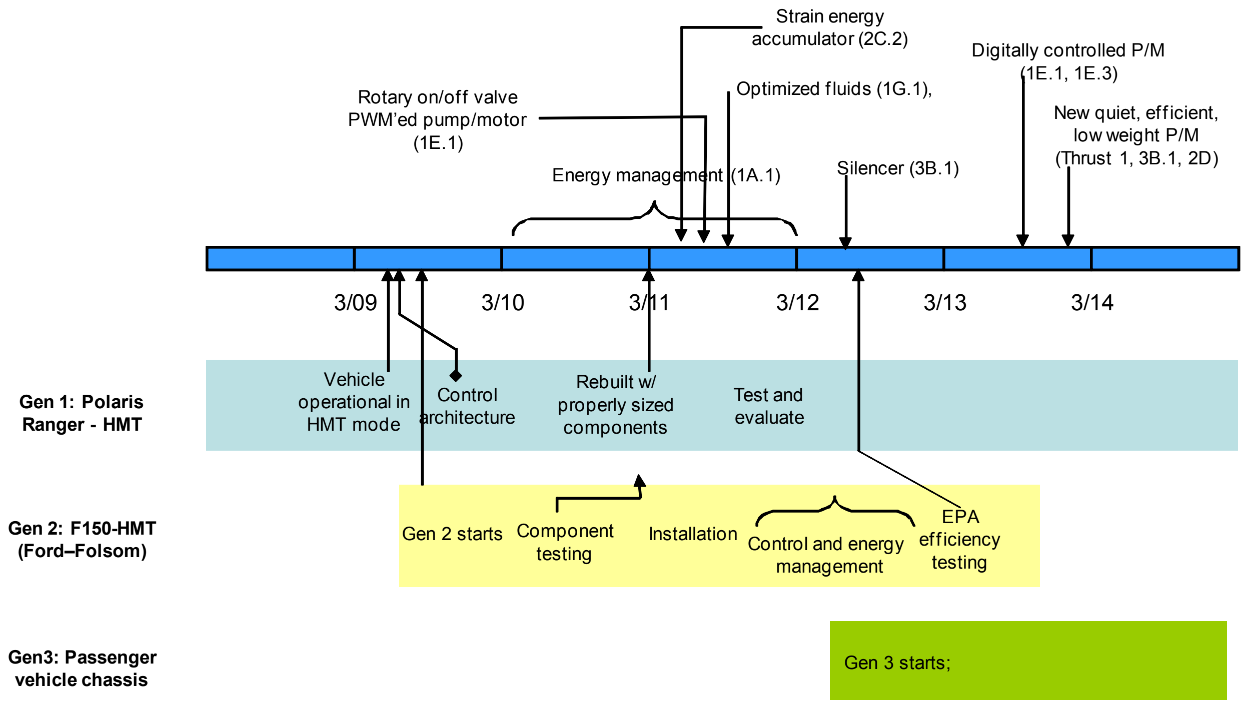
Each thrust is led by a senior faculty member from a different CCEFP core university. The thrust leaders have a seat on both the CCEFP Management Committee and the CCEFP Executive Committee where they participate in determining the strategic direction and allocation of Center resources.

Test Bed Future Milestone Charts
The milestone charts for each test bed are given below. These test beds realize the future engineered systems vision of the Center. The milestone charts have been simplified to highlight the most important system aspects of our research. Further details are available in the strategic action maps (SAMs), which have been placed in a password protected location on the Center's website (www.ccefp.org); the thrust milestone charts in section 2.2; and in the individual project summaries in Volume 2.



Test Bed 1 Future Milestone Chart

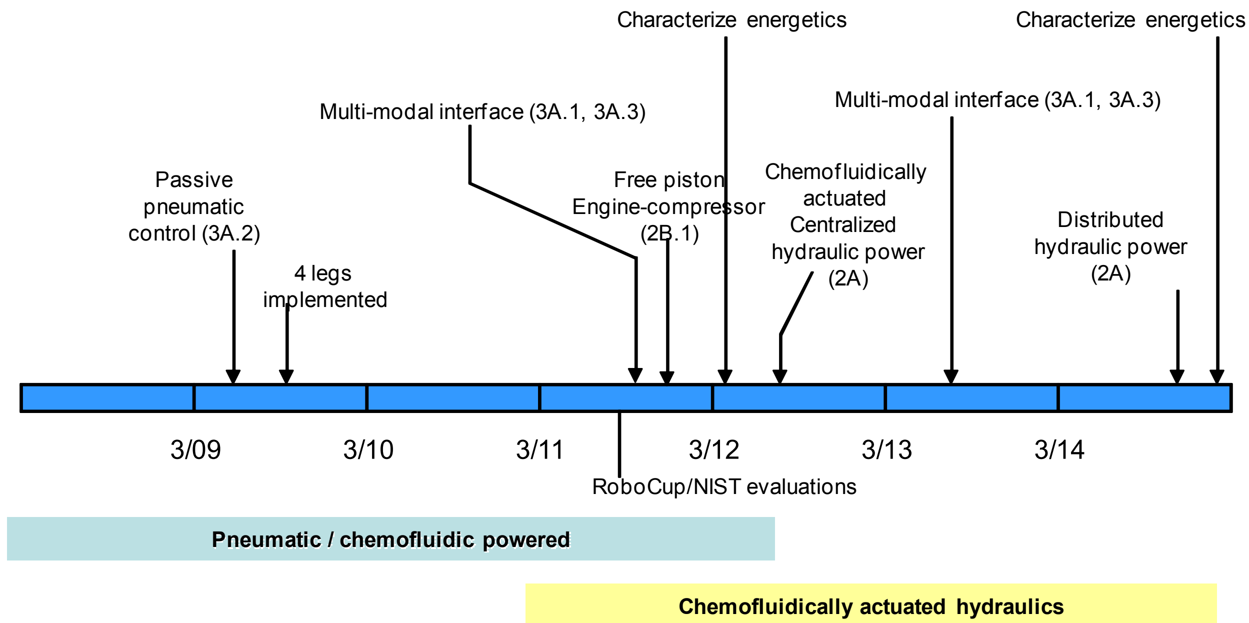
Test Bed 1: Heavy Mobile Equipment - Excavator
The time line for test bed 1 above indicates displacement control, energy management, new pump/motor design, and human machine interfaces being integrated and tested in various points in time. The next phase of test bed 1 will focus on an hybrid displacement control architecture that involves energy storage and engine downsizing for further fuel reduction. Haptic interface is targeted to be test on the test bed in Spring 2011.



Test Bed 3 Future Milestone Chart

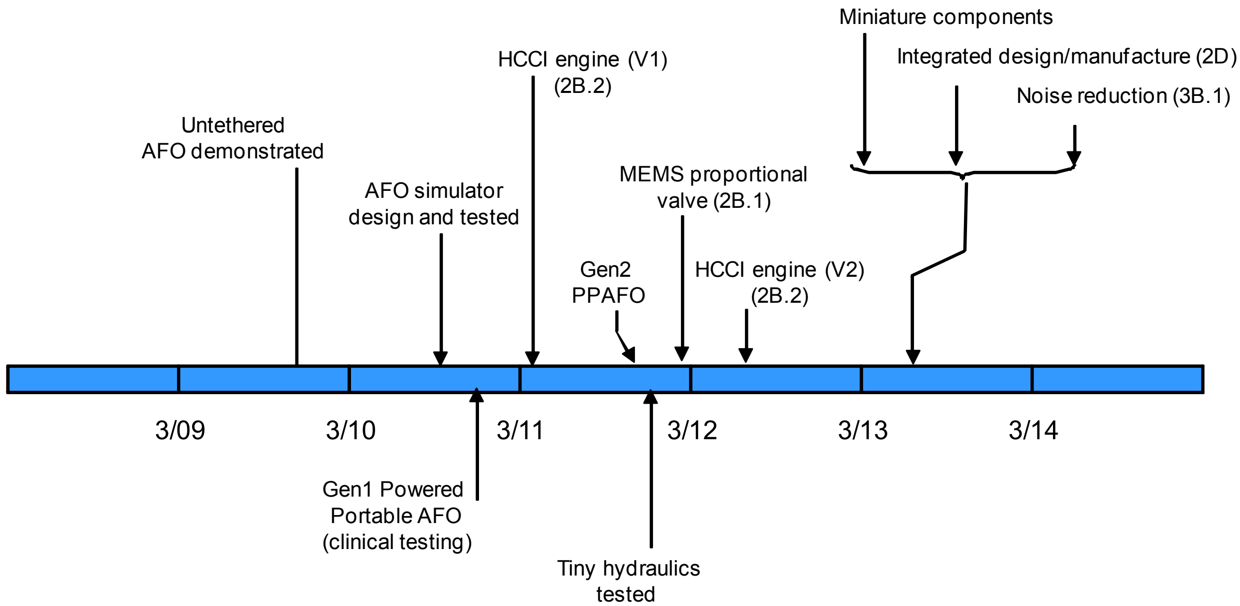
Test Bed 3: Hydraulic Hybrid Passenger Vehicle

The time line for test bed 3 above shows that the test bed is evolving from a focus on the Polaris Ranger utility vehicle chassis (Generation 1) to a Ford F150 pick-up truck chassis (Generation 2) and eventually to a passenger vehicle chassis (Generation 3). While the HMT architecture is planned for all three generations, they allow various levels of design freedom, ruggedness and space constraints. The generation 1 vehicle is currently functional but is also undergoing redesigned with more appropriately sized and efficient components. Analysis of Generation 2 vehicle is underway, and is expected to be available for experimentation later this year. It is expected to be functional and will undergo standardized efficiency testing in 2012. Integration of CCEFP research is continuing. Of note in the short term are a rotary on/off valve controlled pump/motor (1E.1) expected later this year 2011, various energy management approaches (1A.1), and more efficient fluids (1G.1). In the longer term, various new efficiency, quiet pump/motors (1E.3, 1B) are planned for integration in 2013.



Test Bed 4 Future Milestone Chart

Test Bed 4: Compact Rescue Robot
The time line for test bed 4 above shows that pneumatic (2B.1) and conventional chemofluidic hot gas actuation approaches are to be the first power supplies to be implemented on test bed 4. These are to be followed by the chemofluidic hydraulic power supply (2A) starting in 2012. Various human-machine interfaces are also being tested on this test bed (3A.1, 3A.2, 3A.3). The test bed will either enter the 2011 RoboCup or will be tested by NIST in 2011; and will undergo energetic characterizations for both the first generation and second generation power supplies.



Test Bed 6 Future Milestone Chart

Test Bed 6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)
The time line for test bed 6 is shown above. An untethered version of an assistive AFO was demonstrated in 2009, and first generation powered portable AFO (PPAFO) underwent clinical testing in 2010. The first prototype of the micro HCCI engine compressor (2B.2) and a "tiny hydraulics" system will be integrated and tested in Spring/summer 2011. The demonstration of a first MEMS proportional valve will take place in 2012. The development of structures that take loading, thermal effect and noise into consideration will take place in 2013 and beyond.

REU Program
The CCEFP summer REU program continues to involve undergraduate students in significant CCEFP research projects. REU participants are paired with a CCEFP faculty mentor who constructs a summer research project related to the CCEFP research of the faculty. Participants work on core, test bed or associated projects. Participants become members of the faculty's research group and interact with other graduate and undergraduate students working on the project. Participants attend the bi-weekly webcasts and, when possible in person at a center-wide event to connect with other projects. In 2010 this was the CCEFP annual meeting at Purdue, held in June. Participants complete a post-experience survey that probes the quality of their research experience. Twenty-three students participated in summer 2010. Among the participants, 31% were women and an additional 31% of students were of underrepresented racial minority status. The CCEFP continues to expand it recruiting database by identifying key institutions that focus on fluid power education or minority-servings institutions with an emphasis in STEM. The importance of undergraduate researchers to the success of the Center was solidified by the decision to require all research projects and test beds to hire at least one academic year undergraduate research assistant.

2.2 TRANSLATIONAL RESEARCH

A team of faculty and students from University of Minnesota, University of Virginia and Worcester Polytechnic Institute, together with industry partner Lightsail Energy, are investigating a novel compressed air energy storage approach for wind power. The research is funded by a four year grant from the NSF Emerging Frontiers in Research and Innovations Program (EFRI). This partnership is investigating components and systems designs and control strategies that enhance overall system efficiency and effectiveness.

The investigators of the research are: Perry Li (PI) and Terry Simon (Co-PI) at the University of Minnesota, Eric Loth at the University of Virginia, James Van de Ven at the Worcester Polytechnic Institute and Oakland CA based industry partner Lightsail Energy. The research proposes to develop a localized method for storing off-shore wind energy before conversion to electricity in high pressure compressed air vessels. In addition to allowing the storage of wind energy during periods of low demand, the concept will achieve load leveling so that components can be down-sized for average rather than peak power. The concept makes use of the comparative advantages of hydraulics and pneumatics in a so-called "Open Accumulator" architecture, and an isothermal air compressor/expander design. The interdisciplinary research involves fluid flow, heat transfer, machine design and systems and control.

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Table 2: Research Program Organization and Effort						
Cluster/Thrust	1: Efficiency	**Cluster/Thrust Leader**	Monika Ivantysnova			
Personnel: 10 Faculty Members, 5 Undergraduates, 21 Graduate Students, 1 Post Doc, 32 Other Personnel						
Project	**Leader**	**Investigators (name, department, academic institution)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current Award Year Budget**	**Proposed Award Year Budget**
Center-controlled Projects						
1A.1 Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems	Kim Stelson	Andrew Alleyne Mechanical Engineering University of Illinois at Urbana-Champaign Kim Stelson Mechanical Engineering University of Minnesota Monika Ivantysnova Agricultural and Biological Engineering Purdue Perry Li Mechanical Engineering University of Minnesota	Agricultural engineering, Mechanical engineering	U=0 G=2 P=1	$140,293	$140,293
1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=2 P=0	$94,557	$94,557
1B.1: New material combinations and surface shapes for the main tribological systems of piston machines	Monika Ivantysnova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=2 P=0	$92,558	$92,558
1B.2: Surface Effects on Motor Start-Up Friction	Ashlie Martini	Ashlie Martini Mechanical Engineering Purdue University John Lumkes Agricultural and Biological Engineering Purdue University	Agricultural engineering, Mechanical engineering	U=2 G=2 P=0	$90,227	$90,227
1D: Nano-texturing for Fluid Power Lines and Pumps	Prof. William King	William King Mechanical Engineering University of Illinois Urbana-Champaign	Mechanical engineering	U=1 G=1 P=0	$114,132	$114,132
1E.1: Helical Ring On/Off Valve Based 4-quadrant Virtually Variable Displacement Pump/Motor	Perry Li	Perry Li Mechanical Engineering University of Minnesota Thomas Chase Mechancial Engineering University of Minnesota	Mechanical engineering	U=0 G=3 P=0	$104,047	$104,047
1E.2: High Speed On/Off Valves to Enable Efficient and Effective Fluid Power Systems	John Lumkes	John Lumkes Agricultural and Biological Engineering Purdue University Monika Ivantysnova Agricultural and Biological Engineering Purdue Perry Li Mechanical Engineering University of Minnesota	Agricultural engineering, Mechanical engineering	U=1 G=2 P=0	$97,871	$97,871
1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	John Lumkes	John Lumkes Agricultural and Biological Engineering Purdue University Monika Ivantysnova Agricultural and Biological Engineering Purdue Perry Li Mechanical Engineering University of Minnesota	Agricultural engineering, Mechanical engineering	U=1 G=2 P=0	$82,119	$82,119
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	Perry Li	Thomas Chase Mechancial Engineering University of Minnesota	Mechanical engineering	U=0 G=3 P=0	$104,047	$104,047
1G.1: Tribofilm Structure and Chemistry in Hydraulic Motors	Paul Michael	Ashlie Martini Mechanical Engineering Purdue University Paul Michael Fluid Power Institute Milwaukee School of Engineering Scott Bair Mechanical Engineering Georgia Institute of Technology Thomas Wanke Fluid Power Institute Milwaukee School of Engineering	Mechanical engineering	U=3 G=2 P=0	$98,982	$98,982
1G.2: Nano-Additives to Improve Pumping Capacity	Eric Loth	Eric Loth Aerospace Engineering University of Illinois at Urbana-Champaign	Aerospace, aeronautical, astronautical engineering	U=0 G=1 P=1	$16,650	$0

				Subtotal	**$1,035,483**	**$1,018,833**
Sponsored Projects - None						
Associated Projects						
Advanced Energy Saving Hydraulic System Architecture	Monika Ivantysynova	Monika Ivantysynova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$77,972	$0
Advances in External Gear Machines Modeling	Andrea Vacca	Andrea Vacca Mechanical Engineering Purdue University	Mechanical engineering	U=0 G=0 P=0	$37,962	$0
Design, Simulation, and Control of Hydraulic System Topographies with Integrated Energy Recovery	John Lumkes	John Lumkes Agricultural and Biological Engineering Purdue University	Agricultural engineering	U=0 G=0 P=0	$47,331	$0
Development of Drive Train Control Concepts for Power Split Hybrid	Monika Ilvantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$73,432	$0
Displacement Controlled Actuator for Mobile Application	Monika Ilvantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$25,080	$0
Displacement Controlled Hex Productivity/Controllability study	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$49,666	$0
EFRI-RESTOR: Novel Compressed Air Approach for Off-shore Wind Energy Storage	Perry Li	Perry Li Mechanical Engineering University of Minnesota	Mechanical engineering	U=0 G=0 P=0	$333,001	$0
Fluid Efficiency	Paul Michael	Paul Michael Fluid Power Institute Milwaukee School of Engineering	Mechanical engineering	U=0 G=0 P=0	$61,938	$0
Hybrid Power Train for Special Truck Applications	Monika Ilvantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$60,625	$0
Hydrostatic Transmission for Wind Power Generation	Kim Stelson	Kim Stelson Mechanical Engineering University of Minnesota	Mechanical engineering	U=0 G=0 P=0	$0	$0
Mechanical Implementation of Waved Surface and Waved Piston Technologies.	Monika Ilvantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$37,576	$0
Modeling and Analysis of Swash Plate Type Axial Piston Pump Piston/Cylinder and Slipper/Swash Plate Interface	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$43,251	$0
Open accumulator compressed air storage concept for wind power	Perry Li	Perry Li Mechanical Engineering University of Minnesota	Mechanical engineering	U=0 G=0 P=0	$45,832	$0
Performance prediction and system control through coupled multi-domain models - a comparison study	Monika Ilvantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$54,967	$0
Prototype Design of a Hydraulic Hybrid Powertrain	Prototype Design of a Hydraulic Hybrid Powertrain	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$59,892	$0
SGER: Green Energy via Control-Based Design of Free-Piston Stirling Engines	Eric Barth	Eric Barth Mechanical Engineering Vanderbilt University	Mechanical engineering	U=0 G=0 P=0	$38,136	$0
Unrestricted Cash Donation 1	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$8,000	$0
Unrestricted Cash Donation 2	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$16,000	$0
Unrestricted Cash Donation 3	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$5,000	$0
Unrestricted Cash Donation 4	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$5,000	$0
Unrestricted Cash Donation 5	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$1,000	$0
Unrestricted Cash Donation 6	Monika Ivantysynova	Monika Ivantysnova Agricultural and Biological Engineering Purdue	Agricultural engineering	U=0 G=0 P=0	$8,000	$0
				Subtotal	**$1,089,661**	**$0**
Grand Total for 1: Efficiency					**$2,125,144**	**$1,018,833**

Cluster/Thrust	2: Compactness	**Cluster/Thrust Leader**	Andrew Alleyne			
Personnel: 19 Faculty Members, 20 Undergraduates, 17 Graduate Students, 0 Post Docs, 14 Other Personnel						
Project	**Leader**	**Investigators (name, department, academic institution)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current Award Year Budget**	**Proposed Award Year Budget**
Center-controlled Projects						
2A: Chemofluidic Hot Gas Vane Motor	Michael Goldfarb	Michael Goldfarb Mechanical Engineering Vanderbilt University	Mechanical engineering	U=0 G=1 P=0	$86,658	$86,658
2B.1: Free-Piston Engine Compressor	Eric Barth	Eric Barth Mechanical Engineering Vanderbilt University	Mechanical engineering	U=0 G=0 P=0	$73,581	$73,581
2B.2 Miniature HCCI Free-Piston Engine Compressor	David Kittleson	William Durfee Mechanical Engineering University of Minnesota	Mechanical engineering	U=1 G=1 P=0	$80,418	$80,418
2B.3: Free Piston Engine Hydraulic Pump	Zongxuan Sun	Zongxuan Sun Mechanical Engineering University of Minnesota	Mechanical engineering	U=1 G=2 P=0	$79,899	$79,899

2C.1: Compact Energy Storage - Open Accumulator Approach	Perry Li	Perry Li Mechanical Engineering University of Minnesota Terry Simon Mechanical Engineering University of Minnesota	Mechanical engineering	U=0 G=1 P=0	$16,650	$0
2C.2: Advanced Strain Energy Accumulator	Eric Barth	Eric Barth Mechanical Engineering Vanderbilt University	Mechanical engineering	U=1 G=1 P=0	$78,865	$78,865
2D: High Pressure, Light Weight Components Using Engineered Materials	Douglas Cook	James Mallmann Physics and Chemistry Milwaukee School of Engineering Subha Kumpaty Program Director MS Engineering Milwaukee School of Engineering Vito Gervasi Applied Technology Center Milwaukee School of Engineering	Engineering sciences, mechanics, physics, Mechanical engineering, Mechanical engineering-related technologies	U=5 G=3 P=0	$82,364	$82,364
2E: Model-Based Systems Engineering for Efficient Fluid Power	Chris Paredis	Chris Paredis Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=8 G=3 P=0	$70,459	$70,459
2F: MEMS Proportional Pneumatic Valve	Thomas Chase	Thomas Chase Mechancial Engineering University of Minnesota	Mechanical engineering	U=0 G=1 P=0	$71,232	$71,232
2G: Fluid Powered Surgery and Rehabilitation via Compact, Integrated Systems	Robert Webster III	Eric Barth Mechanical Engineering Vanderbilt University Jun Ueda Mechanical Engineering Georgia Institute of Technology Robert Webster III Mechanical Engineering Vanderbilt University Vito Gervasi Applied Technology Center Milwaukee School of Engineering Yuichi Kurita Mechanical Engineering NAIST, Japan, Visiting Scholar, Georgia Tech	Mechanical engineering	U=2 G=2 P=0	$126,998	$126,998
				Subtotal	**$767,124**	**$750,474**
Sponsored Projects - None						
Associated Projects						
Architectural Models for Fluid Power Systems	Chris Paredis	Chris Paredis Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=0 P=0	$48,252	$0
Control Based Design of Free Piston Stirling Engines	Eric Barth	Eric Barth Mechanical Engineering Vanderbilt University	Mechanical engineering	U=0 G=0 P=0	$11,100	$0
Energy Storing Orthosis	William Durfee	William Durfee Mechanical Engineering University of Minnesota	Mechanical engineering	U=0 G=0 P=0	$41,625	$0
Functionally Graded Metallic Lattice Components (FGMLC) for Advanced Propulsion Components	Vito Gervasi	Vito Gervasi Applied Technology Center Milwaukee School of Engineering	Mechanical engineering	U=0 G=0 P=0	$115,884	$0
MRI-R2: Development of a Precise and High Speed Hydrostatic Dynamometer System for Research and Education in Automotive Propulsion Systems	Zongxuan Sun	David Kittleson Mechanical Engineering University of Minnesota Kim Stelson Mechanical Engineering University of Minnesota	Mechanical engineering	U=0 G=0 P=0	$268,971	$0
Optimization Environment for the Architecting of Micro-grids in Ultra Low Energy Communities	Chris Paredis	Chris Paredis Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=0 P=0	$57,705	$0
Precision Pneumatic MRI Compatible Robotic Surgery	Eric Barth	Eric Barth Mechanical Engineering Vanderbilt University	Mechanical engineering	U=0 G=0 P=0	$36,630	$0
				Subtotal	**$580,167**	**$0**
Grand Total for 2: Compactness					**$1,347,291**	**$750,474**

Cluster/Thrust	3: Effectiveness	**Cluster/Thrust Leader**	Wayne Book			
Personnel: 15 Faculty Members, 11 Undergraduates, 16 Graduate Students, 0 Post Docs, 19 Other Personnel						
Project	**Leader**	**Investigators (name, department, academic institution)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current Award Year Budget**	**Proposed Award Year Budget**
Center-controlled Projects						

3A.1: Multimodal Human Machine Interfaces - The impact of operator interface on fuel efficiency	Wayne Book	Eui Park Industrial and Systems Engineering North Carolina Agricultural and Technical State University Perry Li Mechanical Engineering University of Minnesota Steven Jiang Mechanical Engineering North Carolina A&T Wayne Book Mechanical Engineering Georgia Institute of Technology Zongliang Jiang Industrial and Systems Engineering North Carolina Agricultural and Technical State University	Industrial engineering, Mechanical engineering	U=0 G=4 P=0	$91,464	$91,464
3A.2: Human/Machine Interaction via Passified Pneumatic and Chemo-fluidic control	Perry Li	Perry Li Mechanical Engineering University of Minnesota Wayne Book Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=1 P=0	$16,650	$0
3A.3: Human Performance Modeling and User Centered Design	Steven Jiang	Eui Park Industrial and Systems Engineering North Carolina Agricultural and Technical State University Zongliang Jiang Industrial and Systems Engineering North Carolina Agricultural and Technical State University	Industrial engineering	U=7 G=3 P=0	$112,478	$112,478
3B.1: Passive Noise Control in Fluid Power	Ken Cunafare	Ken Cunafare Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=3 G=2 P=0	$84,897	$84,897
3C: Simulations of Cavitation and Noise in Fluid Power	Steven Frankel	Steven Frankel Mechanical Engieering Purdue University	Mechanical engineering	U=0 G=1 P=0	$16,650	$0
3D.1: Leakage Reduction in Fluid Power Systems	Richard Salant	Richard Salant Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=3 P=0	$62,631	$62,631
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems	Scott Bair	Scott Bair Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=1 P=0	$71,928	$71,928
3D.3 Improved Seal Design Based on Adaptive Materials	Barney Klamecki	Barney Klamecki Mechanical Engineering University of Minnesota	Mechanical engineering	U=0 G=1 P=0	$16,650	$0
3E: User-Centered Human-Machine Interface for an Excavator	Silvanus Udoka	Eui Park Industrial and Systems Engineering North Carolina Agricultural and Technical State University Silvanus Udoka Industrial and Systems Engineering North Carolina Agricultural and Technical State University Steven Jiang Mechanical Engineering North Carolina A&T Wayne Book Mechanical Engineering Georgia Institute of Technology Zongliang Jiang Industrial and Systems Engineering North Carolina Agricultural and Technical State University	Industrial engineering, Mechanical engineering	U=1 G=1 P=0	$16,650	$0
				Subtotal	**$489,998**	**$423,398**
Sponsored Projects - None						
Associated Projects						
A Characterization of the Pressure-Viscosity Response of Two Fomblin Oils	Scott Bair	Scott Bair Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=0 P=0	$10,656	$0
Construction of a High-Pressure Viscometer	Scott Bair	Scott Bair Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=0 P=0	$57,726	$0
Construction of a High-Pressure Viscometer (2)	Scott Bair	Scott Bair Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=0 P=0	$45,288	$0
Development of an Experimental Pressurized Thin-Film Couette Viscometer and Consultation	Scott Bair	Scott Bair Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=0 P=0	$13,903	$0

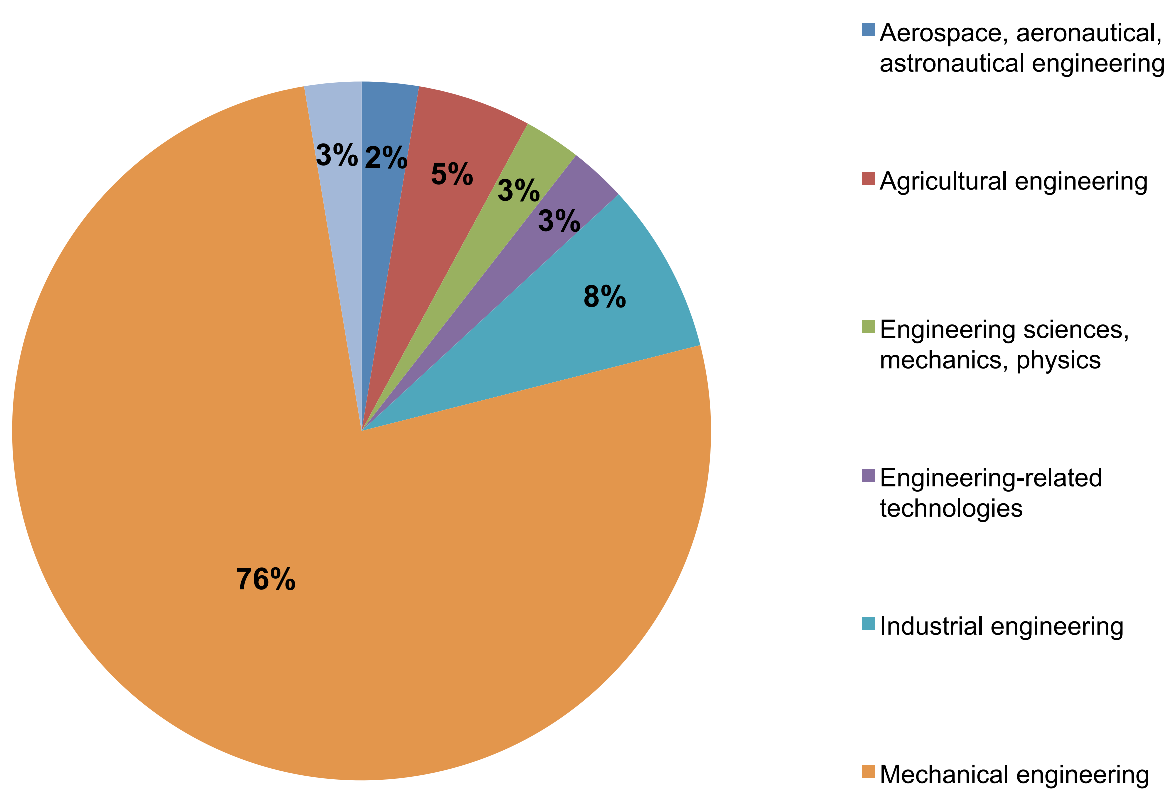
Project	Leader	Investigators (name, department, academic institution)	Disciplines Involved	Number of Students and Post Docs	Current Award Year Budget	Proposed Award Year Budget
Fluid Effectiveness	Paul Michael	Paul Michael Fluid Power Institute Milwaukee School of Engineering	Mechanical engineering	U=0 G=0 P=0	$42,624	$0
Shaft Pumping by Laser Structured Shafts with Rotary Lip Seals	Richard Salant	Richard Salant Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=0 P=0	$31,968	$0
Understanding and Reducing the Adverse Effects of Biodynamic Feedthrough	Wayne Book	Wayne Book Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=0 G=1 P=0	$13,320	$0
				Subtotal	**$215,485**	**$0**
Grand Total for 3: Effectiveness					**$705,483**	**$423,398**

Cluster/Thrust	Test Beds	**Cluster/Thrust Leader**	N/A			
Personnel: 13 Faculty Members, 5 Undergraduates, 19 Graduate Students, 0 Post Docs, 17 Other Personnel						
Project	**Leader**	**Investigators (name, department, academic institution)**	**Disciplines Involved**	**Number of Students and Post Docs**	**Current Award Year Budget**	**Proposed Award Year Budget**
Center-controlled Projects						
1: Mobile Heavy Equipment	Monika Ivantysnova	Andrew Alleyne Mechanical Engineering University of Illinois at Urbana-Champaign Kim Stelson Mechanical Engineering University of Minnesota Monika Ivantysnova Agricultural and Biological Engineering Purdue Paul Michael Fluid Power Institute Milwaukee School of Engineering Wayne Book Mechanical Engineering Georgia Institute of Technology	Agricultural engineering, Mechanical engineering	U=0 G=4 P=0	$87,152	$87,152
3: Hydraulic Hybrid Passenger Vehicle	Perry Li	Perry Li Mechanical Engineering University of Minnesota Thomas Chase Mechancial Engineering University of Minnesota	Mechanical engineering	U=0 G=7 P=0	$126,739	$126,739
4: Compact Rescue Robot	Wayne Book	Michael Goldfarb Mechanical Engineering Vanderbilt University Wayne Book Mechanical Engineering Georgia Institute of Technology	Mechanical engineering	U=3 G=2 P=0	$88,693	$88,693
6: Human Assist Devices (Fluid Powered Ankle-Foot-Orthoses)	Elizabeth Hsaio-Wecksler	Elizabeth Hsaio-Wecksler Mechanical Science and Engineering University of Illinois at Urbana-Champaign Geza Kogler Applied Physiology Georgia Institute of Technology Tim Bretl Mechanical Engineering SE University of Illionois William Durfee Mechanical Engineering University of Minnesota	Mechanical engineering, Engineering-related technologies	U=2 G=6 P=0	$133,137	$133,137
				Subtotal	**$435,721**	**$435,721**
Sponsored Projects - None						
Associated Projects - None						
Grand Total for Test Beds					**$435,721**	**$435,721**

Table 2: Research Program Organization and Effort Totals	**Current Award Year Budget**	**Proposed Award Year Budget**
Total, Center-controlled Projects	**$2,728,326**	**$2,628,426**
Total, Sponsored Projects	**$0**	**$0**
Total, Associated Projects	**$1,885,313**	**$0**
Grand Total, All Projects	**$4,613,639**	**$2,628,426**

LEGEND:
U - Number of Undergraduate Students
G - Number of Graduate Students
P - Number of Postdoctoral Fellows

Figure 2a: Research Project Investigators by Discipline



2.3 RESEARCH PROGRAM BY THRUST

EFFICIENCY

The Efficiency Thrust's focus is the first of the Center's transformational goals: Doubling fluid power efficiency in current applications and in new transportation applications. The technical barriers to achieving this goal include efficient component, efficient systems, and control and energy management. Thus, the projects range from improving fluids and components at the microstructure level, to innovative component design, to improving overall system functionality through the use of novel system architectures and control algorithms.

The table below summarizes the Thrust 1 projects and the barriers they address. Further project details can be found in the following pages and in Volume II.

Key

- Project carried over from Year 4
- New project in Year 5
- Graduated project (last funding in Year 4)

	Technical Barriers								
	Efficient Components	Efficient Systems	Control and Energy Management	Compact Power Supply	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet
Thrust 1: EFFICIENCY									
1A.1: Integrated Algorithms for Optimal Energy Use for Mobile Fluid Power Systems		•	•						
1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems	•	•	•						
1B.1: New material combinations and surface shapes for the main tribo-systems of piston	•								•
1B.2: Surface Effects on Start-up Friction	•								
1.D: Micro-Textured Low-Friction Surfaces	•								
1E.1: Helical Ring On/Off 4-quadrant Pump/Motor	•	•							
1E.2: High Speed On/Off Valves to Enable Efficient and Effective Fluid Power Systems	•	•							
1E.3: High Efficiency, High Bandwidth, Actively Controlled Variable Displacement Pump/Motor	•	•							
1E.4: Piston-by-piston control of pumps and motors using mechanical methods	•	•							
1G.1: Energy efficient fluids	•								
1G.2: Nano-Additives to Improve Pumping Capacity	•								

Efficiency Thrust Technical Barriers

1A.1: Integrated Algorithms for Optimal Energy Use for Mobile Fluid Power Systems
The goal of this project is to identify means of regulating power generation and distribution in mobile fluid power systems that maximize the overall system efficiency. From our previous work in the study of energy management strategies (EMS) we have concluded that there is no single strategy which is optimal for all applications. Therefore, we propose to develop a toolbox of EMS design methods and decision algorithms which will identify the best design method for a chosen application. The design methods we are currently focusing on are rule-based from deterministic dynamic programming, stochastic dynamic programming, and model predictive control. The decision algorithms will select the optimal design from the EMS toolbox based on a number of system attributes such as knowledge of duty cycle, ability to store energy, and problem constraints. In this way, we plan to improve the energy efficiency of mobile fluid power applications without any loss in their performance. The first CCEFP test bed targeted is the hydraulic hybrid passenger vehicle (TB3) where our goal is to demonstrate a 100% improvement in fuel economy over non-hybrid vehicles. Hardware-in-the-loop testing on an augmented earthmoving vehicle powertrain simulator at the University of Illinois will also be used to refine and validate models and demonstrate these methods can be used on a variety of fluid power systems.

1A.2: Multi-Actuator Hydraulic Hybrid Machine Systems
The goal of the original project 1A2 was to develop system architectures and control methods for optimal power management in multi-actuator mobile hydraulic machines using displacement-controlled linear and rotary actuators. These concepts reduce overall machine fuel consumption through use of displacement-controlled actuators by avoiding throttling losses, allowing energy recovery and using control methods to achieve effective machine power management. The goal is to demonstrate that at least 40% reduction of energy consumption for typical working cycles of multi-actuator machines compared to the state of the art of machines is achievable.

Achievements include productivity and fuel measurements of the completed displacement controlled hydraulic system on test bed 1, development of optimal power management algorithms for multi-actuator displacement controlled hydraulic systems and implementation of them on test bed 1, and a feasibility study for designing a hybrid DC hydraulic system for test bed 1 with a reduced engine size. In addition to the achievements described below, a number of publications have resulted from the work on Project 1A2.

1B1: New Material Combinations and Surface Shapes for the Main Tribo-systems of Piston Machines
The goal of this project is to discover the impact of novel material combinations and advanced surface shaping on the reduction of energy dissipation and the increase of load carrying ability of the lubricating gaps of axial piston machines. While studying the role of material properties in combination with gap micro geometry through a fully-coupled fluid-structure-thermal and multi-body dynamics simulation model for the piston cylinder interface a better understanding of the complex physical phenomena characterizing lubricating gaps performance will be generated and finally used to propose new design solutions. The proposed research team will also extend the new piston-cylinder model to the other two main interfaces of axial piston machines – the slipper/swash plate interface and he cylinder block valve plate interface. This will allow studying advanced material combinations and unique surface shapes for the main tribological systems of axial piston machines.

1B.2: Surface Effects on Motor Start-up Friction
A typical internal gear machine used to propel construction equipment must be significantly oversized. This is because the efficiency, while reasonably good during operation, is extremely low when the motor starts. This inefficiency is due to the high static friction between metal surfaces. A mathematical model was developed to estimate the static friction coefficient between two surfaces, which uses data taken from a white-light interferometer to characterize each surface. A test rig was developed and used to measure static friction under point, line and flat contact geometries to validate this model. This rig was used to measure the static friction at high loads with high precision, and used to compare various oils. It was found that static friction increases with viscosity at low loads, and decreases with viscosity at high loads. This is most probably the result of two competing mechanisms. One way to reduce the static friction is by texturing the surfaces in contact. Small dimples in the surface (~100 μm in diameter) have been shown to be effective in reducing friction in many cases. The model is being extended to calculate

the static friction between textured surfaces, and to predict ideal geometries for texturing. These surfaces will also be manufactured and tested on the static friction rig to further validate the approach of the model.

1.D: Micro-Textured Low-Friction Surfaces

Friction losses are one of the biggest impediments to energy efficient fluid power. It is well known that during lubricated sliding, microtextured surfaces have lower coefficient of friction than smooth surfaces of the same material. While this effect has been observed on small, laboratory-scale samples, very little work has been done on scaling up microtextured surfaces to sizes, shapes, and materials relevant for fluid power applications, owing to the cost and relative immaturity of the manufacturing technology. Even if the manufacturing technology were suitable for industrial application, there are no rigorous design rules for these textures that lead to optimum performance for various applications. This study aims at tackling these problems by developing design rules for low-friction sliding surfaces, such that microtexture geometry and shape can be optimally selected depending upon the fluid power operating conditions such as pressure, viscosity, velocity, and other parameters. Select geometries are selected for fabrication and testing using standard sliding friction tests. The overall goal is to produce low-cost micro-textured surfaces that can improve the efficiency of fluid power systems. This is a new project that started in August 2010.

1E.1: Helical Ring On/Off Valve Based 4-Quadrant Pump/Motor

Novel high-speed rotary on/off valves are being developed at CCEFP to address shortcomings in current valve technology that prevent the use of digital control techniques in hydraulic systems. Two valve architectures are being pursued. The first is a self-spinning spool valve that rotates by capturing momentum from the fluid stream. The second is a recently proposed design based on a ring control element that is intended to reduce valve losses at high pressure and frequency. Preliminary analysis indicates that the ring valve has the potential to reduce flow independent losses by approximately 40% in some applications. By pairing the on/off valve with a fixed displacement pump or motor, the effective displacement of the system can be varied by pulse-width-modulating the on/off valve. These virtually variable displacement pumps (VVDP) and pump/motors (VVDPM) have the potential to combine the compactness and cost effectiveness of valve control with the efficiency benefits of traditional variable displacement devices.

Current research is focused on designing a rotary valve controlled VVDPM for use as the wheel speeder pump/motor on a hydraulic hybrid passenger vehicle. The valve is optimized for the EPA Urban Dynamometer Driving Schedule. Results show that the requirement for varying shaft speed, intrinsic to this application, imposes too much constraint on the self-spinning valve (although self spinning was implemented successfully on a VVDP with fixed shaft speed). A 5%-17% improvement in VVDPM efficiency can be achieved by simply externally driving the valve. To realize external actuation, a prototype two-degree-of-freedom rotating and translating driving mechanism has been proposed and experimentally demonstrated. Additional research involves the application of VVDPs and VVDPMs to the control of linear actuators. Load sensing and direct displacement control of hydraulic actuators on a model backhoe have been simulated and demonstrated experimentally.

1E.2: High Speed On/Off Valves to Enable Efficient and Effective Fluid Power Systems

High-speed on/off valves are an important component in digital hydraulic systems. A simulation tool was created to accurately and quickly model the dynamic characteristics of a pilot operated, high speed on/off valve. The modeling technique used in this work couples the fluid domain and the mechanical domain of the valves into a seamless simulation. The developed model was used to investigate pressure drop across the valve, valve timing, and valve transition time in order to design and fabricate a working prototype. Initial experimental results of a prototype pilot operated, high speed on/off main stage valve are presented and compared to the developed valve model for validation.

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

This project involves the development of a hydraulic pump/motor that incorporates actively controlled high speed on/off valves connected to each cylinder to replace the valve plate. Unit displacement is electronically controlled by on/off valve timing, not by a swash plate or other typical means. Pump/motors of this design can have increased efficiency due to reduction of friction, leakage, and compressibility losses as well as increased displacement control bandwidth. The coupled dynamic model of the hydraulic pump/motor developed during this project is crucial to facilitate the development of the pump/motor. The simulation model is used to characterize and predict pump/motor efficiency, define the dynamic response and flow requirements of on/off valves required to provide significant improvements in efficiency and dynamic response over traditional pump/motors, and perform design optimization studies. Different operating strategies have been analyzed to characterize the effects on pump/motor efficiency and flow ripple (valve timing effects, partial fill methods, etc.). A single piston pump/motor test rig has been built for initial testing of valves and operating strategies. A multi-piston pump/motor unit will be built to experimentally validate the model, design, and operating strategies.

1E.4: Piston-by-piston control of pumps and motors using mechanical methods
Piston-by-piston control of pumps and motors is being investigated to improve their hydraulic efficiency, particularly at low displacements. The mechanism for actuating the active portion of the piston stroke and the valving strategies to facilitate piston-by-piston control are developed. The initial phase of the project focuses on customizing a check ball pump. This pump implements piston-by-piston displacement control mechanically using a single rotary valve for all pistons rather than utilizing two solenoid valves for each piston. In the second phase of the project, the concept will be extended to create a piston-by-piston controlled variable displacement pump/motor.

Current research is to build a Simulink piston-pump model including the operation losses and dynamic effects. The objective of this analysis is to demonstrate the feasibility of using piston-by-piston displacement variation for improving pump/motor efficiency. This feasibility is verified by showing that the mechanism of disabling pistons has an advantage over the current approach of varying the stroke length for reducing pump losses. The losses under investigation include: compressibility loss, transition loss in the disabling valve, piston friction, piston leakage, viscous pipe loss, and valve actuation power and leakage. Each loss model describes how the loss scales with the displacement. Preliminary analysis shows that some of these losses are intrinsic to the piston by piston approach, such as transition loss, viscous pipe loss, leakage and the power required to actuate the valves. The goal of this project is to show that a system can be designed in which these losses are less than the losses contributed by the valve plate and slipper/swash plate interface. In the next step, an experimental prototype based on a check-ball pump will be constructed and characterized.

1G.1: Energy Efficient Fluids
This project focuses on investigating the fluid properties that affect starting efficiency in hydraulic motors. Starting motor efficiency is an important design consideration because it often determines the pump horsepower and the minimum motor displacement in mobile hydraulic systems. Five hydraulic fluids have been tested and evaluated in a large-scale hydraulic dynamometer. The boundary friction, mixed-film lubrication, thermophysical, and pressure-viscosity properties of these prototype fluids have been characterized. These hydraulic fluids have been evaluated in geroler, axial piston, and radial piston motors under starting conditions in accordance with the ISO 4329-2 standard test method. Correlations between starting efficiency and fluid boundary friction, traction, thermophysical and pressure-viscosity coefficients have been identified. The results indicate that startability improves with decreasing boundary friction coefficient, decreasing pressure-viscosity coefficient, and increasing thermal conductivity. The relative impact of these fluid properties varied with motor design.

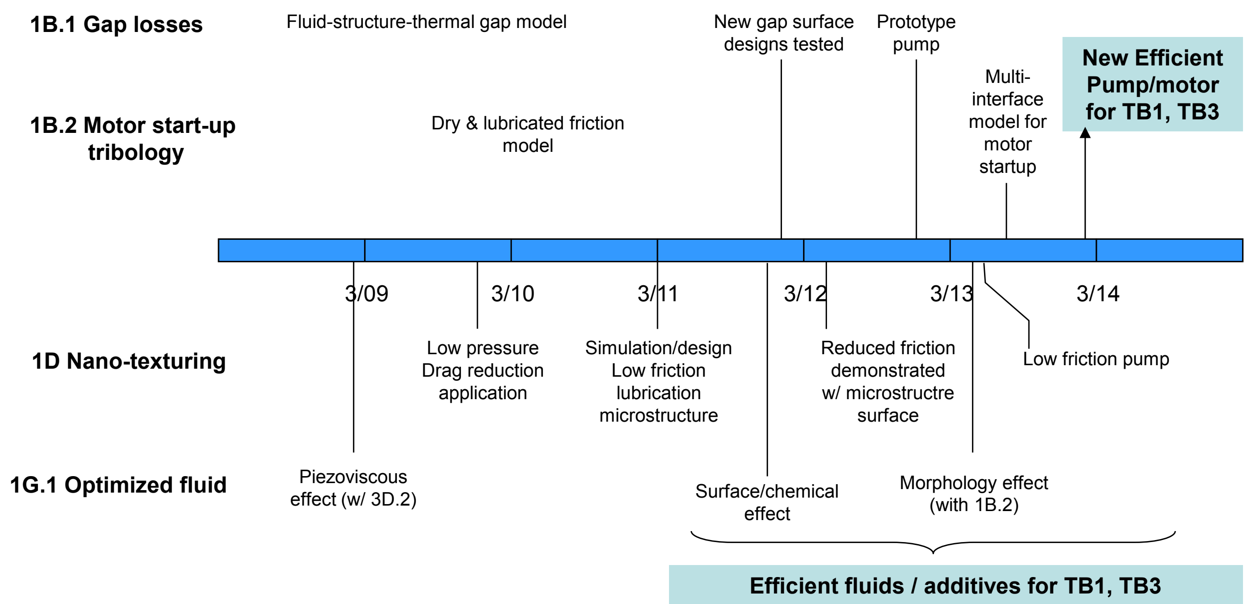
1G.2: Nano-Additives to Improve Pumping Capacity
The objective of the pump research with nanotexturing is to improve lubrication inside fluid power machinery using nano-textured coatings. This is motivated by the growing field of lubrication with nano-structured solid films. If this is successful, both fluid line and pump efficiency may be enhanced. An important and growing field of lubrication lies in the use of nano-structured solid films instead of oils or greases due to the films' superior mechanical properties and environmental benefits.

To investigate nano-additives, high-aspect ratio graphite and multi-wall carbon nanotube additives were added in small amounts (<<1% by volume) to ethanol. Pump efficiency measurements were conducted using a hydraulic loop driven by an external gear pump (1750 rpm). The discharge pressure was manipulated by adjusting the pump's internal relief valve and a needle valve installed downstream of the pump. Pressure rise, pump volumetric flow rate, and electric power were recorded and used to calculate overall efficiency. Some of the accomplishments made to date on the project include:

- We have shown that nanostructured carbon additives can increase volumetric efficiency without significantly increasing the viscosity of the working fluid.
- We observed that the additives deposited permanently on gear and enclosure surfaces creating low shear strength films which can help reduce friction.

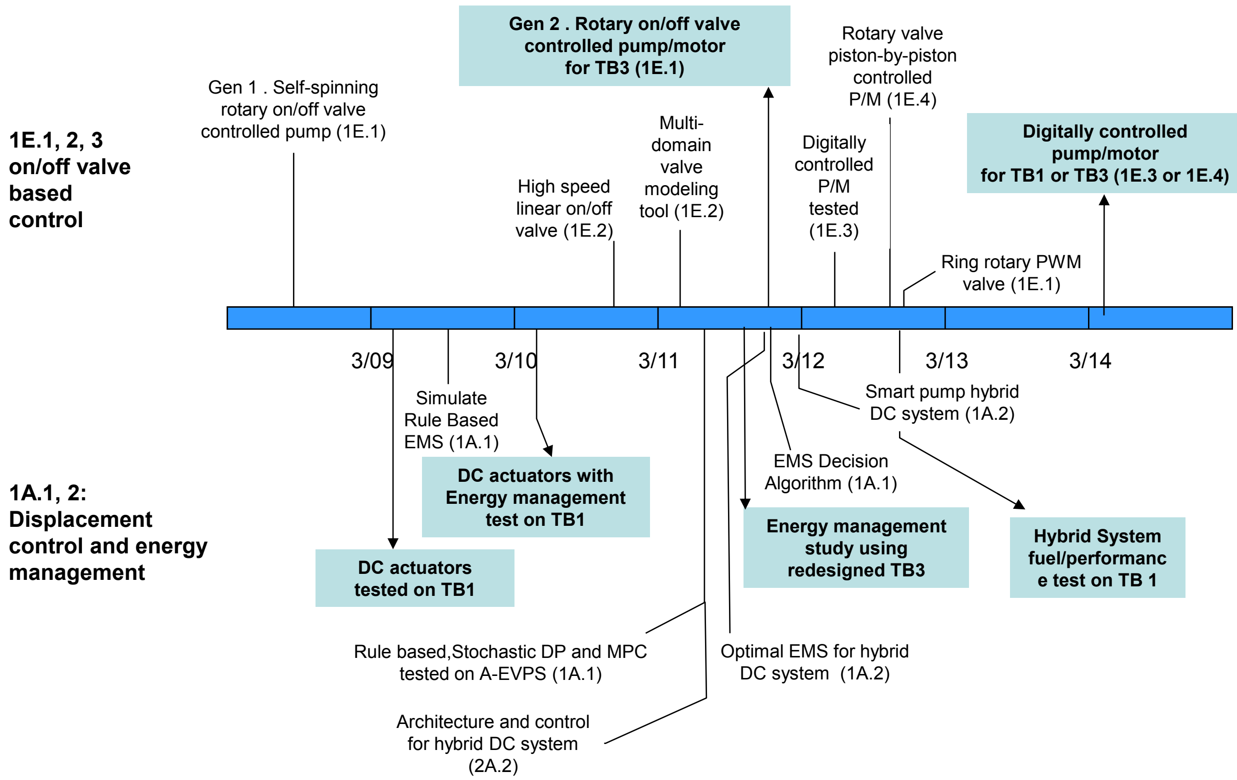
This project has graduated and is not receiving Center funding after Year 4.

Efficiency Thrust Milestone Charts



Efficiency Milestone Chart

Efficient components: The timeline for major activities to tackle the barrier of lack of efficiency component is shown above. In this and other time lines, colored boxes indicate integration and demonstration on a test bed. Current activities are focusing on studying the fundamental sciences of tribological gaps, effect of micro-structured surfaces on friction and fluid properties on lubrication. Results are being integrated into development and testing subcomponents, and ultimately into efficient pump/motors that utilize these principle and demonstrated on test beds.



Efficient Systems, Control and Energy Management Milestone Chart

Efficient systems, control and energy management: Timeline for major activities in the areas of efficient systems, control and energy management is shown above. In the area of on/off valve based control, new and improved digital valves of different designs are being pursued. They are also being applied in the development of efficient digitally controlled pump/motors.

In the area of displacement control of mutli-actuator systems, a non-hybridized version has recently been demonstrated on test bed 1 (excavator). Hybrid versions (i.e. with accumulator and reduced engine size) with even greater potential for fuel saving will be demonstrated in the 2nd five years of the center's existence.

Various high level energy management schemes are being developed for the test bed 3 (on-highway vehicle). They will be tested on the vehicle at various stages and refined starting from 2011.

Efficiency Thrust Publications

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

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COMPACTNESS

The Compactness Thrust is primarily focused on the Center's third major goal: Create portable, un-tethered human-scale fluid power applications. The CCEFP strategy identifies the technical barriers to achieving these goals. These are compact power supplies, compact energy storage, and compact integration. The table below summarizes the Thrust 2 projects and the barriers that they address. Further project details can be found in the following pages and in Volume II.

Key

- Project carried over from Year 4
- New project in Year 5
- Graduated project (last funding in Year 4)

	Technical Barriers								
	Efficient Components	**Efficient Systems**	**Control and Energy Management**	**Compact Power Supply**	**Compact Energy Storage**	**Compact Integration**	**Safe and Easy to Use**	**Leak-free**	**Quiet**
Thrust 2: COMPACTNESS									
2A: Chemo-fluidic Hot Gas Vane Motor				•					
2B.1: Free-Piston Engine Compressor				•					
2B.2: Miniature HCCI Free-Piston Engine-Compressor				•					
2B.3: Free Piston Engine Hydraulic Pump			•	•		•			
2C.1: Compact Energy Storage - Open Accumulator					•				
2C.2: Advanced Strain Energy Accumulator					•				
2D: Multi-Functional Fluid-Power Components Using Engineered Structures and Materials						•			
2E: Model-Based Systems Engineering for Efficient Fluid Power		•	•			•			
2F: MEMS Proportional Pneumatic Valve			•			•			
2G: Fluid-Powered Surgery and Rehabilitation via Compact, Integrated Systems			•			•			

Compactness Thrust Technical Barriers

Thrust 2: COMPACTNESS

2A: Chemo-fluidic Hot Gas Vane Motor
The goal of this project is to develop, demonstrate, and characterize the performance of a monopropellant-powered vane motor for use in high bandwidth actuation of a hydraulic pump. One of the objectives of the Center is to develop compact (i.e., human-scale) fluid powered systems. This project is targeted at providing a means of efficiently powering and controlling human-scale fluid-powered systems.

The project is focused on developing, fabricating, and testing the monopropellant-powered vane motor. Some of the accomplishments made to date on the project include:

- Several prototypes have been designed, fabricated, and tested. The most recent motor prototype was experimentally shown to provide a power density of approximately 800 W/kg which is roughly 5 times the power density of a brushless electric motor.
- Work to experimentally characterize the motor efficiency is currently underway.

2B.1: Free-Piston Engine Compressor
The goal of this project is to develop a compact high energy density pneumatic power supply applicable to untethered fluid-power applications. The device will be integrated into the Compact Rescue Crawler Test Bed by 2012. The project is closely aligned with the Center's compactness thrust. It will also contribute to the Center's goal of breaking the barrier of low energy density power sources for untethered devices.

The approach taken is to model, design, build and test a free-piston engine utilizing spark-ignited fuel that is specifically load matched to the task of compressing air. Some of the accomplishments made to date on the project include:

- Determined that exploiting the geometry of a liquid piston could create a high inertance, which advantageously slows the dynamics of the system without the penalty of adding more mass.
- An optimization of piston dynamics to achieve performance goals of the High Inertance Free Liquid Piston engine Compressor (HI-FLPC) was presented.
- An inertance-based dynamic model for the liquid piston was developed, validated, and incorporated into a system model of the HI-FLPC. Critical model parameters for components and subsystems of the model were experimentally characterized independently for use in the system model.

2B2: Miniature HCCI Free-Piston Engine Compressor
The objective of this project is to continue development a compact high efficiency air compressor providing 10 W of pneumatic power that can be used for the Test Bed 6 ankle foot orthosis (AFO) and for other applications needing a tiny fluid power supply. The power source is a free piston engine operating in a homogeneous charge compression ignition (HCCI) two-stroke cycle, integrated with a free-piston air compressor. This engine compressor package, coupled with a fuel tank, will provide much higher power density and energy density than a battery – electric motor package, thus enabling a more compact design and longer run time of tiny fluid power systems.

The approach for the development of the engine compressor is based on an integrated program of testing and modeling. The design of prototype engines is based on mathematical modeling which is supported by testing of components from a very small conventional engine, and testing of prototypes themselves. With the experimental results, appropriate models with fitted parameters can be chosen to better simulate the engine, which in turn will guide the design and optimization of further generations of prototypes. These optimizations will include improvements in compactness and efficiency as well as reductions in emissions, noise, and heat rejection.

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) 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. This

configuration has the potential to significantly increase the ICE and pump efficiency while increasing system modularity. Specifically, the ICE efficiency can be improved with the variable compression ratio, advanced combustion such as homogeneous charge compression ignition (HCCI) and less fiction due to the elimination of the crankshaft. The pump efficiency can be improved with reduced fiction and leakage due to a simpler design. Previous work on free piston engine has shown limited success mainly due to the complex dynamic interactions between the combustion and the fluid power in real-time. To address the challenge, we propose to investigate the two fundamental technical barriers of the free piston engine driven hydraulic pump. They are the seamless coordination of the combustion and the fluid power and the design optimization of the system. To support the proposed research, our industrial partner Ford Motor Company has donated a free piston engine driven hydraulic pump to the University of Minnesota. A dynamic model for the system that includes HCCI combustion, two zone scavenging, the hydraulic dynamics and the piston dynamics has been built. We have also investigated control strategy for regulating load control, compression ratio control and combustion phasing control. The model has been tested exclusively for different operating conditions. Observations from the dynamic model will help develop advanced controls.

2C.1: Compact Energy Storage - Open Accumulator
The goal of this project is to increase the fluid power energy storage density by an order of magnitude. The potential and feasibility of a novel "open accumulator" approach, as well as solutions to its technical barriers are investigated. This project primarily focuses on the Center's goal of compact energy storage. Lack of compact energy storage is preventing regeneration and hydraulic hybrid technology from being deployed in compact applications, such as hydraulic hybrid passenger vehicles, where energy densities of existing hydraulic accumulators are 100 times lower than those of electric batteries.

In the proposed open accumulator approach, the compressed gas used for energy storage is exhausted to the atmosphere during expansion, and intake is also taken from the atmosphere during compression. This results in a much higher expansion ratio (350 at 35 MPa), and the available energy from the compressed gas with the same volume is increased by 6.5 times over conventional closed accumulators. Some of the accomplishments made to date on the project include:

- We have refined our understanding of the optimal compression/expansion profiles.
- We have modified the liquid piston compressor/expander of the 3rd experimental prototype system to study methods for improving heat transfer.

The research on this project has shifted from an energy storage device for on-highway hydraulic hybrid vehicles to an energy storage device capable of storing energy at the utility sale (MW-hr). Thus, this project has graduated and is not receiving Center funding after Year 4 (May 2010). However, it is continuing as an affiliated project.

2C.2: Advanced Strain Energy Accumulator
The objective of this project is to extend the current state of knowledge in the use of strain energy storing materials in the design of compact energy storage devices. Specifically, this project seeks a low cost, low/no maintenance, high energy density accumulator primarily targeted toward a fluid powered automotive drivetrain and/or regenerative braking system (hydraulic hybrid). This project will contribute to the Center's goal of breaking the barrier of a lack of compact energy storage. The task of designing new compact energy storage devices is central to the Center's vision of "significantly reducing energy consumption" by "enabling the migration of fluid power to passenger cars".

This project will investigate, design and experimentally implement a compact energy storage accumulator via strain energy in materials not traditionally utilized in existing accumulators. A control strategy and control laws for regulating power flow will be formulated and implemented. Some of the accomplishments made to date on the project include:

- An snalysis of the worst case scenario (the charging and discharging phases of the accumulator occur on time scales at least an order of magnitude faster than the holding times) reveals that conventional gas charged accumulators demonstrate a measured efficiency close to that described by the worst-case scenario.

- A geometry was found that could achieve arbitrarily higher hydraulic pressures than maximum material stresses.

2D: Multi-Functional Fluid-Power Components Using Engineered Structures and Materials
Despite the high theoretical volumetric and gravimetric energy/power densities of fluid-power, its penetration in the competitiveness/market is significantly hindered by the lack of efficient commercial components and the levels of noise generated. Heat must be effectively removed from the components and working fluid to maintain maximum efficiency throughout the operation period, and shielded from end users to prevent injury. Excessive noise levels prevent the use of fluid-power components and devices in personal assistive devices or passenger vehicles due to the resulting discomfort of the user. Add-on components or systems to mitigate these issues increase mass and volume of the system, hindering performance of mobile systems. Additionally, traditional design-for-manufacturability constraints result in "dead weight." The challenges are then thermal and noise management, while also considering total mass and size. Mass minimization has been addressed in the first four years through; structural optimization, unit-lattice structural characterizations, and the preliminary development of stress-field-directed, structure-generation algorithms. The use of multi-functional cellular structures to include thermal and noise management into the design of fluid-power components is being addressed in Years 5&6 of the CCEFP. These multi-functional structures will be demonstrated on the active-orthosis (TB6), and in the design of pump components, that can later be implemented in other test beds. Through additive-manufacturing methods, engineered materials can be designed and fabricated that couple all of these functions, to specified degrees of optimality, into the component designs.

2E: Model-Based Systems Engineering for Efficient Fluid Power
As modern fluid power systems become increasingly complex and diverse, there is a growing need to use formal systems engineering processes for the design of such systems. We introduce a model-based systems engineering (MBSE) approach for the development of efficient fluid power systems. In this approach, the systems engineering process is supported with a variety of formal models, through which the team of experts involved in the process can express and share knowledge precisely, succinctly and unambiguously. These models are stored in model libraries using the Systems Modeling Language (OMG SysML). They span a broad range of perspectives including descriptive models of fluid power components, corresponding functional representations, cost analysis models, reliability and physics-based behavioral models.

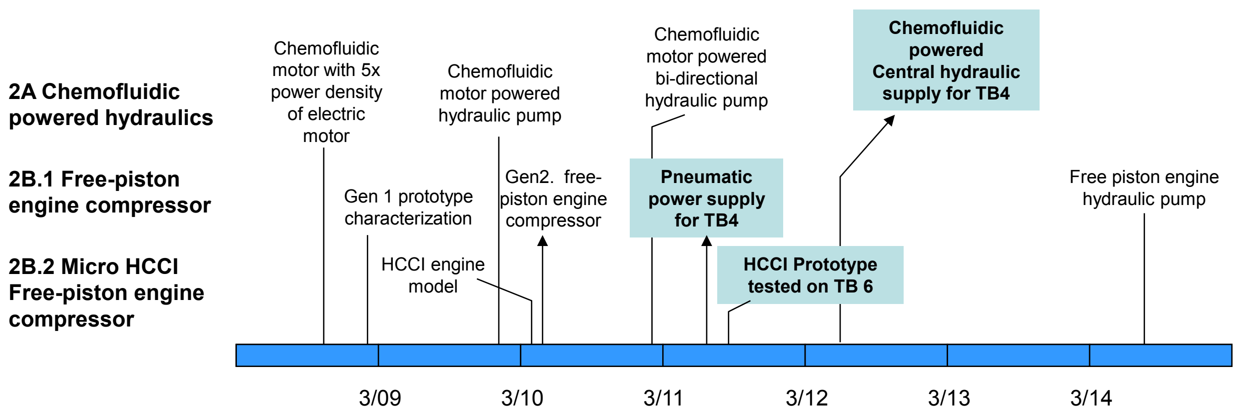
During the design process, these models are used to verify design alternatives with respect to design requirements. To enable the exploration of a broad range of different find power circuit topologies, the analysis process is automated through the use of model transformations. The starting point for the model transformations is a set of formal models expressing the structure of a candidate fluid power system architecture, the system requirements, and experiments to verify the requirements. To facilitate comparison between design alternatives, the experiment and requirement models are expressed independently from the structure models. To translate descriptive models of system alternatives then into a set of corresponding analysis models, a model transformation approach is used that converts the descriptive system architecture into a set of corresponding analysis models through a composition operation. This set of analysis models is subsequently transformed into executable simulations, which are used to guide the search for suitable system alternatives. To facilitate performing this search using commercially available optimization tools, the analyses are represented using the General Algebraic Modeling System (GAMS). By relying on automated model transformations, the effort required to create and simulate analysis models is significantly reduced.

2F: MEMS Proportional Pneumatic Valve
The goal of this project is to create an efficient miniature proportional valve for controlling air flow in pneumatic systems based on Micro-Electrical Mechanical Systems (MEMS) technology. The valve is intended to operate at pressures up to 7 bar (700 kPa / 100 psi) with a pressure drop of no more than 1 bar (100 kPA / 14.5 psi) when operated at a flow rate of 40 slpm in the fully open state. Actuation efficiency is equally important to fluidic efficiency: the goal is to be able to hold a normally closed valve in the fully open state with an actuation power of 1 Watt or less. The target envelope of the valve is 1 cm^3.

Currently available microvalves can only deliver flow rate on the scale of milliliters per minute. The new valve will be able to provide macro scale flow rate while maintaining compactness, efficiency and low leakage. This will be achieved by a unique parallel architecture supported by design models that can correctly predict the actuator behavior and fluid flow phenomena. While the valve will be a generic proportional valve for pneumatic applications, its first use will be for the Ankle-Foot Orthosis Project (Test Bed 6 of CCEFP).

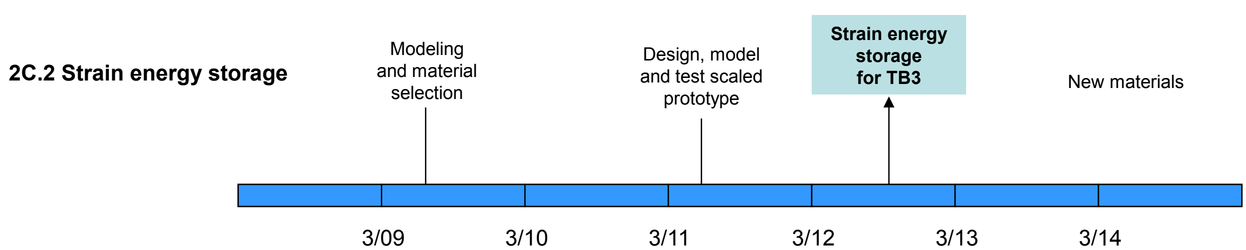
2G: Fluid-Powered Surgery & Rehabilitation via Compact, Integrated Systems
Magnetic resonance imaging is one of the most useful methods available to study neuroscience, evaluate rehabilitation therapies, and perform image-guided interventions and surgeries. Functional MRI (fMRI) is a new technique that can observe the brain structure activities by measuring blood flow in a certain area such as motor cortex. The goal is to build a fully MRI compatible sensor that is compact and highly accurate for a fluid-powered haptic interface. Fiber optic extrinsic sensor technologies are considered to be suitable for this project. We designed a displacement amplification mechanism (DACM) which is compact and convenient for sensing tasks in a limited volume. The design of the unit has been improved by a series of finite element simulations.

Compactness Thrust Milestone Charts



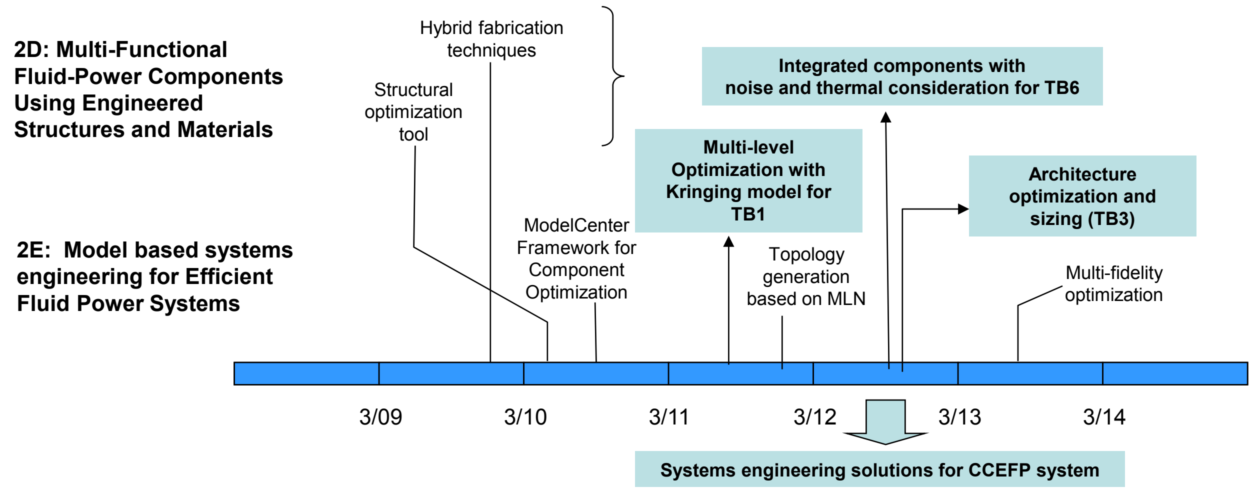
Compact Power Supply Milestone Chart

Compact power supply: Two potential power supply concepts targeted for test bed 4 (rescue robot): chemofluidic hydraulic pump (2A) and a free-piston engine compressor (2B.1) are planned for integration with test beds in the 2011-2012 timeframe. The HCCI micro-free piston engine compressor (2B.2) is targeted for test bed 6 (assistive orthosis) and testing of the first generation engine is planned for Spring/Summer of 2011.



Compact Energy Storage Milestone Chart

Compact energy storage: The strain energy accumulator approach (2C.2) is being pursued by the CCEFP to significantly increase energy storage density. It has the potential of increasing energy density by 2-3 times and appears to be quite simple to implement and maintain. This project is undergoing various design phases and is planned to be tested on test bed 3 (on-highway vehicle) in 2012.



Compact Integration Milestone Chart

Compact integration: Research on engineered structures and materials for multi-functional fluid power components (2D) are bearing fruit in the area of compact integration and are being utilized in development of components for test bed 6. Of note is the integrated structure that is optimized for load, thermal and NVH to be implemented in test bed 6 in 2013.

Development of tools and methodology the use of systems engineering to fluid power systems are being carried out in Project (2E). These tools are increasing in complexity to handle more realistic design questions. As the tools are being developed, they are also being applied to the test bed designs.

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EFFECTIVENESS

The Effectiveness Thrust is focused on the Center's fourth major goal: ubiquity. The means for achieving this goal are to make fluid power safe, quiet, clean and easy to use so that it can be used anywhere. The CCEFP strategy identifies the technical barriers to achieving these goals. These are safe and easy to use, quiet and leak-free operation. The table below summarizes the Thrust 3 projects and the barriers they address. Further project details can be found in the following pages and in Volume II.

Key

(white)	Project carried over from Year 4
(green)	New project in Year 5
(light blue)	Graduated project (last funding in Year 4)

	Technical Barriers								
	Efficient Components	Efficient Systems	Control and Energy Management	Compact Power Supply	Compact Energy Storage	Compact Integration	Safe and Easy to Use	Leak-free	Quiet
Thrust 3: EFFECTIVENESS									
3A.1: Multimodal Human-Machine Interfaces							•		
3A.2: Passive pneumatic and chemo-fluidic actuators							•		
3A.3: Human-machine interface design for fluid power systems							•		
3B.1: Passive Noise Control in Fluid Power									•
3C: Computational and experimental studies of cavitating hydraulic flows	•								•
3D.1: Leakage reduction in FP systems								•	
3D.2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems						•			
3D.3: Improved Seal Design Based on Adaptive Materials								•	
3E: User-Center Human-Machine Interface for an Excavator							•		

Effectiveness Thrust Technical Barriers

Thrust 3: EFFECTIVENESS

Project 3A1: Multimodal Human-Machine Interfaces
In some operator-controlled machines, motion of the controlled machine excites motion of the human operator, which is fed back into the control device, causing unwanted input and sometimes instability; this phenomenon is termed biodynamic feedthrough. In operation of backhoes and excavators, biodynamic feedthrough causes control performance degradation. This work utilizes a previously developed advanced backhoe user interface which uses coordinated position control with haptic feedback, using a SensAble Omni six degree-of-freedom haptic display device. Backhoe user interface designers and our own experiments indicate that biodynamic feedthrough produces undesirable oscillations in output with conventionally controlled backhoes and excavators, and it is even more of a problem with this advanced user interface. Results indicate that the coordinated control provides more intuitive operation, and the haptic feedback relays meaningful information back to the user. But the biodynamic feedthrough problem must be overcome in order for this improved interface to be applicable in industry. For the purposes of reducing model complexity, the system is limited to a single degree of freedom, using fore-aft motion only. This paper investigates what types of controller-based methods of compensation for biodynamic feedthrough are most effective in backhoe operation, and how they can be implemented and tested with human operators.

3A.2: Passive Pneumatic and Chemo-fluidic Actuators
The goal of this project is to develop control design methodologies for pneumatic and chemofluidic actuations such that the controlled system can interact safely and stably with a wide range of physical environments, and controlled intuitively by the human operator. This project supports the Center's objectives by developing control systems that are safe, intuitive, and stable that will be integrated into several of the Center's Test Bed systems such as TB4 (rescue crawler) and TB6 (assistive orthosis).

The approach of the project is to develop a passive control system. A passive system is one that does not generate energy but only stores, dissipates, and releases it. The amount of energy that a passive system can impart to the environment is limited by the external input and so some safety is ensured compared to non-passive systems. This is a very useful characteristic in devices where there is human interaction. Some of the accomplishments made to date on the project include:

- A major accomplishment in the past year is an appropriate definition of a storage function that enables passivity analysis and passive control design to be carried out naturally. The storage function is defined as the maximum work output from the actuator, for a given mass, from the current temperature, and volume of air in the actuator to the mechanical and thermal equilibrium state, under any heat transfer scenario.
- An analytical model of the chemofluidic actuator has been developed and preliminary control design and simulation studies on achieving force amplification through chemo-fluidic actuators have also been performed.

Project 3A.2 has graduated and is not receiving Center funding after Year 4.

3A.3: Human-machine interface design for fluid power systems
The goal of the project is to develop an integrated human performance model that can address both cognitive and physical perspectives simultaneously 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.

To achieve optimal overall system performance, both machine performance and operator performance need to be improved and the effectiveness of any design advancements need to be investigated to better understand the human-machine interaction. Human performance modeling provides a means to simulate these design changes and evaluate their impact on the human operator without developing costly prototypes. The most promising of these changes can then be implemented and tested. Some of the accomplishments made to date on the project include:

- Developed an integrated framework for modeling operator performance in complex FP systems.

- Conducted a pilot study on excavator operator performance with the integrated model.
- Conducted empirical studies using various developed Jack models (physical model) for the rescue robot operators
- Conducted an empirical study using eye tracking to assess the effectiveness of the trust instrument for human robotic interaction
- Conducted a usability study to evaluate the haptically controlled excavator simulator at Georgia Tech
- Developed a conceptual model for a user interface suite that interfaces the pneumatic-power ankle-foot orthosis (PPAFO) with clinicians and patients.

3B1: Passive Noise Control in Fluid Power
Noise is an ongoing issue with fluid power systems. The high speed of sound of hydraulic fluids and the low fundamental frequencies of typical pumps make creating compact noise control solutions difficult. Project 3B.1: Passive Noise Control in Fluid Power seeks passive solutions to reducing levels of fluid-borne noise. While hydraulic noise control components typically use pressurized bladders to abate fluid-borne noise, this project applies engineered, compliant linings to traditional noise control sources such as an in-line silencer, Helmholtz resonator, tuning coil and Quincke tube. The compliant lining has the same basic effect as a pressurized bladder, but may have lower manufacturing costs and require less maintenance. The project is two-fold: create functional prototypes with measured noise-reduction properties, and develop predictive models which capture the relevant physics. A test rig has been built to measure the transmission loss of two-port fluid power components, and predictive models have been generated for an in-line silencer and a Helmholtz resonator. First-cut prototypes of each device reveal the in-line silencer exhibits at least 25 dB of transmission loss from 200-3000 Hz, and the Helmholtz resonator exhibits 25 dB of transmission loss at a resonance frequency of 37 Hz. The prototype resonator is two orders of magnitude smaller than an unlined device designed for the same resonance frequency.

3C: Simulation of Cavitation and Noise in Fluid Power
The goal of this project is to better understand cavitation in hydraulic components such as pumps and valves to reduce its deleterious effects. The project targets on the Center's goals of creating compact, efficient, and quiet fluid power systems.

Computer codes are being developed and applied based on state-of-the-art high-fidelity computational fluid dynamics (CFD) tools to study, predict, and control cavitation noise in fluid power components. Interactions will industry also features the use of commercial CFD codes depending on the nature of the problem being addressed. The focus is on the large eddy simulation (LES) technique for computing turbulent flows.

With a motivation to extend the higher order LES solver to complex geometries, the current research on this project concentrates on developing an incompressible LES solver (*WenoHydro). WenoHydro* solver has been validated for its numerical accuracy, and its ability to accurately simulate turbulent flows as shown in the published results of Shetty et al. (2010).

This project has graduated and is not receiving Center funding after Year 4.

3D1: Leakage Reduction in Fluid Power Systems
The elastomeric rod seal, which seals the gap between the protruding rod and the housing of a linear hydraulic actuator, is one of the most critical elements in a hydraulic system because it must prevent the leakage of hydraulic fluid directly into the environment. At the CCEFP a numerical viscoelastic model of the rod seal has been developed. It is capable of predicting the key seal performance characteristics, especially seal leakage and friction, and will serve as a design tool. The model simulates the dominant physical processes governing the operation of the seal. It analyzes the behavior of the hydraulic fluid in the interface between the seal and the rod, the contact between asperities on the seal and the rod, and deformation of the seal. Previous models treat the seal material as elastic, reacting instantaneously to changes in the sealed pressure within the actuator. However, the polymeric materials used for seals are viscoelastic and have a delayed reaction to pressure changes. Since they have a memory, the behavior

of the seal depends on its past history. Such viscoelastic effects are taken into account in the CCEFP model.

3D2: New Directions in Elastohydrodynamic Lubrication to Solve Fluid Power Problems
The field of Elastohydrodynamic Lubrication (EHL), a branch of lubrication science specific to the full-films which occur between non-conformal rolling/sliding machine elements, has been lacking a fundamental rheological foundation since its inception. For instance, to predict Newtonian film thickness, a proper pressure-viscosity coefficient definition is still missing to quantify piezoviscous strength regardless of the underlying nature of the piezoviscous function. Additionally, the properties for inclusion to calculate film thickness when Newtonian assumptions fail have not been formalized. Furthermore, the necessary parameters for full-film friction calculation are not all understood. This project is centered on providing the rheological foundation to solve these important problems and to develop engineering design tools for improved film thickness calculations and reduced mechanical losses.

Truly substantial progress, which is transforming the field of EHL, has been realized. Initially, through analysis using realistic shear dependent viscosity, we showed that the classical Newtonian theory understates the dependence of film thickness on scale. We later experimentally validated this effect by measuring film thickness for various size steel balls against glass discs. Further analysis indicated that a similar effect was important to contact pressure (load) and experimental measurements using a WC ball against a sapphire disc proved this. The findings above hold for any process which increases the pressure gradient within the inlet zone. Although the contacts studied were ostensibly pure rolling contacts, the most obvious explanation was molecular degradation from the shear applied to the liquid. This theory was tested by taking time dependent film thickness measurements using the most shear dependent liquid studied, a gear oil, and then generating flow curves as a function of increasing shear stress and then decreasing shear using a pressurized Couette viscometer. We found that exposure of the liquid to high stress permanently decreased the viscosity measured at low stress, an indication of molecular scission. Next, by examining the measured and predicted film thicknesses for very low viscosity liquids, ordinary liquids at very high temperature and water-based solutions, we have developed the first film thickness formula for linear piezoviscous liquids. The new formula predicts that the speed sensitivity will be reduced at high temperatures for many low-viscosity liquids. The formula has since been experimentally validated. Recently, the phenomenon of EHL entrapment where a pressurized pocket of fluid generated by a rapid stop or impact, was studied and discovered to minimize start-up friction. The persistence of these entrapments, whether seconds or days, depends upon the characteristics of the liquid lubricant. We have now constructed a test-bench for testing ways to implement EHL entrapment into a geroller type hydraulic motor.

3D.3: Improved Seal Design Based on Adaptive Materials
The overall goal of this project was to significantly increase the effective sealing life of elastomeric seals through seal material behavior design. The effectiveness thrust of the Center's mission explicitly recognizes the need for fluid power systems to be safe, quiet, clean and easy to use. The visible results of fluid leakage are obvious, and when coupled with the degrading of system performance, serious losses of system efficiency and effectiveness result.

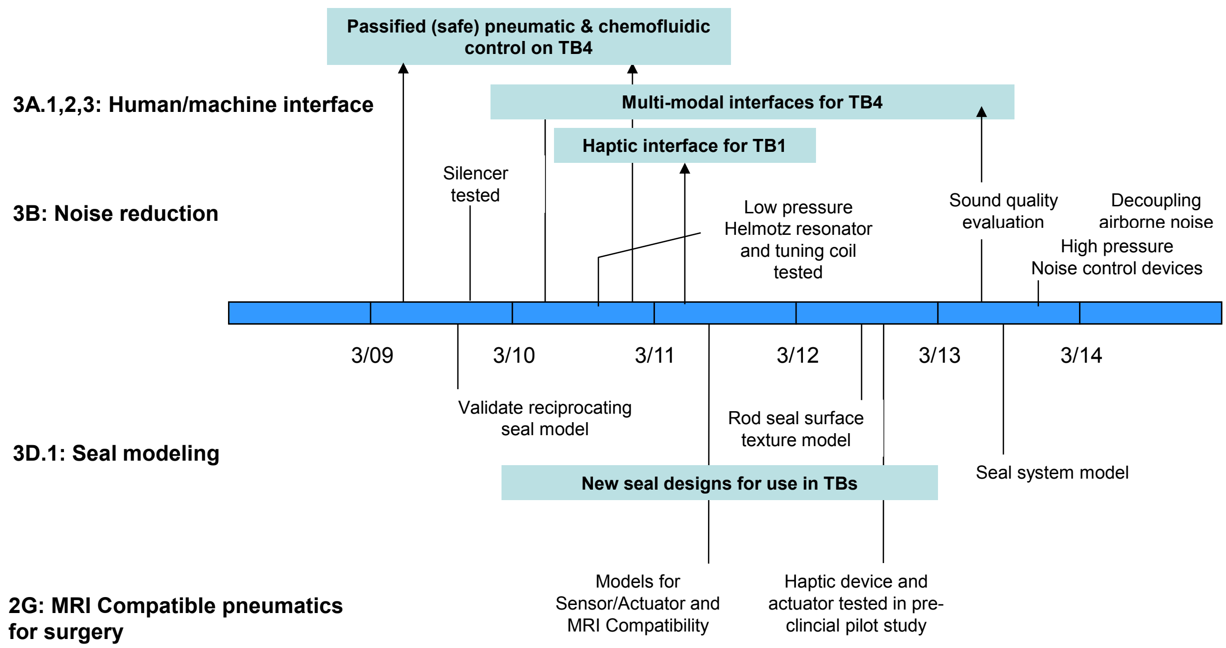
The approach followed in this research was to design seals with non-homogeneous material behavior over the seal section. The intent was to minimize the rate of overall seal material permanent deformation by producing regions of different deformation in the seal. The variation of deformation behavior can be produced by using different materials or by producing different deformation behavior for the same material, for example by slightly changing the composition and/or structure of a given polymer. Some of the project accomplishments include:

- Quantitative models of the strain energy stored in deformed elastomeric specimens were developed and used to explain experimental results.
- The results show that as the material strain energy increases the amount of permanent deformation increases and that the material stress-strain behavior changes so that less stress is produced for a given imposed strain. The major conclusion is that controlling strain energy is a rational, useful concept to guide the design of seals.

Project 3D.3 has graduated and is not receiving Center funding after Year 4.

3E: User-Centered Human-Machine Interface for an Excavator
This project seeks to develop an environment for experimentation to facilitate configuration of an efficient user-interface for test bed 1 (High Efficiency Excavator) using Multimodal Design (MD) and Augmented Reality (AR). An AR environment will be rendered to provide a biologically inspired combination of modalities, providing realistic test environment to inspire effective user interface design. Success will be measured by the ability for the environment developed to capture realism natural operator environment.

At this point in the research, the development of human-system interaction test environment has explored the relationship between criteria (User-System-Task) to establish important design activities (or objectives) and constraints that relates to the overall set of design goals. The critical design activities were identified by exploring the inter-relationship between the three major components of any human-machine interaction, that is, task, user and system. Between the system and task, the design objective was to develop a multimodal interface to provide multiple sensing cues to aid the operator. Between user and system, the design objective was to develop a user-centered interface metaphor. Between task and user, the design objective was system ergonomics.



Effectiveness Thrust Milestone Chart

Quiet, leak-free, safe-and-easy-to-use: The timeline for activities to make fluid power more quiet, leak-free, safe-and-easy-to-use are shown above. Various human-machine interfaces are moving from the development phases and are being tested on test bed 1 and test bed 4. In the area of noise reduction, nonlinear materials are being designed for desirable acoustic properties. Seal modeling and projects that make fluid power quieter are also proceeding. A new research theme of developing MRI compatible pneumatic surgical tools has been added this year. This theme is targeted for the new associated test bed of MRI guided surgical robot.

Effectiveness Thrust Publications

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

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

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

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

Durbha V. and P. Y. Li, “Independent Metering of Pneumatic Actuator for Passive Human Power Amplification,” Proceedings of the 2010 American Control Conference, Baltimore MD (2010).

Earnhart, N, K. Marek, and K.A. Cunefare, “Evaluation of hydraulic silencers,” Proceedings of Noise-Con 2010, joint with the 159th Meeting of the Acoustical Society of America, Baltimore, MD, U.S.A, 19-23 April, (2010).

Elton, M. and W. Book, “Operator Efficiency Improvements From Novel Human-Machine Interfaces,” Proceedings of the 6th FPNI-PhD Symposium, West Lafayette, Indiana, June 15-19 2010, pp.315-322.

Enes, A., "Towards Shared Control of Hydraulic Excavators," in Fluid Power Net International 6th Annual PhD Symposium, West Lafayette, IN, July 2010.

Enes, A. and W. Book, “Blended Shared Control of Zermelo's Navigation Problem,” Proceedings, 2010 American Control Conference, Baltimore, MD, June 30-July 1, (2010).

Enes, A. and W. Book, “Optimum Point to Point Motion of Net Velocity Constrained Manipulators,” 2010 IEEE Conference on Decision and Control, Atlanta, GA, Dec. 15-17 (2010).

Franklin, C. and Z. Jiang, "Applying the Learning Curve to the Haptic Feedback Controller." Proceedings of the 16th International Conference on Industry, Engineering, & Management Systems, Cocoa Beach, FL (2010).

Hughes, K., X. Jiang, Z. Jiang, D. Mountjoy, and E. Park, “A Preliminary Study of an Integrated Human Performance Model“, Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Hughes, K., and X. Jiang, “Using Discrete Event Simulation to Model Excavator Operator Performance.” International Journal of Human Factors and Ergonomics in Manufacturing and Service Industries 20(5), 408-423 (2010).

Humphreys, H. C. and W. J. Book, "Possible Methods for Biodynamic Feedthrough Compensation in Backhoe Operation," in Fluid Power Net International 6th Annual PhD Symposium West Lafayette, IN, July (2010).

Jenkins, Q., X. Jiang, “Measuring Trust and Application of Eye Tracking in Human Robotic Interaction,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Klop, R. and M. Ivantysynova, “Sound Intensity Measurements to Investigate Noise Generation of Hydrostatic Transmissions,” Proceedings of the 7th International Fluid Power Conference Aachen 2010 (7IFK), Vol. 2, 229-242, (2010).

Klop, R. and M. Ivantysynova, “Validation of a Coupled Pump-Motor-Line Model to Predict Noise Sources of Hydrostatic Transmissions,” Proceedings of the 6th FPNI PhD Symposium, West Lafayette, USA, pp 665 – 680, (2010).

Kumar, P., S. Bair and I. Krupka, “Newtonian Elastohydrodynamic Film Thickness with Linear Piezoviscosity.” Tribology International 43(11): 2159-2165 (2010).

Kumar, P., M.M. Khonsari and S. Bair, “Anharmonic Variations in Elastohydrodynamic Film Thickness Resulting from Harmonically Varying Entrainment Velocity.” Proc. I. Mech. E., Part J, Journal of Engineering Tribology 224(J3): 239-248 (2010).

Liu, Y., X. Jiang, Z. Jiang, and E. Park, “Predicting Backhoe Excavator Operator Performance Using Digital Human Modeling,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Marek, K., N. Earnhart, and K.A. Cunefare, “Numerical model for a hydraulic in-line silencer,” Proceedings of Noise-Con 2010, 159th Meeting of the Acoustical Society of America, Baltimore, MD, U.S.A., 19-23 April, (2010).

Martini, A. and S. Bair, “The role of Fragility in EHL Entrapment.” Tribology International 43: 277–282 (2010).

Osafo-Yeboah, B., M. Elton, X. Jiang, W. Book, and E. Park, “Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback,” Proceedings of the 2010 Industrial Engineering Research Conference, Cancun, Mexico, June 5-9, (2010).

Salant, R. F., B. Yang and A. Thatte, “Simulation of Hydraulic Seals.” Journal of Engineering Tribology 224: 865-876 (2010).

Thatte, A. and R.F. Salant, “Visco-Elastohydrodynamic Model of a Hydraulic Rod Seal During Transient Operation.” Journal of Tribology 132: 041501-1 – 041501-13 (2010).

Yang, B. and R.F. Salant, “EHL Simulation of O-ring and U-cup Hydraulic Seals,” Proceedings of Nordtrib 2010, 14th Nordic Symposium on Tribology, Lulea, Sweden (2010).

Young, A. and S. Bair, “Experimental Investigation of Friction in Entrapped Elastohydrodynamic Contacts.” Tribology International 43(9): 1615–1619 (2010).

Test Bed and General Publications

Hsiao-Wecksler, E. T., E. Loth, G.F. Kogler, K.A. Shorter, J.A. Thomas, and J.N. Gilmer, “Portable Active Pneumatically Powered Ankle-Foot Orthosis,” United States Patent Pending (12/898,519).

Ivantysynova, M., “Maha Fluid Power Research Center – Future Trends in Fluid Power.” Journal of the Japan Fluid Power System Society, Vol. 41, No 1, pp. 31 – 34 (2010). – invited paper.

Stelson, K. A., “Center for Compact and Efficient Fluid Power (CCEFP), A National Science Foundation Engineering Research Center, United States,” Journal of the Japan Fluid Power Society, Vol. 41, No. 1, Jan. 2010, pp. 60-63.

Li, Y., K.A. Shorter, T. Bretl, and E.T. Hsiao-Wecksler, “Modeling and Control of a Portable Powered Ankle Foot Orthosis,” 6th Annual FPNI – PhD Symposium, West Lafayette, Indiana, June 15-19, (2010).

Morris, E.A., and E.T. Hsiao-Wecksler, “Time normalizing gait data based on gait events,” 34th Annual Meeting of the American Society of Biomechanics, Providence, RI, August 18-21, (2010).

Shorter, K.A., G.F. Kogler, E. Loth, W.K. Durfee, and E.T. Hsiao-Wecksler, “A pneumatically powered portable ankle-foot orthosis,” 34th Annual Meeting of the American Society of Biomechanics, Providence, RI, August 18-21, (2010).

Shorter, K.A., E.A. Morris, Y. Li, and E.T. Hsiao-Wecksler, “A Pneumatically Powered Portable Ankle-Foot Orthosis,” presented at the 4th Annual Symposium of the Center on Health, Aging and Disability, University of Illinois, Urbana, IL, December 9, 2010.

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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 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 Center's mission, vision and strategy are the basis for each of its education and outreach projects. The projects are organized around five thrust areas: public outreach, pre-college education, college education, industry, and evaluation. The following figure is a snapshot of the CCEFP education project portfolio showing the target audiences for each project. While most projects are specific to fluid power education, there are some that focus instead on STEM education, with examples drawn from fluid power when appropriate. The project reports in Volume 2 provide detailed information on each project.

PROJECT	UNIVERSITY EDUCATION	PRE-COLLEGE OUTREACH	INDUSTRY
Thrust A: Public Outreach			
Bringing the message of fluid power to the general public			
A.1 Interactive Exhibits	x	x	x
A.3 Fluid Power Video	x	x	x
Thrust B: Pre-College Education			
Bringing fluid power education to K-12 students, with a focus on middle and high school			
B.1 Research Experiences for Teachers (RET)		x	
B.2 Project Lead The Way		x	
B.3 Hands-on Fluid Power Workshops	x	x	
B.4 gidaa STEM Programs		x	
B.5 High School Research Opportunity Program (in development)	x	x	x
Thrust C: College Education			
Bringing fluid power education to undergraduate and graduate students			
C.1 Research Experiences for Undergraduates (REU)	x		
C.2 Fluid Power OpenCourseWare	x		x
C.3 Fluid Power Projects in Capstone Design Courses	x		x

C.4 Fluid Power Courses	x		
C.5 giiwed'anang North Star Alliance	x		
C.6 Fluid Power Simulation Application (in development)	x	x	x
Thrust D: Industry			
Making connections between CCEFP and industry			
D.1 Fluid Power Scholars/Interns	x		x
D.2 CCEFP Network	x		x
D.3 Advanced Fluid Power Engineering Workshops	x		x
D.5 CCEFP Webcasts	x		x
D.6 Publications	x	x	x
Thrust E: Evaluation			
Measuring to determine if CCEFP programs are effective			
E.1 External Evaluation of E&O Programs	x	x	x

Recent highlights resulting from the Center's education and outreach program include:

- 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 hundreds of museum visitors of all ages about fluid power. (Project A.1)
- The hands-on fluid power workshops have been refined and offered to hundreds of high school and younger students. (Project B.3)
- The gidaa STEM program is growing, and now includes science camps, a robotics program, and a college network. Hundreds of Native American students of all ages have been impacted. Additional direct funding for programs has been awarded. Partnering with affiliated projects and programs has further leveraged the gidaa reach. (Project B.4)
- The Fluid Power Scholars Program was launched. Eight high-performing undergraduate engineering students completed a fluid power boot camp followed by a full-time summer internship at a CCEFP member company. (Project D.1)
- Twenty-three enthusiastic REU students conducted research in CCEFP labs at all seven universities in the center. REU students joined the rest of the CCEFP family at the CCEFP annual meeting in June 2010. The REU recruiting database was expanded to 750 schools. (Project C.1)
- Lecture notes from three college-level courses in fluid power posted on the Fluid Power OpenCourseWare site. Draft of second mini-book on the topic of hydraulic fluids completed. (Project C.2)
- Six RET participants conducted research in CCEFP labs and developed significant middle and high school curriculum related to fluid power. (Project B.1)

3.1 UNIVERSITY EDUCATION PROGRAM

The objective of the CCEFP university education program is to train graduate and undergraduate students in fluid power with the expectation they will become the future leaders in the fluid power industry and the future leaders in fluid power academic research. 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 latest research.

Examples from CCEFP education projects illustrate progress towards the goals:

Integration of Fluid Power into Core Curriculum: The Fluid Power OpenCourseWare site was launched in 2010 to be a single repository of high quality, college level curriculum related to fluid power. 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. A major effort, led by Prof. Vacca, is underway at Purdue to incorporate fluid power into the core undergraduate fluid mechanics course with curricular materials to be posted on the opencourseware site. While the site is used within CCEFP, the next step is broader dissemination. In addition, as listed in Project C.4, a growing number of courses taught by CCEFP faculty now include a fluid power component and new graduate and undergraduate courses have been developed.

REU Program: The center calculated that committing significant funding to its REU program would yield undergraduate students with research experience who were knowledgeable in fluid power. Twenty-four REU students participated in 2009 and 23 in 2010, more than in many REU site programs. Again, the program evaluation showed that the program is working to increase participants' awareness of fluid power and showed that most REU students wished to continue their engineering education in graduate school. The REU program is complemented by the Fluid Power Scholars program, successfully launched in 2010, which provided eight students with an exceptional fluid power summer internship experience. This growing cadre of REU and Scholar students with skills in fluid power is precisely the pool that industry and NFPA members were expecting when they committed to supporting the CCEFP five years ago.

Capstone Design Projects: This year was marked by an important commitment from NFPA whose member companies are the most important source of significant fluid power capstone projects. With CCEFP playing a matchmaking role between industry and engineering programs, every NFPA board member committed to sponsoring a capstone project. This example provides the role model for all NFPA members. We are hopeful that the number of fluid power capstone projects will soon spike up.

The following are examples of recent CCEFP graduates who are making an impact in fluid power and related fields.

CCEFP Student	Course of Study, Graduation, Institution	Current Employment	Contributions to the Field
Felicitas Mensing	MSME 2010 University of Minnesota	PhD Candidate, Lyon, France, AMPERE Laboratory, **University INSA** (Lyon) in collaboration with **French Institute of Science and Technology for Transport, Development and Network**	Goal is to decrease fuel consumption and emission generation in the transportation sector and to develop eco-driving strategy. Currently evaluating and analyzing optimal energy utilization of various drive-trains (conventional, electric and hybrid) and how to apply the concept to eco-driving. The final goal is to design a tool that advises the driver of the optimal vehicle operation for the desired mission.
Christopher Williamson	PhD 2010 Fluid Power Specialization Purdue University	Senior Staff Engineer - Simulation and Control **Bucyrus International**	Purpose is to design and analyze hydraulic systems and controls for large surface mining equipment such as excavators and shovels in the 1000-ton class.

Daniel Matus	MSME 2010 University of Minnesota	Project Manager **HJ Foundation**	Responsibilities are to manage all aspects of planning, scheduling, project costs, and quality assurance of various construction projects in the South Florida area. Conduct value engineering analyses on proposed foundation designs, and prepare estimates and proposals to secure new projects.
José Ríofrio*	Ph.D. 2008 Vanderbilt University	Principal Engineer **Enfield Technologies**	Goals are new product development and advanced customer applications. Serving as a member of Enfield's mechatronics design team, the focus is mainly on product architecture, control systems and critical mechanical design. Lead design engineer on advanced systems and custom product design projects.
Joel Gilmer*	BSME 2009 University of Illinois at Urbana-Champaign	Applications Engineer **Enfield Technologies**	As a lead applications engineer, responsibilities include customer technical sales, systems engineering, and technical training for Enfield's resellers. Also responsible for specifying, designing, and field-testing new products.
Brett Nagel*	BSME 2010 University of Minnesota	Applications Engineer **Enfield Technologies**	Focuses on inside applications engineering, mechanical design engineering, and the production of new product prototypes.

*Three students in this section have been selected because their current work exemplifies the CCEFP's potential for making a positive impact on industry--in this case, on one of the Center's smallest member companies, Enfield Technologies. Founded in 1991, Enfield provides advanced automation control solutions for companies in the processing, assembly, testing, packaging and animatronics industries. It is a winner of *Design World's* 2010 Leadership in Engineering Program, based on voting by this trade publication's readership. Note that these students represent three different stages of academic preparation and are graduates of three of the Center's seven universities. In commenting on the CCEFP's role in his company's growth, R. Edwin Howe, Enfield's President, states that "The CCEFP has been our best source of highly skilled engineers. The CCEFP students, from bachelors through masters to doctoral students, tend to be the most inventive, enthusiastic, self-sufficient and well rounded 'mechatronics' engineers we have hired. In every case, our CCEFP hires have taken on key new product development projects and key custom system designs for customers within their first year at Enfield Technologies."

Priorities for the Future

The college education program continues with its same two priorities: infuse fluid power into the core curriculum and provide high quality research experiences for undergraduates. We hope that the opencourseware site will grow in content and use, and in particular that it will be used by universities outside the CCEFP. Along with the REU program, significant numbers of undergraduate students will gain fluid power research experience during the academic year through the requirement that every CCEFP research project carry a budget line item to support an undergraduate research student.

3.2 PRE-COLLEGE PROGRAM

The core objective of the CCEFP pre-college outreach program is to expose young students to fluid power with the outcome of increasing the number of students pursuing STEM fields in college. The outcome is 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 at the earlier ages, increasing the interest in STEM is a valuable goal as the number of students engaged in fluid power should increase as the overall interest in STEM increases.

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

PLTW: The partnership with PLTW has matured. Fluid power is now part of the core PLTW *Principles of Engineering* course, which means thousands of high school students are being exposed to fluid power each year. Now that fluid power is in the course, as well as other PLTW courses, the CCEFP emphasis has shifted to developing effective means for training PLTW teachers, most of whom have no experience with fluid power, in how to teach the material. Video training materials and workshops for PLTW teachers are part of this new strategy as is engaging PLTW teachers as participants in the CCEFP RET program.

gidaa STEM Programs: Year 5 saw yet another expansion in the suite of education programs targeted at Native American students of all ages. The Year 5 thrust was to continue leveraging by partnering with connecting programs. Year 5 was also marked by receiving supplemental funding to expand the program. The list of partnering organizations is now one of the larger ones for programs in Native American STEM activities.

Priorities for the Future

Now that the CCEFP is at the half-way point, planning for E&O sustainability is underway. The pre-college programs could be vulnerable and we have identified, as a top priority, development of a long term strategy for receiving federal grant and other CCEFP funds to sustain these important programs. Another priority is to move the hands-on workshops (Project B.3) from developing to delivering. Materials and instruction materials for the workshops are reasonably well developed, while dissemination is still in the early stages. As noted about, the same is true for the PLTW program where the emphasis is shifting from assisting PLTW with curriculum development to assisting PLTW teachers in teaching material relevant to fluid power.

3.3 INDUSTRY EDUCATION PROGRAM

Industry is an essential component of the CCEFP as evidenced by the over 50 companies that are center members. Time and time again we have been told that the education outcomes of the center are as important to industry as the research outcomes. The primary education outcome for industry is the same as the primary education outcome for the Center: graduating students with expertise and experience in fluid power. Beyond that, our industry education thrust, which makes connections between CCEFP and industry, has two goals: first, to connect students and industry and second, to provide industry with specialized, research-driven education. Highlights from projects illustrate progress towards these goals:

Fluid Power Scholars: Despite the challenged economy, the Fluid Power Scholars program launched in 2010 and, by the results of the evaluation, was a success. The program will continue in 2011.

Professional Short Courses: Short courses related to CCEFP research will debut at the 2011 IFPE conference. CCEFP will use this opportunity to evaluate the content and to survey participants on topics for future courses. The aim is to deliver topics in advanced fluid power engineering that do not overlap with existing courses by the MSOE Fluid Power Institute or the in-service courses offered by CCEFP members.

Priorities for the Future
Continue to develop short courses for 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.

3.4 WEAKNESSES IDENTIFIED BY 2010 SITE REVIEW TEAM

Weakness	Response
Uneven distribution of minority students across the center. Low number of students with disabilities participating.	Addressed in the diversity section of this report.
Job placement of PhD students in fluid power industry and faculty positions in the CCEFP universities weak.	Job placement nationwide, including faculty positions, has been challenging because of the economy. Many universities are under hiring freezes or pauses. The University of Minnesota is currently conducting a faculty search that includes CCEFP candidates.
All students should have the opportunity to take graduate courses in fluid power.	The differences in semester calendars and the challenges of cross-institution credit make formal enrollment in courses at other universities a continuing difficulty.

Weaknesses Identified by CCEFP Scientific Advisory Board

Weakness	Response
Some CCEFP graduate students weak in technical communication skills.	Better mentoring by faculty. Arranged a webcast in effective communications techniques for all CCEFP students (January 2011). This webcast is archived at the CCEFP website.

Weaknesses Identified Internally

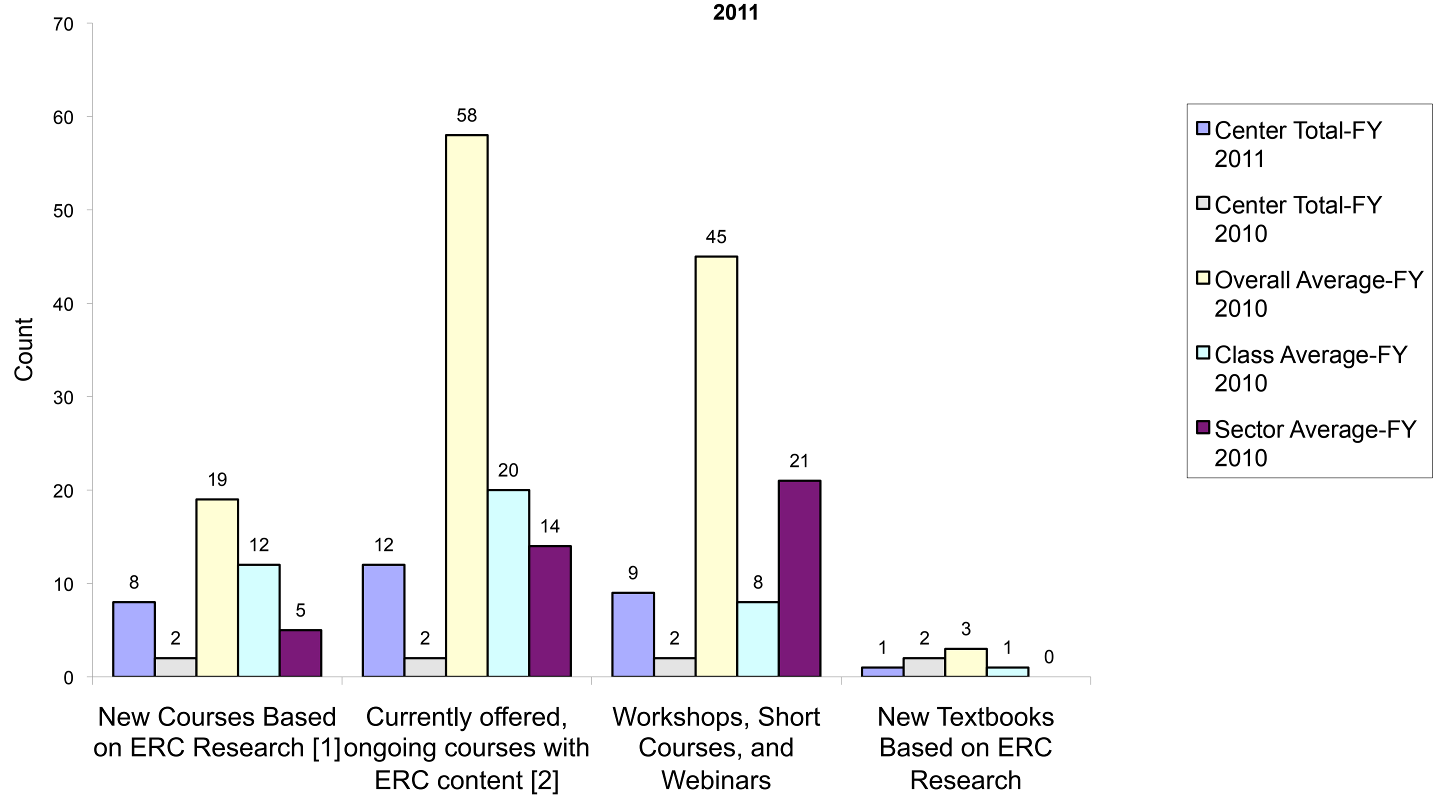
Weakness	Response
Undergraduate participation in research activities still not where it should be.	Increase number of academic year undergraduate research students.
Few publications based on education and outreach programs. (We also noted this weakness in 2008 and 2009.)	Will identify appropriate conferences with published proceedings for submitting papers.
Museum projects local to Minneapolis.	Move towards dissemination. See Project A.1 report for details.

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

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, 2010 - Jan 31, 2011	%	Feb 01, 2010 - Jan 31, 2011	%	Feb 01, 2010 - Jan 31, 2011	%	Feb 01, 2010 - Jan 31, 2011	%	Feb 01, 2010 - Jan 31, 2011	%	Feb 01, 2010 Jan 31, 2011	%	
New courses currently offered [1]	8	2	25	2	25	2	25	1	13	1	13	0	0	14
Currently offered, ongoing courses with ERC content [2]	12	5	42	4	33	0	0	5	42	3	25	0	0	39
Workshops, Short Courses, and Webinars	9	1	11	0	0	1	11	1	11	1	11	0	0	41
New textbooks based on ERC research	1	0	0	0	0	N/A	N/A	0	0	1	100	0	0	4

Table 3a: Educational Impact - Comparison of Center, ERC Program Overall, Center Class, and Center Sector, FY 2011



[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 ERC's 2010	**42**	**79**	**1.9**	**15**	**136**	**15**	**151**
Average Energy Sector FY 2010	**35**	**96**	**2.7**	**13**	**144**	**5**	**149**
Average for Class of 2006 - FY 2010	**44**	**67**	**1.5**	**24**	**135**	**39**	**174**
Engineering Research Center for Compact and Efficient Fluid Power FY 2010	51	76	1.5	27	154	2	156
Engineering Research Center for Compact and Efficient Fluid Power FY 2011	62	95	1.5	27	184	0	184

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

Industry interest in the CCEFP remains high. Total membership in year five remained unchanged at 51 member companies. The challenging economic conditions caused 3 members to leave the Center, but 3 new members were added. These new members are The Lubrizol Corporation, Takako Industries, and Hoowaki, LLC. We are pleased with the stability in our membership level and our ability to recruit new members in strategically targeted market segments.

4.1 VISION, GOALS, AND STRATEGY

With more than 50 industrial members, CCEFP has adequate scale and reach to effectively accomplish its mission. The Center has adopted a strategic recruitment approach for new members. The plan is to target companies that provide a strategic diversification. One example of a newly targeted industry is automotive companies. Hydraulic hybrids are in production today in heavy-duty vocational vehicles, such as refuse trucks, so the core technology is being validated in the real world. The work that the Center is doing on the hybrid hydromechanical transmissions targeted at the passenger car market should resonate well with the car companies. We are also targeting other niche technology segments such as bearing and seal manufacturers with whom the Center's research aligns well.

In addition to maintaining or slightly increasing our membership numbers, we are also focusing on increasing the commitment of our industrial members. One approach we are planning is to provide increased differentiation between the benefits of the three membership levels in order to encourage members to upgrade their membership. One idea being discussed is the creation of an academic champion for our highest level members who acts as a conduit for the member company and visits the company at least once during the year. Other examples of methods for increasing membership commitment include adding more associated projects and the exchange of personnel between industry and academia.

4.2 MEMBERSHIP

During the development of the ERC funding proposal for CCEFP, industrial member companies were aggressively recruited to join in the proposal and become members once the award was made by NSF. Due to this effort, CCEFP had more than 50 industrial members at its inception and has continued to maintain membership in the 50-60 member range throughout its existence. Although the recent economic downturn has caused a few members to cease or suspend their membership in CCEFP, the primary cause of turnover/loss of members is the consolidation that is taking place in the fluid power industry. Larger companies are acquiring smaller companies and when this occurs the membership of the smaller company is vacated. In general, the acquiring company is an existing CCEFP member, but each of the acquisitions reduces the CCEFP membership by one company. In order to maintain our membership level, CCEFP must continually target new member market segments and new member companies.

The initial fluid power-related companies that were targeted for CCEFP membership were manufacturers of fluid power components and systems and OEMs that incorporate those components and systems into their products. A key partner in targeting and recruiting specific companies was the National Fluid Power Association (NFPA). Many of CCEFP's members are also NFPA members. NFPA itself is a CCEFP member and continues to be a strong advocate for the Center.

The fluid power component and system manufacturers are a natural fit with the CCEFP's activities since they would integrate the new technologies developed by the Center. We targeted members ranging from the largest fluid power manufacturers with a broad range of products to small manufacturers or start-ups who might offer a single type of fluid power product, such as a specialty valve. Our goal was to have all of the largest 4-5 fluid power manufacturers as CCEFP members and a strong representation from both the medium and small sized manufacturers. We were successful in recruiting the largest fluid power manufacturers during the formation of the CCEFP and these companies remain strongly involved in Center activities. These companies include multi-national corporations such as Bosch Rexroth, Eaton, Parker Hannifin, and Sauer Danfoss. Working collaboratively with NFPA, we targeted a wide variety of medium and small hydraulics manufacturers and distributors. Many have joined and we continue to encourage those who did not to become a member.

The recruiting of OEMs who use fluid power in their products was more challenging than recruiting fluid power manufacturers. The OEMs are further removed from the pre-competitive research that an ERC spends much of its time doing and rely on their suppliers to bring these technologies to them. We did get several OEMs who also designed, developed, and manufactured some of their own fluid power components and systems to join the Center. These were manufacturers of mobile off-highway agricultural, construction, forestry, and mining equipment. Examples of this sort of company are Caterpillar, John Deere, Bobcat, Toto, and Tennant. We continue to target other OEMs and are close to bringing additional off-road vehicle companies into the Center as members. CCEFP is also targeting other industries for membership including automotive, aerospace (where hydraulics is already widely used), hydraulic components suppliers (e.g., bearings and seals), fluid and fluid additive companies, and members interested in the associated test beds of medical devices and wind power.

Membership Agreement
All members have signed the Center's standard Membership Agreement 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. A tiered royalty rate is used which is tied to membership level at the time of disclosure. The membership dues levels are shown in the table below.

Member's Annual US Fluid Power-Related Revenues	Annual Membership Dues		
	Sustaining Level	Principal Level	Supporter Level
Less than $25 million	$10,000	$5,000	$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

Companies signing the Membership Agreement pledge their support for 5 years, so the original Center member companies will be asked to sign a new Membership Agreement prior to the end of Year 5. Several items in the existing Membership Agreement are being reviewed for possible modification. For example, access to intellectual property generated by the Center is limited to "members-only" unless no member demonstrates interest. This can cause challenges to the creation of new start-ups by PIs or their graduate students since neither are a member of the Center. The Membership Agreement will be reviewed and, ideally, improved prior to being sent to members for their commitment to participate for the next five years of the Center's existence.

The process for handling ERC generated intellectual property (IP) is as follows:

- The PI makes an invention disclosure to the technology transfer office (or similar entity) at their respective University.
- The technology transfer office provides the disclosure(s) to the CCEFP Industry Liaison Officer (ILO).

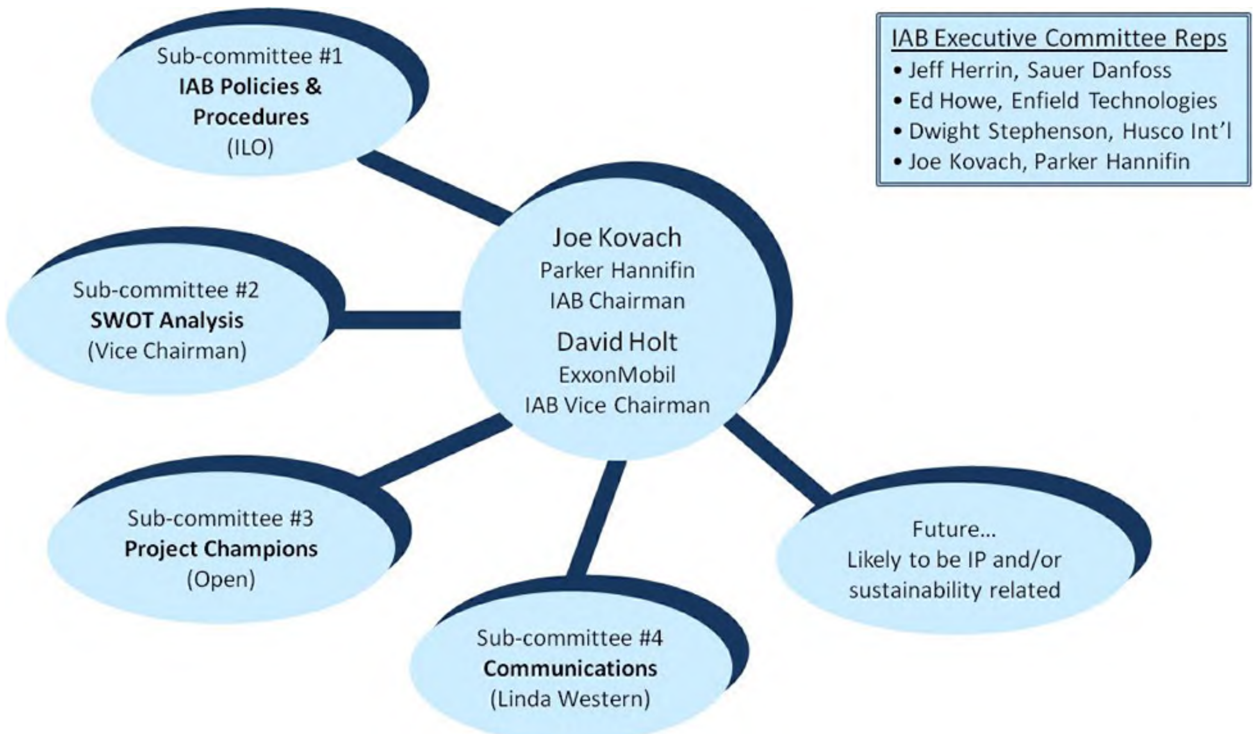
- The ILO works with the PI to create a 1-2 page, non-confidential overview of the invention that is provide to all CCEFP members. With this overview is a notice of a web-meeting in which the PI will provide additional details about the invention. Member companies can attend the web-meeting if they have 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 the costs of pursuing a patent for the invention.
- If a Member elects not to exercise its option to participate in the pursuit of a patent, or decides to discontinue the financial support of the prosecution or maintenance of the protection, the Member shall have no rights in the invention.
- If only one Member bears the costs of protection, the Inventing University shall grant that Member the first option to a royalty bearing exclusive license to the invention. If only one Member is interested in a license for a particular field of use, the Inventing University shall grant that Member an option to a royalty bearing exclusive license for that field of use. In either case, if the Member is a Sustaining Member, then the Sustaining Member shall have an option to obtain a royalty-free, non-exclusive license, without a right to sublicense, rather than a royalty bearing exclusive license; further, when a Sustaining Member elects to obtain an exclusive license, the royalty shall be at a reduced rate to be negotiated at a discount from a commercially reasonable royalty. If the Member is either a Supporter Member or a Principal Member, the exclusive license shall bear a full reasonable royalty to be negotiated on commercially reasonable terms. Any exclusive licensee under this Paragraph will have a right to sublicense on terms and conditions to be mutually agreed upon. The option shall extend for a time period of (180) days from the date of filing the first patent application, which period may be extended by mutual agreement.
- If more than one Member bears the costs of prosecution, the Inventing University shall grant to each of those Members options to a license to the invention on terms and conditions to be mutually agreed upon. The license shall be exclusive as to the rest of the world, but non-exclusive as among those Members which bear the cost of prosecution, provided that, where only one Member seeks a license for a particular field of use, the preceding paragraph, and not this paragraph, shall apply. The Inventing University shall grant all Sustaining Members that have borne the cost of prosecution of the patent a royalty-free license. The Inventing University shall grant all Principal Members that have borne the cost of prosecution a royalty-bearing license, but the royalty amount will be a reduced rate. The Inventing University shall grant all Supporter Members that have borne the cost of prosecution a royalty-bearing license, the royalty to be negotiated on commercially reasonable terms, but in any event the royalty amount will be higher than the amount paid by Principal Members. Except in cases of fully exclusive licenses as provided in the preceding paragraph (either for all uses or for particular fields of use), there shall be no right to sublicense; provided, however, that with the consent of the Inventing University and of all Members that have entered into licenses, either the University or a Member may sublicense the invention on such terms as the parties may agree.
- If no members elect to exercise their option, or if all members discontinue their support, then the Inventing University shall be free to file or continue prosecuting or maintaining any such application(s), and to maintain any protection issuing thereon in the U.S. and in any foreign country at that University's sole expense.

Industrial Advisory Board
The Industrial Advisory Board (IAB) is composed of one representative from each member company at the Sustaining or Principal membership level. The IAB conducts ten teleconferences annually. They are held monthly with the exception of July and December. The focus of the meeting is to identify and address key issues facing the Center. Face to face discussions are held at the annual meetings and site visits. In addition, the IAB decided in November 2010 to have 3-4 of their meetings on-site at Center participating Universities on a rotating basis. These on-site meetings will allow the industry members to

get a much better understanding of the research being done by the PIs and the total capabilities of the Center Universities.

The IAB continues to work within an organizational framework developed with the help of its members during year 1 of the Center. Within this framework, roles and responsibilities for key leadership positions (Chairman, Vice Chairman, subcommittee chairs, etc.) are clearly defined and major IAB goals/objectives are identified on an ongoing basis. Continuity of leadership is assured by a transition policy under which the existing Chairman's role is assumed by the Vice Chairman, whose vacancy is subsequently filled through a nominating and voting procedure involving all IAB members. At the beginning of their term, the Chairman becomes a member of the CCEFP Executive Committee (EC) replacing the person who was Chairman 4 years before their term. Thus, the current IAB Chairman and their 3 immediate predecessors are the members of the CCEFP Executive Committee (EC).

The current IAB organizational structure is depicted below.



CCEFP IAB Organization

Industrial/Practitioner Membership and Support
The attrition of members at CCEFP is quite low with the loss of the vast majority of members being through the acquisition/industry consolidation process. The number of CCEFP members has been stable between 50 and 60 for the Center's entire existence. Our ongoing efforts to recruit new members in the original core focus areas of fluid power system and component manufacturers and mobile off-highway equipment OEMs has reached a plateau and we have begun recruiting members from different adjacent market segments or industries. One such segment is the fluids industry. Hydraulic fluid is a critical element in the operation of a hydraulic component or system and affects efficiency, durability, operating pressure, operating temperature range, and a number of other parameters. Because of our targeted recruiting, a number of fluid suppliers and fluid additive suppliers have joined the Center in the past two years. They include ExxonMobil, Evonik RohMax, Shell, and Lubrizol, among others. CCEFP continues to add industries to its targeted members list. Recently, we have begun recruiting companies in the

automotive industry for membership based largely on the hydraulic hybrid work being done at the Center. Chrysler recently announced that it has signed a contract with the US EPA to work cooperatively to integrate the EPA's hydraulic hybrid technology into their minivan platform. We believe that this development bodes well for the use of fluid power in the automotive market. CCEFP is also targeting other industries for membership including aerospace (where hydraulics is already widely used), hydraulic components suppliers (e.g., bearings and seals), and members interested in the associated test beds of medical device and wind power.

Industrial Collaboration and Technology Transfer Strategy
Our industry focus in year five continues to be on the tactical execution of the CCEFP industrial collaboration and technology transfer strategy. This strategy contains the following key elements: retention and recruitment, communications, engagement and commercialization. An overview of the strategy elements and the tactics for accomplishing them is provided below.

Retention and Recruitment
The number one industrial collaboration priority remains retention of its existing members. This has been challenging due to the difficult economic climate the world and our members are experiencing. We are very pleased to report that our membership has been stable in the past year at 51 industrial members and 3 non-profit, industry association members. 3 industrial members left the Center and 3 new members joined.

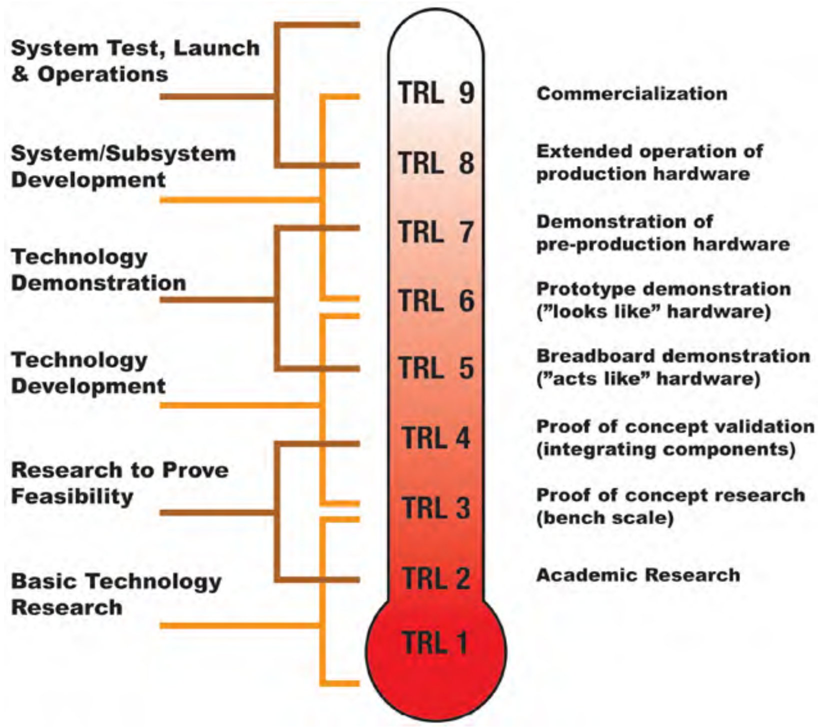
A coordinated communications effort between the CCEFP Director, ILO, AD and Communications Director was executed to reinforce the value of the Center to its members. The Center Director and ILO continued their face to face visits with IAB member companies. In addition, Center students visited nearby industry members to make connections and tour the member's facilities. Not surprisingly, this activity was quite popular with both students and industry. As the economy rebounds, industry access to high caliber fluid power trained students will take on increased importance.

As previously stated, CCEFP's efforts to strategically recruit new industry members, such as fluids companies, have been successful. The focus in the next year will be on recruiting automotive companies, aerospace companies (where hydraulics is already widely used), hydraulic components suppliers (e.g., bearings and seals), and companies interested in the associated test beds of medical device and wind power.

Communication
Enhancing its communications efforts was a primary focus of the CCEFP this past year. From an industry standpoint these efforts were targeted at three distinct stakeholders: executives, technology leaders and individual technologists. We discovered that each of these stakeholders prefers their information in a unique format. For instance, an impactful, information-rich packet was personally addressed to each of our member company executives. Inside were individual information sheets detailing specific results in the areas of research, education and industry benefits. A popular "by-the-numbers" summary was included. Other communication efforts include, but are not limited to, e-news blasts, personal letters from the Director, the quarterly newsletter, biweekly webcasts, postings on the private "Members-only" section of the Center website. Each of these is tailored to meet the expectations of a specific type of stakeholder. Further information regarding these activities is detailed in section 5.3 of this report.

<u>Technology Readiness Level</u>

CCEFP introduced a system called Technology Readiness Level (TRL) to its industry members in the reporting period. The TRL system is widely used by the US Department of Defense and NASA to define the maturity of a project. The numbering system ranges from 1 to 9. A project rated TRL 1 is the least mature (could be just an idea) and TRL 9 represents full commercialization. Projects above roughly TRL 4 are moving from pre-competitive to competitive, so when Center research reaches this level the projects are "graduated" (i.e., Center funding is stopped). The technology resulting from the research can then be directly transferred to industry or could involve a directed/sponsored project partnership between industry and the PI. The use of this standardized terminology has helped make communications about the maturity of a project much easier. The figure below provides information about the definition of the various TRL levels.



Technology Readiness Level (TRL) Definitions

Engagement

The Industrial Advisory Board expanded its monthly meeting from the normal one hour to one and a half days in November. This "IAB Summit" was held at the University of Minnesota and was attended by a majority of the IAB members. The first day of the meeting featured presentations on research being done by Center PIs from the University and a tour of the facilities. Several IAB members commented that the presentations and tours gave them a much deeper understanding of the PI's research and the capabilities available at the University. The second half day of the summit was focused on discussing key Center and IAB issues, processes, and procedures as well as on brainstorming focused on achieving Center sustainability. The IAB members embraced the on-site aspect of the IAB meeting and decided to have 3-4 of their meetings on-site at Center Universities on an ongoing basis. The next on-site IAB meeting is being planned for May 2011 at Georgia Tech and another in July/August at Purdue.

Commercialization

One effective method of promoting the results of the Center PI's research to members and persons of interest, in general, is the creation of a two page project summary for the research being done at the Center. In the reporting period, these sheets were created for roughly half the Center's projects. Our plan is to have these documents available for all projects by the time of the CCEFP 5th Annual Meeting. A sample of one of these promotional sheets is provided in Section 4.3 below.

We are also developing a short (1-3 page) "executive summary" of the Center projects that can be used to quickly communicate the scope and potential of the research being performed. This document was suggested by the IAB Chairman and will be created in time for distribution at the 5thAnnual Meeting of the CCEFP and the IFPE Conference in March 2011. We view this as a means to effectively communicate with senior managers at out member companies as well as with prospective Center members.

Table 4: Industrial/Practitioner Members, Affiliated and Contributing Organizations, and Funders of Associated Projects

Summary:
54 - Industrial/Practitioner Members
0 - Affiliate Organizations
5 - Contributing Organizations
17 - Funders of Associated Projects

Section 1: Industrial/Practitioner Members - 54 Industrial/Practitioner Members

Organization	Sector	Product Focus	Type of Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Member (Yes/No)	Total # of Sponsored Projects
54 Industrial/Practitioner Members								
Industrial/Practitioner Members That Have Already Provided Current Award Year Support								
Afton Chemical Corp.	Industry	Fluid Additives	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Small (<500 employees)	No	0
Air Logic	Industry	Fluid Additives	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Bimba Manufacturing Company	Industry	Fluid power components	Membership cash - fees for unrestricted use In-kind Equipment, Materials, or Supplies	None Listed	Domestic	Medium (500-1000 employees)	No	0
Bobcat	Industry	Fluid power systems	Membership cash - fees for unrestricted use	Technology Transfer	Domestic	Large (>1000 employees)	No	0
Bosch Rexroth Corporation	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use In-kind Equipment, Materials, or Supplies	Member of Center's Industrial Advisory Board	Foreign	Large (>1000 employees)	No	0
Caterpillar, Inc.	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Large (>1000 employees)	No	0
Deltrol Fluid Products	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Small (<500 employees)	No	0
Eaton Corporation	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Large (>1000 employees)	No	0
Enfield Technologies	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Small (<500 employees)	No	0
Evonik RohMax USA	Industry	Fluid Additives	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Small (<500 employees)	No	0
Exxon Mobil	Industry	Fluids	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Large (>1000 employees)	No	0

Organization	Sector	Product Focus	Type of Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Member (Yes/No)	Total # of Sponsored Projects
Festo Corporation	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Foreign	Medium (500-1000 employees)	No	0
Fluid Power Educational Foundation	Non-Profit	N/A	Membership cash - fees for unrestricted use	None Listed	Domestic	N/A	No	0
G.W. Lisk Company	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Domestic	Medium (500-1000 employees)	No	0
Gates Corporation	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Domestic	Large (>1000 employees)	No	0
Hagglunds Drives, Inc.	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Medium (500-1000 employees)	No	0
Haldex Hydraulics Corporation	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Foreign	Medium (500-1000 employees)	No	0
Heco Gear, Inc.	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Hedland Flow Meters	Industry	Fluid power components	Membership cash - fees for unrestricted use In-kind Equipment, Materials, or Supplies	None Listed	Domestic	Small (<500 employees)	No	0
High Country Tek, Inc.	Industry	Fluid power systems	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Hoowaki, LLC	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	Yes	0
Husco International, Inc.	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Large (>1000 employees)	No	0
Hydac Corporation	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Hydraquip Corporation	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Medium (500-1000 employees)	No	0
International Fluid Power Society	Industry	N/A	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Kepner Products, Co.	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Linde Hydraulics Corp.	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Small (<500 employees)	No	0

Organization	Sector	Product Focus	Type of Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Member (Yes/No)	Total # of Sponsored Projects
Master Pneumatic-Detroit, Inc.	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Mico, Inc.	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Moog, Inc.	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	None Listed	Domestic	Large (>1000 employees)	No	0
MTS Systems Corporation	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Domestic	Medium (500-1000 employees)	No	0
National Fluid Power Association	Non-Profit	N/A	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	N/A	No	0
National Tube Supply Company	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Nexen Group, Inc.	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Parker Hannifin Corporation	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Large (>1000 employees)	No	0
PHD, Inc.	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Medium (500-1000 employees)	No	0
PIAB Vacuum Products	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Poclain Hydraulics	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Foreign	Medium (500-1000 employees)	No	0
Quality Control Corporation	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Domestic	Small (<500 employees)	No	0
Ralph Rivera	Other	N/A	Membership cash - fees for unrestricted use	None Listed	Domestic	N/A	No	0
Ross Controls	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Domestic	Medium (500-1000 employees)	No	0
Sauer-Danfoss	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use In-kind Equipment, Materials, or Supplies	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Large (>1000 employees)	No	0
Simerics, Inc.	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Domestic	Small (<500 employees)	Yes	0

Organization	Sector	Product Focus	Type of Support	Type of Involvement	Domestic / Foreign	Size (Industry Only)	New Member (Yes/No)	Total # of Sponsored Projects
Sun Hydraulics	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use In-kind Equipment, Materials, or Supplies	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Medium (500-1000 employees)	No	0
Takako Industries	Industry	Fluid power components	Membership cash - fees for unrestricted use	None Listed	Foreign	Small (<500 employees)	Yes	0
Tennant	Industry	Fluid power systems	Membership cash - fees for unrestricted use	Technology Transfer	Domestic	Large (>1000 employees)	No	0
The Lubrizol Corporation	Industry	Fluids	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Domestic	Large (>1000 employees)	Yes	0
The Toro Company	Industry	Fluid power systems	Membership cash - fees for unrestricted use	Technology Transfer	Domestic	Large (>1000 employees)	No	0
Trelleborg Sealing Solutions	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Foreign	Medium (500-1000 employees)	No	0
Veljan Hydrair Private Limited	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Foreign	Small (<500 employees)	No	0
Industrial/Practitioner Members That Will Provide Support by the End of the Current Award Year								
Donaldson Company	Industry	Fluid power components and systems	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board	Domestic	Large (>1000 employees)	No	0
Netshape Technologies	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Small (<500 employees)	No	0
R.T. Dygert International	Industry	Fluid power components	Membership cash - fees for unrestricted use	Member of Center's Industrial Advisory Board Technology Transfer	Domestic	Small (<500 employees)	No	0
Shell Global Solutions	Industry	Fluids	Membership cash - fees for unrestricted use	None Listed	Domestic	Large (>1000 employees)	No	0

Section 2: Affiliate Organizations - No Affiliate Organizations

Section 3: Contributing Organizations - 5 Contributing Organizations					
Organization	**Sector**	**Type of Involvement**	**Domestic/Foreign**	**Size (Industry Only)**	**Total # Sponsored Projects**
5 Contributing Organizations					
Contributing Organizations That Have Already Provided Current Award Year Support					
Dynasonics	Industry	None Listed	Domestic	Small (<500 employees)	0
Ford	Industry	None Listed	Domestic	Large (>1000 employees)	0
Precision Associates	Industry	None Listed	Domestic	Small (<500 employees)	0
Vex Robotics	Industry	None Listed	Domestic	Small (<500 employees)	0
Contributing Organizations That Will Provide Support by the End of the Current Award Year					
Deere & Company	Industry	None Listed	Domestic	Large (>1000 employees)	0

Section 4: Funders of Associated Projects - 17 Funders of Associated Projects						
Organization	**Sector**	**Type of Involvement**	**Sponsor's Role**	**Domestic/Foreign**	**Size (Industry Only)**	**Total # of Associated Projects**
Casappa S.p.A.	Industry	None Listed	Principally Research/Technology Transfer	Foreign	Large (>1000 employees)	1
DARPA	Federal Government	None Listed	Principally Research/Technology Transfer	Domestic	N/A	1
Deere & Co.	Industry	None Listed	Principally Research/Technology Transfer	Domestic	Large (>1000 employees)	1
Funding Sources (7) kept confidential due to Intellectual Property Rights	Industry	None Listed	Principally Research/Technology Transfer	Domestic	Medium (500-1000 employees)	9
Laboratoire de Mecanique; INSA de Lyon	Other	None Listed	Principally Research/Technology Transfer	Foreign	N/A	1
National Defense Science and Engineering Fellowship Grant (NDSEG)	Federal Government	None Listed	Education/Outreach	Domestic	N/A	1
National Institutes of Health (NIH)	Federal Government	None Listed	Principally Research/Technology Transfer	Domestic	N/A	1
National Science Foundation (NSF)	Federal Government	None Listed	Principally Research/Technology Transfer	Domestic	N/A	3
Oak Ridge National Laboratory	Other	None Listed	Principally Research/Technology Transfer	Domestic	N/A	1
Purdue Research Park Trask Funds	Other	None Listed	Principally Research/Technology Transfer	Domestic	N/A	1
The Martin Company	Industry	None Listed	Principally Research/Technology Transfer	Domestic	Small (<500 employees)	1
The Timken Company	Industry	None Listed	Principally Research/Technology Transfer	Domestic	Large (>1000 employees)	1
Total Oil Company	Industry	None Listed	Principally Research/Technology Transfer	Foreign	Large (>1000 employees)	1
United Technologies Research Center	Other	None Listed	Principally Research/Technology Transfer	Domestic	N/A	1
University of MN; IonE and IREE	Other	None Listed	Principally Research/Technology Transfer	Domestic	N/A	2
University of Stuttgart/German Research Foundation	Other	None Listed	Principally Research/Technology Transfer	Foreign	N/A	1
Vanderbilt University	Other	None Listed	Principally Research/Technology Transfer	Domestic	N/A	1

Section 5: Summary					
Sector	**Industrial/Practitioner Members**	**Percent Foreign**	**Percent Small**	**Percent Medium**	**Percent Large**
Industry	51	14%	47%	24%	29%
Non-Profit	2	0%	N/A	N/A	N/A
Other	1	0%	N/A	N/A	N/A
Total	**54**	**20%**	**N/A**	**N/A**	**N/A**

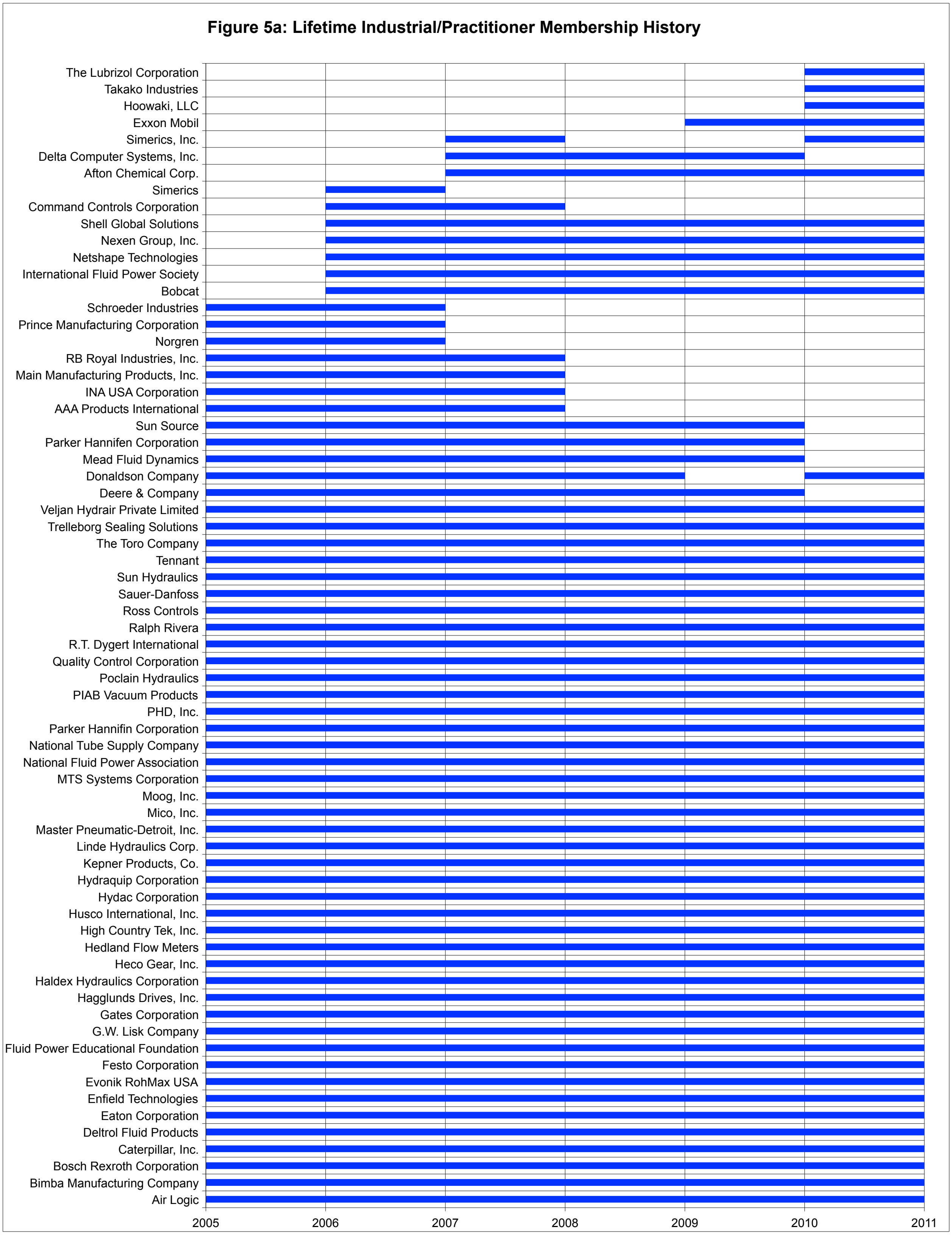


Figure 5a: Lifetime Industrial/Practitioner Membership History
The Lubrizol Corporation
Takako Industries
Hoowaki, LLC
Exxon Mobil
Simerics, Inc.
Delta Computer Systems, Inc.
Afton Chemical Corp.
Simerics
Command Controls Corporation
Shell Global Solutions
Nexen Group, Inc.
Netshape Technologies
International Fluid Power Society
Bobcat
Schroeder Industries
Prince Manufacturing Corporation
Norgren
RB Royal Industries, Inc.
Main Manufacturing Products, Inc.
INA USA Corporation
AAA Products International
Sun Source
Parker Hannifen Corporation
Mead Fluid Dynamics
Donaldson Company
Deere & Company
Veljan Hydrair Private Limited
Trelleborg Sealing Solutions
The Toro Company
Tennant
Sun Hydraulics
Sauer-Danfoss
Ross Controls
Ralph Rivera
R.T. Dygert International
Quality Control Corporation
Poclain Hydraulics
PIAB Vacuum Products
PHD, Inc.
Parker Hannifin Corporation
National Tube Supply Company
National Fluid Power Association
MTS Systems Corporation
Moog, Inc.
Mico, Inc.
Master Pneumatic-Detroit, Inc.
Linde Hydraulics Corp.
Kepner Products, Co.
Hydraquip Corporation
Hydac Corporation
Husco International, Inc.
High Country Tek, Inc.
Hedland Flow Meters
Heco Gear, Inc.
Haldex Hydraulics Corporation
Hagglunds Drives, Inc.
Gates Corporation
G.W. Lisk Company
Fluid Power Educational Foundation
Festo Corporation
Evonik RohMax USA
Enfield Technologies
Eaton Corporation
Deltrol Fluid Products
Caterpillar, Inc.
Bosch Rexroth Corporation
Bimba Manufacturing Company
Air Logic
2005
2006
2007
2008
2009
2010
2011

Table 5: Industrial/Practitioner Membership and Support by Year

	June 01, 2007 - May 31, 2008	June 01, 2008 - May 31, 2009	Jun 01, 2009 - May 31, 2010	Jun 01, 2010 - May 31, 2011 [1]
Industrial/Practitioner Members	57	58	54	54
Affiliated Organizations	0	0	0	0
Contributing Organizations	0	0	2	5
Total Participating Organizations	**57**	**58**	**56**	**59**
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	$701,000.00	$741,500.00	$666,265.00	$652,500.00
Membership Fees expected from prior year members [2]	N/A	N/A	N/A	$36,500.00
Member-Sponsored Projects Total Dollar Amount	$0.00	$12,000.00	$0.00	$0.00
Member-Associated Projects Total Dollar Amount	$615,235.00	$503,806.00	$197,091.00	$166,864.00
Member In-Kind Total Dollar Amount [3]	N/A	N/A	$18,300.00	$123,861.00
Total Dollar Amount, Industrial/Practitioner Member support to Center	**$1,316,235.00**	**$1,257,306.00**	**$881,656.00**	**$979,725.00**

[1] Partial Award Year data only.

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

Organizations section. There is no data prior to 2010 since it is a new field
that year

Figure 5b: Total Number of Industrial/Practitioner Members

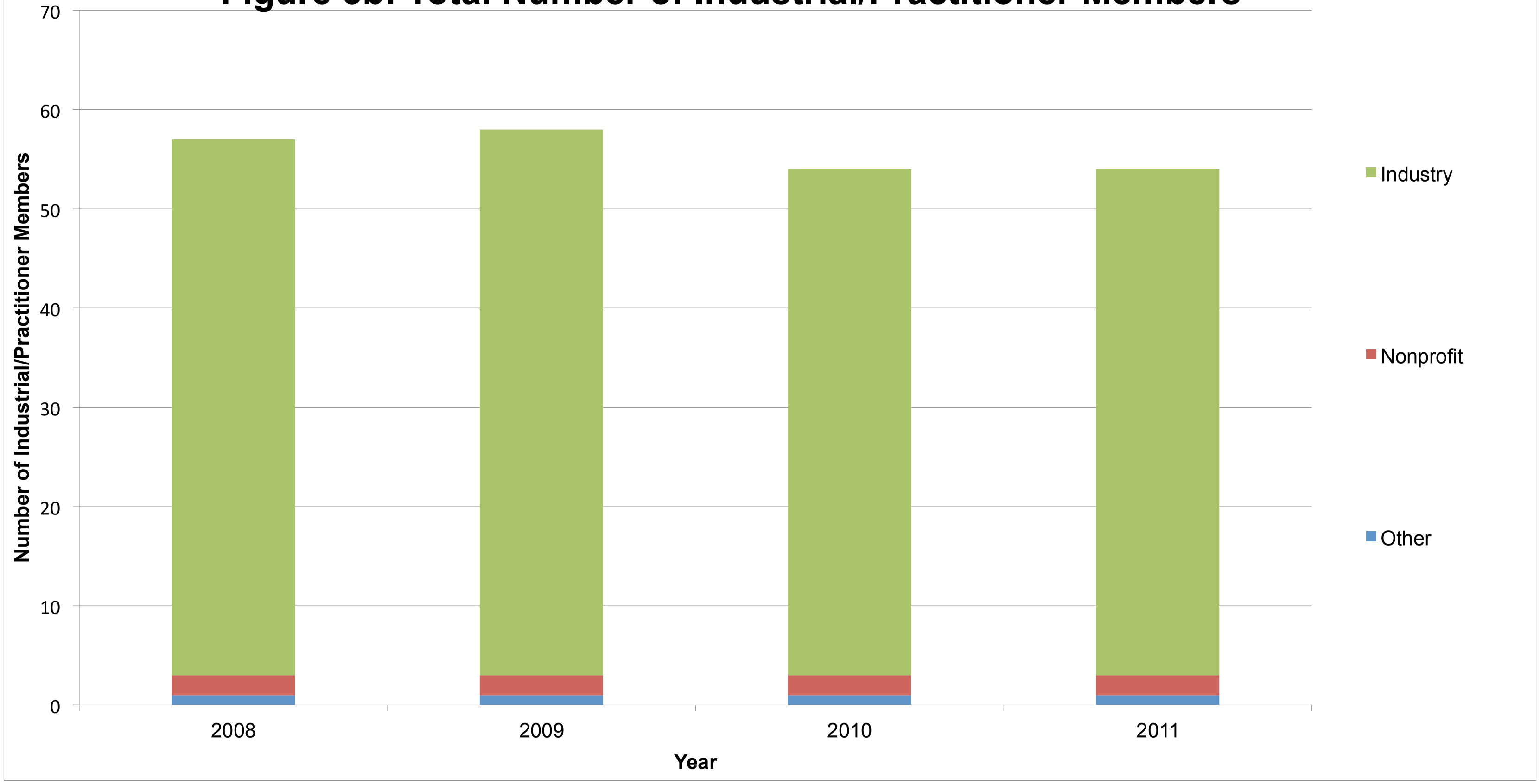
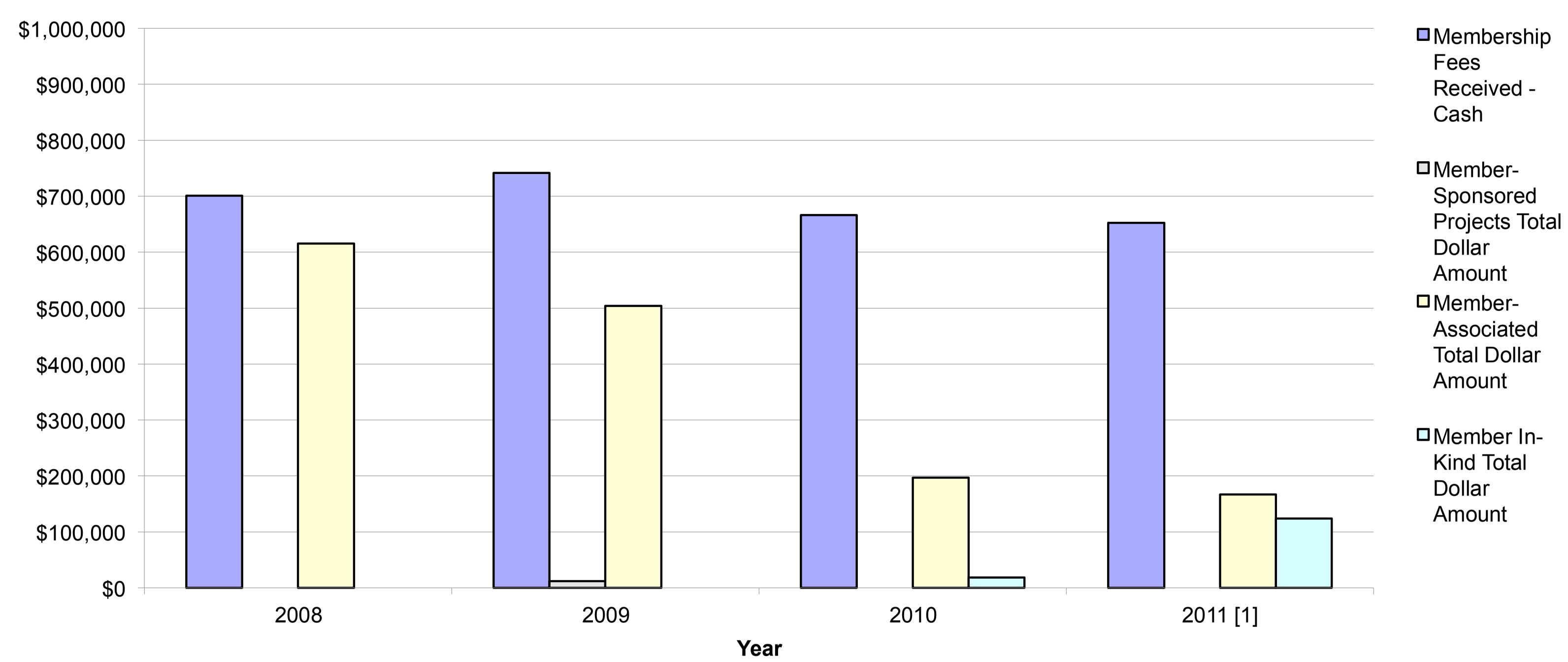


Figure 5c: Industrial/Practitioner Member Support by Year, FY 2011



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

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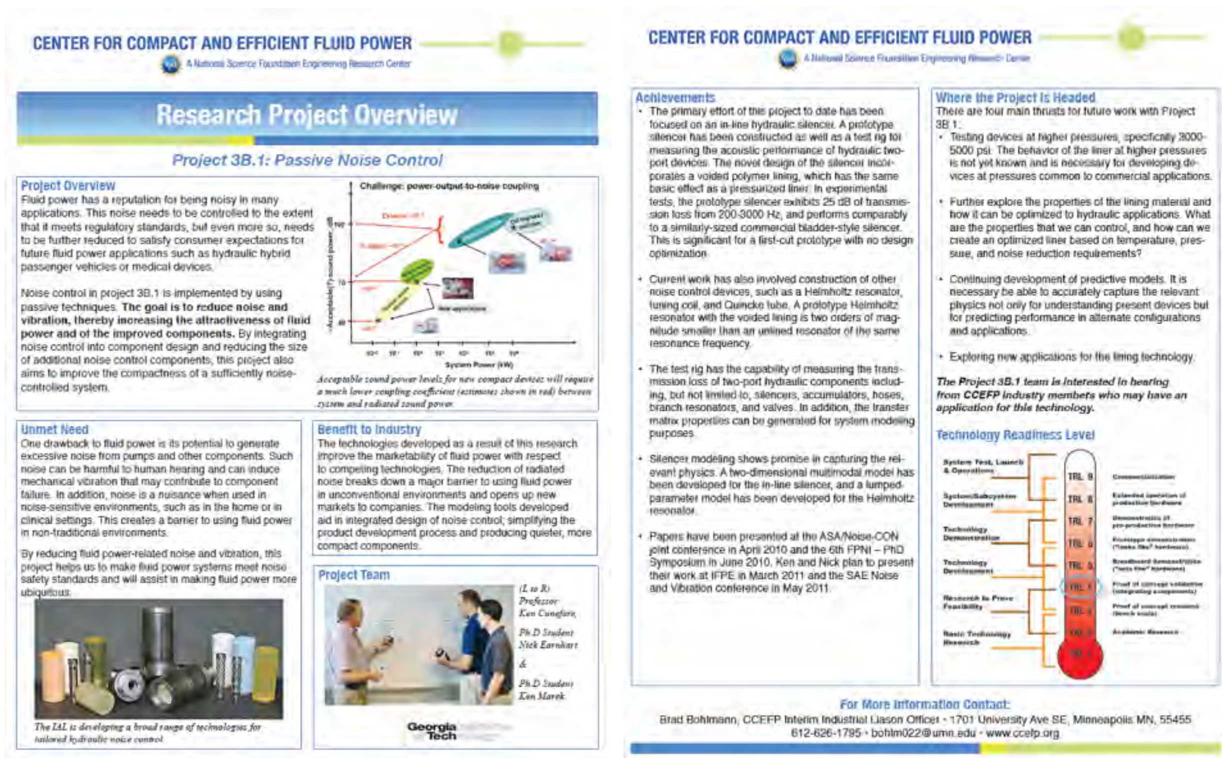
4.3 TECHNOLOGY TRANSFER AND NEW BUSINESS DEVELOPMENT

In order to facilitate technology transfer, the Center is creating two page project summaries for the research being done at the Center. As of this writing, roughly one half of the summaries sheets are completed. We plan to have them all completed by the CCEFP Annual Meeting in March 2011. A sample of one of these documents is provided below.



CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Research Project Overview

Project 3B.1: Passive Noise Control

Project Overview

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

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

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

Unmet Need

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

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

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

Benefit to Industry

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

Project Team

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

Georgia Tech

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Achievements

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

Where the Project Is Headed

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

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

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

Technology Readiness Level

For More Information Contact:

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

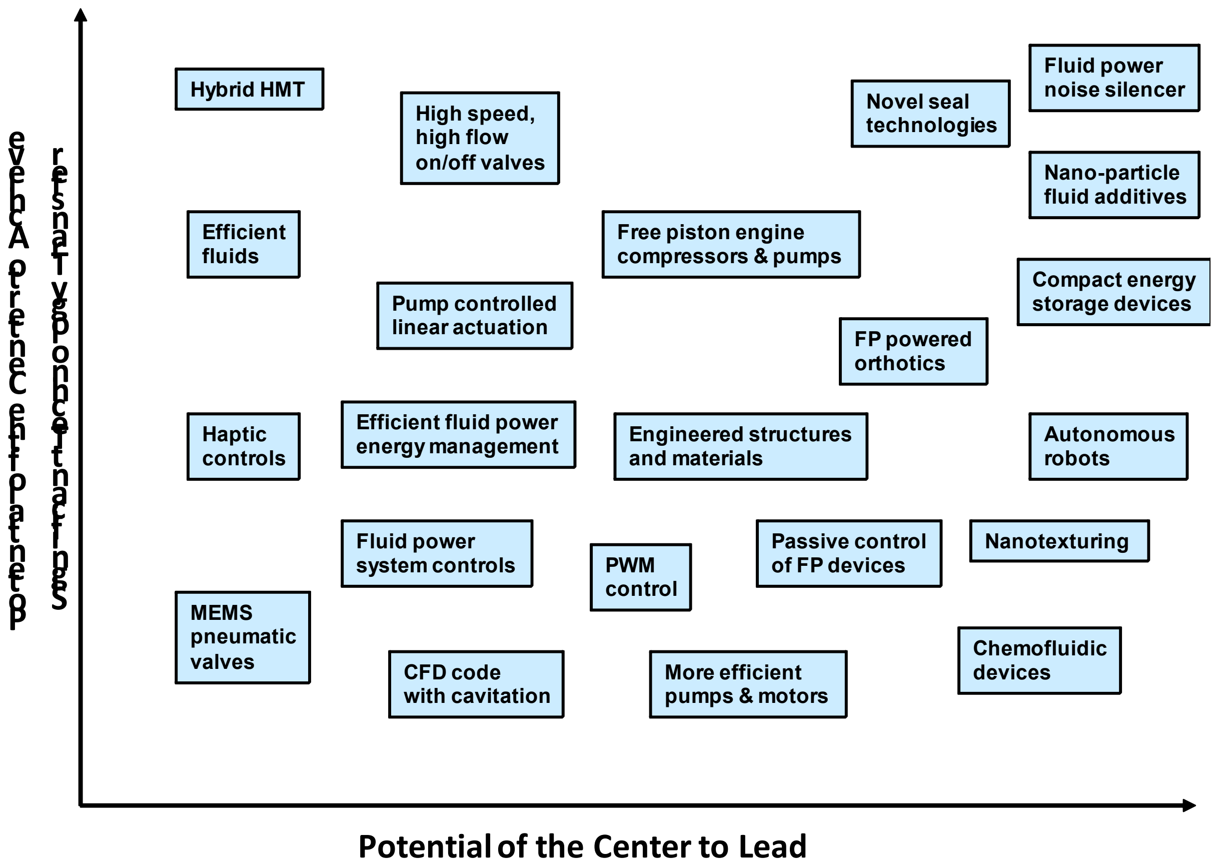
Project Summary Sheet

The project summary sheets will be available in printed form on a heavy gauge, glossy paper printed on two sides creating a single leaf document. These hard copies will be mailed to targeted member companies and can also be used by the University to market the technology if no CCEFP exercise their rights for the IP. In addition, these sheets will be available for download in pdf format from the CCEFP website.

Center PIs were awarded one patent for Center-related research in the reporting period. In addition, two licenses were issued for Center-related research. Both of the licenses were issues by Purdue University on May 26, 2010. The license titles are “Axial sliding bearing and method of reducing power losses thereof” and “Positive displacement machine piston with wavy surface form”. Negotiations are on-going for a second license on both of these technologies.

With the licenses above and some additional projects that are approaching commercial viability, the Center is beginning to transfer its technology to industry. None of the technologies has yet to be offered commercially yet, but a number are approaching readiness.

The figure below shows areas of technology transfer where the Center is expected to impact industry.



CCEFP Technology Transfer Potential

4.4 INNOVATION

One of the Center projects that ran its course and was part of the Year 5 graduating class was research on an “open accumulator”. The project was started to develop the technology for use in the hydraulic hybrid passenger car test bed. Researchers learned that the technology showed a great deal of promise, but was not well-suited for a small mobile application. However, the technology appears to have potential in large, stationary applications such as the storage of wind energy. With the loss of Center funding due to graduation, a team of faculty and students from University of Minnesota, University Virginia and Worcester Polytechnic Institute, together with industry partner, Lightsail Energy, applied for and received a four year grant from the NSF Emerging Frontiers in Research and Innovations Program (EFRI). Their work will continue the investigation of the “open accumulator” as a novel compressed air energy storage for wind power. The partnership is investigating components and systems designs and control strategies that enhance overall system efficiency and effectiveness. This research can be transformational if it can provide a low cost, efficient means of storing large amounts of energy (MW-hour scale). The partnership between academia and a small firm is focused on developing and translating Center-generated innovations.

4.5 FUTURE PLANS

The SWOT developed by the Industrial Advisory Board provides a roadmap for the Center to continuously improve its alignment with our industrial member’s wants and needs. Some of the SWOT items ranked as being most important by industry are discussed below.

- **New structured project selection process [that] allows for significant industry participation**

The project selection process was significantly changed prior to the selection of the Year 5/6 projects. A standardized project scoring matrix was created with industry input. The projects were rated by all members and the results were collated into a spreadsheet that reflected the industry consensus for project selection. The process appears to have worked as every one of the industry's priority projects was funded for Year 5/6.

- **CCEFP does not proactively use/involve industry advisors**
  The project champions approach for involving industry in Center activities has proven less than robust. The approach saw some initial traction due to the actions of a strong project champions committee chair, but the committee currently is all but inactive with no industry member currently chairing the group. Reviving and improving the project champions is a priority for the Center in 2011.

- **Favorable market conditions exist for wind power**
  Center PIs started multiple associated projects in wind power not directly funded by the Center. One example is the open accumulator project discussed in the "Innovation" section above. A second is research into using a hydrostatic transmission to replace the gearbox in wind turbines. Analysis shows that this approach could offer a lower cost, more robust technology to replace one of the highest maintenance items in the wind turbine (the gearbox). A test stand to take the research beyond the analysis stage is planned for construction at the University of Minnesota.

- **CCEFP researchers don't meet industry member expectations**
  This challenge is closely related to the first two bullets above. Part of the misalignment between the research results and industry expectations can be traced to the selection of the projects that were funded by the Center. The industry has always been involved in the process, but in the early years of the Center most of the project proposals came from PIs with little input from industry members. In addition, the diverse nature of the industry member companies makes it challenging to develop a true consensus about what is important or expected. The IAB has discussed methods for improving the project selection process, some of which have been implemented already. This remains a priority for 2011.

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5. INFRASTRUCTURE

5.1 CONFIGURATION AND LEADERSHIP EFFORT

The CCEFP institutional configuration is shown in Table 6. "Domestic Location of Lead, Core Partner, Outreach, and REU and RET Participating Institutions" is shown in Figure 6a. "Foreign Location of Lead, Core Partner, Outreach, and REU and RET Participating Institutions," are shown in Figure 6b, and "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 6b 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 expect for REU student institution. 23 REU students, 31% women in addition to 31% underrepresented racial or ethnic minority status and 8 Fluid Power Scholar students, 25% women and 13% underrepresented 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 2010 REU and FPS program include: Case Western Reserve University, Duke University, Embry-Riddle Aeronautical University, Illinois Institute of Technology, Iowa State University, Montana State University, North Carolina State University, University of Arizona, University of Arkansas, University of Cincinnati, University of Florida, University of Michigan, University of Portland, University of South Florida, University of Texas at El Paso and Washington State 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 shown himself to be highly effective in guiding, leading and managing the CCEFP by effectively implementing key management tools in strategic planning, project selection, budgeting, progress tracking and communication. The strategic plan has gone through multiple iterations and now effectively identifies the Center's goals and their links to the research, education and outreach programs that are designed to reach them. Since the CCEFP's launch in June 2006, projects have been both terminated and initiated, and two test beds have been terminated to reflect the evolving strategic plan. Two associated test beds have also been started with DOE and industry funding. The appropriate management structure is in place to manage this process. Beginning in Year 5, five projects will be terminated, and four projects will be initiated. An effective budgeting process has been implemented where resource allocations and project efforts are closely coupled. An effective progress tracking process has 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. There has been a change in Administrative Director in the last year, and the new Administrative Director has come up to speed rapidly and is very effective. The Communication Director has become increasingly effective, as our communication strategy has improved. The Deputy Co-Directors now have a bi-weekly meeting with the Director and Industrial Liaison Director causing improved communication and increased engagement in these positions. The Industrial Liaison Director's extensive background in industry enhances his strong connections to the industrial supporters of the Center and his ongoing work with the Industrial Advisory Board (IAB). He is well suited to enhancing interaction between industry and universities. The Education Co-Directors communicate and strategize with the Education and Outreach Director on education and outreach programs at all levels. The Education and Outreach Director has successfully engaged the Student Leadership Council (SLC), facilitating student feedback to CCEFP management and guiding 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 lead by the Executive Committee (EC). The Director is Chair of the EC and there is 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. Central to facilitating CCEFP internal communication and decision-making is the Management Committee and the Education and Outreach Network (EON). Each has at least one representative from each university. The Management Committee has responsibility for the day to day operation of the Center. The EON serves as both an advisory group for the Center's education and outreach projects as well as a facilitator for those programs that directly involve faculty and students (e.g., REU, RET, outreach, etc.).

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 January 2010. The analysis and CCEFP leadership response are shown below.

Y5 SLC SWOT

Center Strength:

- Diversity of Research and Multidisciplinary work
- Industry Interaction & Support
- Outreach programs
- Forum for sharing status of projects
- SLC
- Close communication between faculty and students

- Inter-University Collaboration and Collaborative Learning
- Imminent impact of research goals
- Career Positions/ Student Leadership/ Networking with Industry Members
- Student specialization in fluid power
- Experience

CCEFP response: The SLC has done a great job of identifying key strengths within the Center. Going forward the Center must continue to nurture these strengths so that the students reach their full potential.

Center Weaknesses:

- Isolation
  - Geographically
  - Institutionally
  - Physical Resources
- Lack of professional and social activities at the University level
- Industry Champion program is underutilized
- Communication

CCEFP response: With seven universities located in seven different states the Center can understand why SLC students may feel somewhat isolated. Several regularly scheduled activities were specifically designed to address this issue, including annual student retreats, student representation at the annual meeting and NSF site visit and joint research projects with students from different locations. Without exception, every time the students get together new relationships are formed that improve the effectiveness and potential of the CCEFP.

A common message is that the CCEFP has a communication challenge. This is true of all stakeholders including the students. A major new development was the greatly enhanced web site that we launched in March 2009. New capabilities include archives of all web casts and a calendar of events and deadlines. In the future all semi-permanent information will be posted on the web site for easy access by all. This will assure that everyone has the most current version of any information. It will also raise awareness and eliminate bottlenecks. We have implemented guidelines for communication clarifying the need for every presentation to show strategic alignment, connection with other projects and test beds, and relationship to the current state of scientific knowledge. To improve internal communication, the leadership team has agreed to give periodic web casts on broader subjects such as strategy, intellectual property, education and outreach, new policies and research directions, etc.

Several new initiatives have been created to overcome the identified weaknesses. The Administrative Director has improved administrative processes to reduce bureaucracy and inefficiency and to give adequate notice of required activities. Support will be provided to the SLC representatives so that each university can have an annual orientation program for new students. Efforts to reinvigorate the industry champions program will commence after the new Industrial Liaison Officer is hired. This should improve research progress and provide valuable networking opportunities for students seeking employment in the fluid power industry. In the communications area, it has been recognized that our current collaborative communication tool, Sakai, has not been well received. Plans are underway to replace Sakai with Google Groups, a more user friendly collaborative tool.

Center Opportunities:

- Synergy
- International Fluid Power presence
- Entrepreneurial opportunities
- Support for startup companies
- Societal, environmental and economical benefits
- Enhanced web presence / collaboration tool
- Cultural Diversity
- Expansion of outreach program
- Innovative fluid power applications
- Undergraduate mentoring
- Career advancement mentoring
- Student Visitation
- New Student Orientation
- Utilizing common conferences that aren't necessarily CCEFP related as networking tools

CCEFP response: From potential overseas research assignments with notable foreign research centers, to internships at one of the many industry member companies, the CCEFP experience provides opportunities for students. Also with opportunities to give back to society through outreach, mentoring, diverse cultural interaction, and the real possibility of entrepreneurial enterprise, potential for student growth is limitless. The most lasting impact the Center will have on fluid power will be the educated workforce of students who contribute to fluid power long after they have graduated. It is incumbent upon the Center leadership to create an environment where the students feel both challenged and supported.

Some new opportunities have recently been created as a result of CCEFP activities. The last CCEFP Annual Meeting at Purdue in June 2010 was collocated with the Seventh Fluid Power Net International (FPNI) Ph.D. Symposium, allowing CCEFP graduate students to meet their peers at overseas universities. Industry opportunities will also be greatly enhanced with the project champions serving as mentors for graduate students, and the CCEFP Fluid Scholars Program providing opportunities for undergraduate students to serve as interns in industry. In March 2011 the CCEFP Annual Meeting and Site Visit will be held at the International Fluid Power Exposition (IFPE) in Las Vegas. This will provide good opportunities to network and learn about fluid power activities in industry. IFPE is part of Con-Ag Con-Expo, the largest trade show in the western hemisphere.

Center Threats:

- Management of projects/ resources institutionally and center-wide
- Loss of interest or Maintaining Vision (Students/ Faculty/ Industry)
- Spread too thin (re: Balancing research/visits/ meetings/outreach programs)
- Availability of and access to resources
- Timeliness and effectiveness of scheduling
- Lack of synchronization of efforts between universities on closely related projects
- Student turnover (graduating students and recruiting new students)

- Disagreements on how funding should be used and how it should be divided among all schools
- Industry economic situation and impact on center participation
- Decrease in student attendance/involvement in SLC

CCEFP response: The SLC has rightfully identified many of the same threats as the CCEFP leadership team. Project management techniques like scoping the project, identifying major milestones and regular progress tracking updates have been deployed on all research projects. Similarly, allocating budgets based on deliverables not location has become the standard CCEFP practice. To avoid spreading funding too thin, five projects were cancelled last year to enable four new projects to be initiated. It is anticipated that the number of projects will be further reduced from twenty-four to twenty for Years Seven and Eight to assure that adequate funding is provided for the projects we do support. It must be recognized that increased funding from other sources is a key to our long term success. To improve communication, the Center Director has been attending the SLC teleconference at least once a year and the SLC leadership has been reciprocating by making a presentation to a Management Committee teleconference. This practice will be continued with increased frequency in the future.

SLC Recommendations:

- Centralized Calendar
    - A centralized calendar will help students and faculty be aware of upcoming Center events while removing some of the communication bottlenecks. This calendar could also be used to give automatic notification of new events, and could cut down on 'reminder' emails. Example: Google Calendar

- Student Visitation Proposal
    - Visit a project that your project either feeds into or is fed by, for a few days, once a year.
    - Get to know their lab, what their priority issues are, and how your projects relate to one another.
    - Get to know the students who work on those projects and their PI's.
    - Report back to your PI and the center about what you've learned and how each project can help one another. Maybe with specific proposed dates that the two will begin assisting one another, and how.

- New Student Orientation
    - Once/twice a year, let new students and SLC members know what the SLC is, what their responsibilities are.
    - Inform of their expectations and their accountability to participate.
    - Positive incentives for joining an office of the SLC, and/or a typical member.
    - What funds/resources are available to them, and how they should be used.

- Center sponsored extern program
    - An externship is a brief (1 week) student visit at a company with the purpose of learning about said company. This will give center students an opportunity to interact with industry champions and learn how they can work together on their project. The short nature of this exchange limits the time students spend away from research and the expense for the hosting company.

CCEFP response: We agree with all of these recommendations. The centralized calendar has been implemented. Student visitation is taking place on a limited basis. Visitation could increase if more widely encouraged and supported. The first student orientation program will be led by the SLC at IFPE. The extern program is a promising idea, but it requires company support. The improved project champions program would increase support for such an initiative.

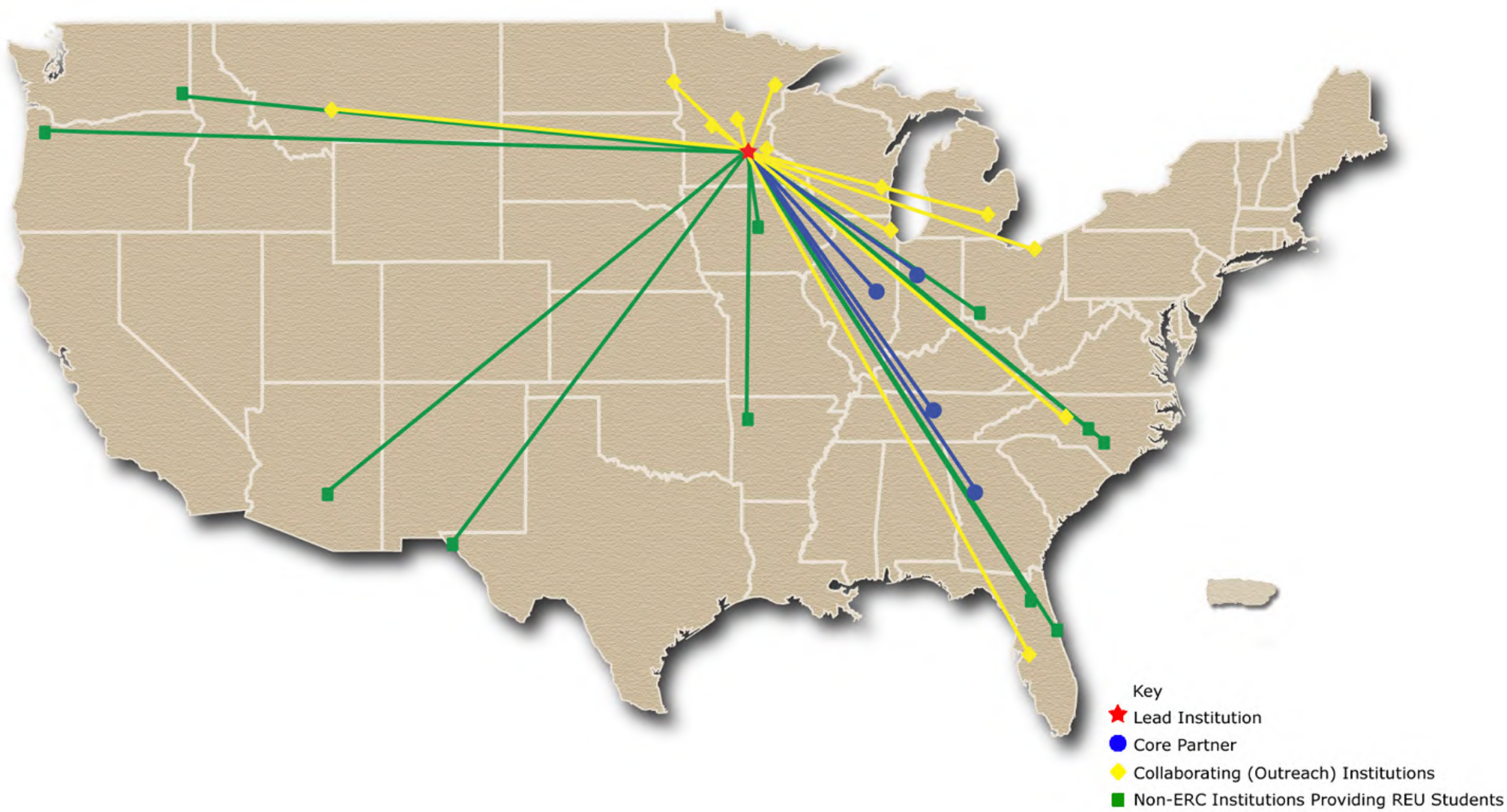
Table 6: Institutions Executing the ERC's Research, Technology Transfer, and Education Programs												
Institutions				**Personnel in ERC Activities [1]**								
						Students				**Teachers**		
Name and Type	**Total**	**Female Serving**	**Minority Serving**	**Faculty**	**Post Docs**	**UG Non-REU**	**REU**	**Graduate**		**Non-RET**	**RET**	**Young Scholars**
								Masters	**Doctoral**			
I. Lead	**1**	**0**	**0**	**12**	**1**	**15**	**0**	**13**	**18**	**0**	**0**	**N/A**
University of Minnesota, Minneapolis, MN				12	1	15	0	13	18	0	0	N/A
II. Core Partners	**4**	**0**	**0**	**22**	**1**	**8**	**10**	**16**	**35**	**0**	**0**	**N/A**
Georgia Institute of Technology, Atlanta, GA				9	0	8	3	1	12	0	0	N/A
Purdue University, West Lafayette, IN				5	0	0	5	8	12	0	0	N/A
University of Illinois at Urbana-Champaign, Urbana, IL				5	1	0	1	5	7	0	0	N/A
Vanderbilt University, Nashville, TN				3	0	0	1	2	4	0	0	N/A
III. Collaborating Institutions	**12**	**0**	**2**	**6**	**0**	**32**	**2**	**7**	**6**	**0**	**0**	**N/A**
Case Western Reserve University, Cleveland, OH				0	0	1	0	0	0	0	0	N/A
Fond du Lac Tribal and Community College, Cloquet, MN			✓	0	0	2	0	0	0	0	0	N/A
Illinois Institute of Technology, Chicago, IL				0	0	1	1	0	0	0	0	N/A
Milwaukee School of Engineering, Milwaukee, WI				1	0	9	0	5	0	0	0	N/A
Montana State University, Bozeman, MT				0	0	2	0	0	0	0	0	N/A
North Carolina Agriculture and Technical State University, Greensboro, NC			✓	4	0	0	1	2	6	0	0	N/A
Science Museum of Minnesota, St. Paul, MN				0	0	0	0	0	0	0	0	N/A
St. Cloud State University, St. Cloud, MN				1	0	3	0	0	0	0	0	N/A
University of Michigan, Ann Arbor, MI				0	0	1	0	0	0	0	0	N/A
University of Minnesota - Morris, Morris, MN				0	0	6	0	0	0	0	0	N/A
University of North Dakota, Fargo, ND				0	0	6	0	0	0	0	0	N/A
University of South Florida, Tampa, FL				0	0	1	0	0	0	0	0	N/A
IV. Non-ERC Institutions Providing REU Students	**11**	**0**	**0**	**0**	**N/A**	**0**	**13**	**0**	**0**	**0**	**0**	**N/A**
Duke University, Durham, NC				0	N/A	0	1	0	0	0	0	N/A
Embry-Riddle Aeronautical University, Daytona Beach, FL				0	N/A	0	1	0	0	0	0	N/A
Iowa State University, Ames, IA				0	N/A	0	1	0	0	0	0	N/A
North Carolina State University, Raleigh, NC				0	N/A	0	1	0	0	0	0	N/A
University of Arizona, Tempe, AZ				0	N/A	0	2	0	0	0	0	N/A
University of Arkansas, Fayetteville, AR				0	N/A	0	1	0	0	0	0	N/A
University of Cincinnati, Cincinnati, OH				0	N/A	0	1	0	0	0	0	N/A
University of Florida, Gainesville, FL				0	N/A	0	2	0	0	0	0	N/A
University of Portland, Portland, OR				0	N/A	0	1	0	0	0	0	N/A
University of Texas at El Paso, El Paso, TX				0	N/A	0	1	0	0	0	0	N/A
Washington State University, Pullman, WA				0	N/A	0	1	0	0	0	0	N/A

Institutions				Personnel in ERC Activities [1]								
						Students				Teachers		
Name and Type	Total	Female Serving	Minority Serving	Faculty	Post Docs	UG Non-	REU	Graduate		Non-	RET	Young Scholars
V. NSF Diversity Program Awardees	**4**	**0**	**2**	**0**	**N/A**	**12**	**2**	**0**	**0**	**0**	**0**	**N/A**
Alliances for Graduate Education and the Professoriate (AGEP)	**0**	**0**	**0**	**0**	**N/A**	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**
No AGEP Awardees were entered.												
Louis Stokes Alliances for Minority Participation (LSAMP)	**4**	**0**	**2**	**0**	**N/A**	**12**	**2**	**0**	**0**	**0**	**0**	**N/A**
Purdue University(Louis Stokes Alliance for Minority Participation (LSAMP) Indiana)				0	N/A	0	1	0	0	0	0	N/A
North Carolina Agricultural And Technical St Univ, Greensboro (North Carolina Louis Stokes Alliance for Minority Participation)			✓	0	N/A	0	1	0	0	0	0	N/A
University of Minnesota Twin-Cities(North Star STEM Alliance)				0	N/A	8	0	0	0	0	0	N/A
Salish Kootenai College, Pablo (The All Nations Louis Stokes Alliance for Minority Participation)			✓	0	N/A	4	0	0	0	0	0	N/A
NSF Diversity Program Collaborations (NSF Diversity Program Collaborations)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**
No NSF Diversity Program Collaborations Awardees were entered.												
VI. Pre-College Partners	**21**	**0**	**8**	**0**	**0**	**0**	**0**	**0**	**0**	**33**	**6**	**0**
Albrook School, Saginaw, MN			✓	0	0	0	0	0	0	4	0	0
Bemidji High School, Bemidji, MN				0	0	0	0	0	0	1	0	0
Bemidji Middle School, Bemidji, MN				0	0	0	0	0	0	6	0	0
BugONayGeShig School, Leech Lake, MN			✓	0	0	0	0	0	0	3	0	0
Cass Lake Middle School, Cass Lake, MN			✓	0	0	0	0	0	0	2	0	0
Cloquet High School, Cloquet, MN				0	0	0	0	0	0	1	0	0
Cloquet Middle School, Cloquet, MN				0	0	0	0	0	0	1	0	0
Deer River School, Deer River, MN				0	0	0	0	0	0	1	0	0
Gibbon, Fairfax, Winthrop School, Gibbon, MN				0	0	0	0	0	0	0	1	0
Lafayette Jefferson High School, Lafayette, IN				0	0	0	0	0	0	0	1	0
Mahnomen High School, Mahnomen, MN			✓	0	0	0	0	0	0	2	0	0
McCutcheon High School, Lafayette, IN				0	0	0	0	0	0	0	1	0
Metropolitan Nashville Public School, Nashville, TN				0	0	0	0	0	0	0	1	0
Naytawaush Charter School, Naytawaush, MN			✓	0	0	0	0	0	0	1	0	0
Ojibwe School, Cloquet, MN			✓	0	0	0	0	0	0	2	0	0
Ponemah Elementary School, Ponemah, MN			✓	0	0	0	0	0	0	3	0	0
Red Lake Middle School, Red Lake, MN			✓	0	0	0	0	0	0	4	0	0
Robbinsdale Armstrong High School, Robbinsdale, MN				0	0	0	0	0	0	0	1	0

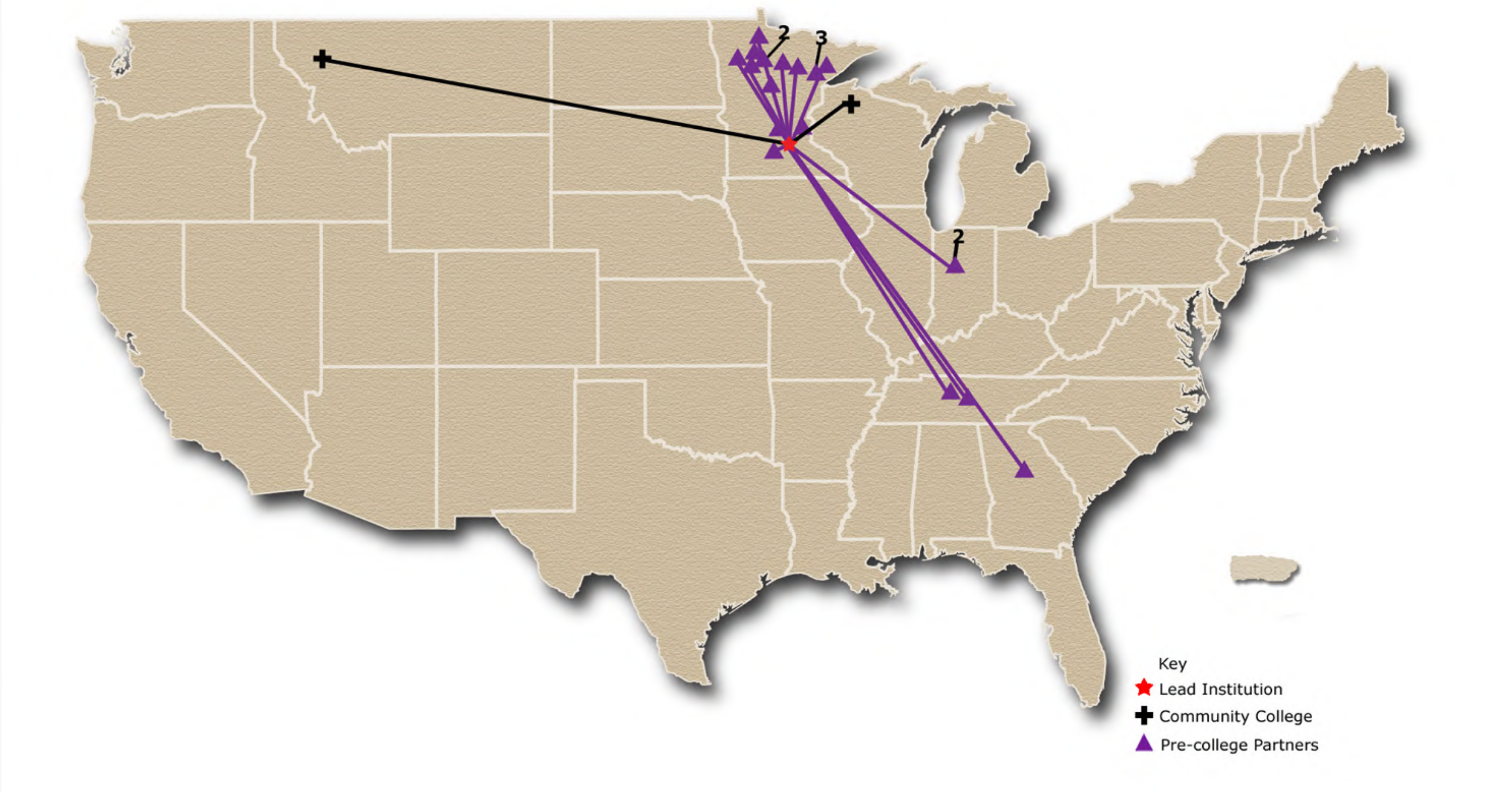
Institutions				Personnel in ERC Activities [1]								
						Students				Teachers		
Name and Type	Total	Female Serving	Minority Serving	Faculty	Post Docs	UG Non-	REU	Graduate		Non-RET	RET	Young Scholars
Rockdale Magnet School for Science and Technology, Conyers, GA				0	0	0	0	0	0	1	0	0
Smyrna High School, Smyrna, TN				0	0	0	0	0	0	0	1	0
Walker Alternative School, Walker, MN				0	0	0	0	0	0	1	0	0
VII. Community Colleges	**2**	**0**	**2**	**2**	**0**	**7**	**0**	**0**	**0**	**0**	**0**	**N/A**
Lac Courte Oreilles Ojibwa Community College, Hayward, WI			✓	0	0	3	0	0	0	0	0	N/A
Salish Kootenai College, Pablo, MT			✓	2	0	4	0	0	0	0	0	N/A
VIII. Foreign Partners	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**N/A**
No Foreign Partners were entered.												
Total	**55**	**0**	**14**	**42**	**2**	**74**	**27**	**36**	**59**	**33**	**6**	**0**

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

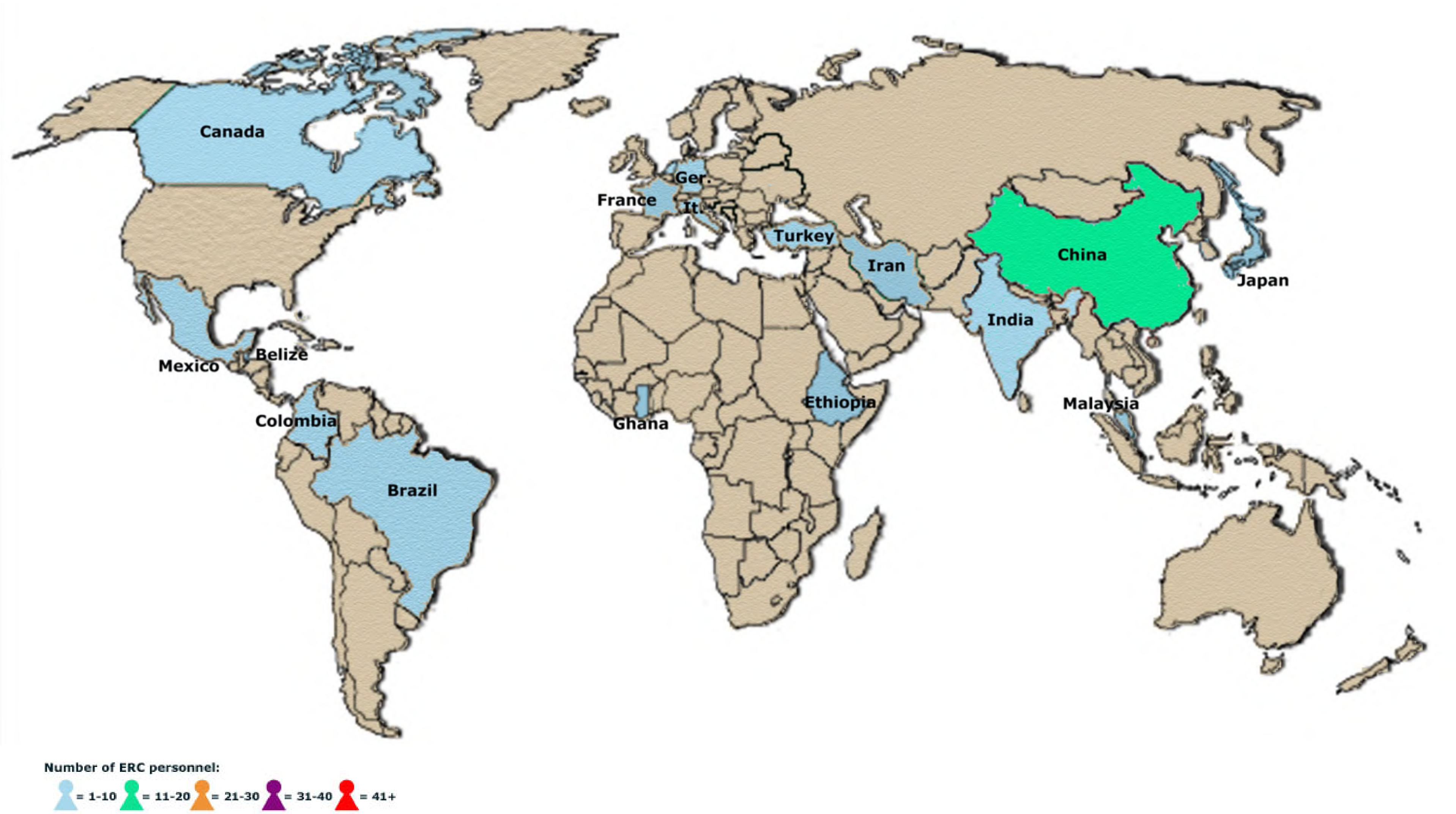
Domestic Location of Lead, Core Partner, Outreach, and REU and RET Participants' Institutions for the Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota—Twin Cities



Domestic Location of Lead, Community College, and Pre-College Partner Institutions for the Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota—Twin Cities



Country of Citizenship of ERC Foreign Personnel for the Engineering Research Center for Compact and Efficient Fluid Power at the University of Minnesota—Twin Cities



5.2 DIVERSITY EFFORT AND IMPACT

The Center for Compact and Efficient Fluid Power has an 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. Projects and programs on this agenda emphasize increasing diversity throughout the Center as well as in the fluid power industry and among students of all ages engaged in STEM-related initiatives.

The Center's Diversity Program: Goals and Mission

A CCEFP-stated goal calls for an increase in the diversity of students, faculty, fluid power industry practitioners, and those involved in STEM-relevant studies. A Center-led mission is to assure that individuals in each of these groups reflect the gender, racial and ethnic composition of the country. In its fifth year, the CCEFP has continued to see sustained growth in the engagement of women and those of ethnically diverse backgrounds in Center activities. We continue to work to assure similar opportunities for those with disabilities and recent war veterans.

The Center's Approach

We strive to reach these outcomes through a variety of approaches. Key among them are:

- Work and support efforts at partner schools and other ERCs to recruit and fund underrepresented students in CCEFP-related undergraduate and graduate research
- 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, insuring widespread awareness of opportunities within the CCEFP and the fluid power industry itself, establish relationships with engineering faculty across the country in ABET-accredited colleges and universities, with an emphasis on those in minority-serving institutions and those engaged in fluid power and related engineering curricula.
- Through the Center's cooperative efforts with Project Lead The Way and its Research Experiences for Teachers (RET) Program, develop new understandings of scientific research and fluid power technology among a growing number of teachers who can, in turn, impact students in schools across the country. Because of their CCEFP experiences, these teachers can take lead roles in developing and teaching curriculum modules that are STEM-oriented, using examples from fluid power where appropriate, and encouraging their colleagues to do the same.
- 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.
- Build relationships with outreach and diversity offices across partner institutions to bridge learning and teaching opportunities and this includes NSF Louis Stokes' Alliances for Minority Participation (LSAMP) Programs.

Our Progress
Table 7a indicates the percentage of the Center's diversity statistics in comparison to the National Engineering Average data and averages data within other ERCs. Line by line, the CCEFP tells a promising story, even better than in the Center's previous report. Following are added details.

- 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 you will see in the Table 7a, the CCEFP's data indicates that we compare favorably with these national engineering percentages.
- It is clear that the Center for Compact and Efficient Fluid Power is significantly impacting underrepresented students as compared to the national averages of graduating students in engineering.
    - As in previous years, in 2010, the Center continues to demonstrate a strong representation of women by matching or exceeding national averages at the undergraduate, Masters and faculty level. As previously noted, mechanical engineering typically serves the smallest percentage of females. Sustaining the positive numbers of women across the Center is critical.
    - The Center has experienced another sharp improvement in the number of underrepresented racial minorities, well above the national averages in all categories of academic participants.
    - In recent years 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, and 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 has been low, hovering just at national averages. The Center will continue to identify resources, organizations and affiliations where programs can be disseminated and students with disabilities can be reached through means of recruitment, not yet utilized.
- Representation of women, persons with disabilities and ethnic and racial minorities within the CCEFP faculty continues to exceed, or at minimum, equal national averages. Current data reflects little change. This is due to recent hiring freezes throughout the Center's seven-university network, a reflection of widespread uncertainty about the long-term health of the economy, We are hopeful that once confidence in the economy returns and freezes are lifted, future data will reflect new inroads.
- The Center has successfully received funding for two consecutive years to support two women in the field of engineering with an emphasis in fluid power research--one at the University of Minnesota and the other at the University of Illinois, Urbana-Champaign--under the NSF Graduate Research Diversity Supplement. The Center has recently submitted a request for a third year of funding.
- The Center's diversity strategy continues to focus on building a network of recruiting partners across the country. The strategy starts with identifying key colleges and universities, including ABET-accredited programs and minority-serving institutions (including 2-year and 4-year) with engineering or related academic paths. Once the primary institution is identified, the next step is to locate programs or people within the organization whose focus is directly related to providing student services, including support, to under-served populations. A third step aims at identifying and making connections with individuals within a specific program or teaching speciality who have demonstrated interests in mechanical engineering, fluid power research and applications. The e-relationships built upon this strategy tend to generate positive outcomes for student recruitment and relationship retention.
- The Center took a lead recruiting effort in 2010, by coordinating two NSF ERC booths at the national conferences of *SACNAS* (Society for Advancing Chicano/Latino and Native Americans in Science)

and *AISES* (American Indians in Science and Engineering Society). A total of 10 of the 15 ERCs participated in joint exhibitor booths. This effort will be expanded in 2011.

- The outreach efforts of the CCEFP report a significant representation of diverse populations in programs across the Center. The REU program has served as an effective and influential tool in recruiting underrepresented students for research within the CCEFP, as well as in developing a strong and diverse network of schools outside of the Center. The new Fluid Power Scholars Program holds promise here, too.
- 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 (CCEFP Project C.5) and considers this program an official undergraduate activity for Native American students in the LSAMP. This partnership includes recruiting efforts; disseminating 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.

The Center recognizes opportunities to expand on the recruitment, retention and participation of underrepresented students—women, racial 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 - 5, the CCEFP will continue its efforts in engaging individuals within each of these underrepresented groups, paying particular attention to the Hispanic/Latino population and persons with disabilities.

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 its 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. Going forward our focus will be on helping teachers to effectlvely understand and teach this content. Our partnership with PLTW continues to grow (several RETs are also PLTW teachers, five in 2009, three in 2010) and the pneumatics hands-on workshop has drawn added support from corporate sponsors, thereby helping the Center to extend its reach among pre-college audiences.

College: At the university level, the Center continues to build the communications and database networks needed in recruiting 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.

At the grass-roots level: members of the Center's Education Outreach 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 the diversity, LSAMP and AGEP programs of its collaborating institutions. CCEFP also works with associated Deans and Department Chairs to increase diversity through faculty hiring.

Major Initiatives
Every research and every education project at every CCEFP institution is committed to actively recruit 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 a summer experience in a university research lab. An objective of the program is to increase the number of top students, reflecting the ethnic and gender composition of our country, who attend graduate schools in STEM areas. Every summer the CCEFP hosts an average of 20 REU students. Within this total, the number of participants from outside the Center's network is greater than the number of students admitted from its seven universities. The CCEFP REU students begin the summer with an e-orientation to 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 at least twice during the summer. The CCEFP actively recruits underrepresented students in STEM including racial minorities, women and persons with disabilities for its REU program.

Outcomes:

Research Experiences for Undergraduates		
Number of Students enrolled / demographics	Number of Students	23
	Male	16
	Female	7
	Percentage of students from underrepresented groups 1) racial minority 2) gender minority 3) disability	 1) 31% 2) 31% 3) 1%
	% LSAMP Students	1) 17%

Fluid Power Scholars Program (Project D.1)
As interns, students gain hands-on experience in fluid power technology. Companies hosting interns benefit, too, 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.

Outcomes:

Fluid Power Scholars		
Number of students enrolled / demographics	Number of Students	8
	Male	6
	Female	2
	Percentage of students from underrepresented groups 1) racial minority 2) gender minority 3) disability	 1) 13% 2) 25% 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, the teacher completes a research project and develops curriculum to be used in their classes. Every summer the CCEFP hosts at least six RET teachers at at least three CCEFP universities. A special CCEFP RET focus is recruiting teachers from area high schools participating in the PLTW program.

Outcomes:

Research Experiences for Teachers		
Number of Teachers enrolled / demographics	Number of Teachers	6
	Male	6
	Female	0
	% from underrepresented groups	0%
	% PLTW Teachers	50%

gidaa STEM Programs (Projects B.4, B.4a, B.4b)
CCEFP, Fond du Lac Tribal and Community College (FDLTCC), together with the National Center for Earth-surface Dynamics (NCED) organize programs in the Cloquet, Minnesota region that is home to the Fond du Lac Indian Reservation. Camps for K-12 Native students originally known as *gidakiimanaaniwigamig* (Our Earth Lodge, in Anishinaabe) have been held on a regular seasonal basis since *gidaa's* inception in 2003. Since then the "*gidaa*" program has taken on a life of its own to include programs that bridge several federally funded organizations. *gidakiimanaaniwigamig* is committed to engaging Native American students as they work towards their high school graduation while helping them to prepare for their post-secondary education in the areas of science, engineering, technology and mathematics (STEM). Since its first year, the Center has co-sponsored the gidaa STEM Programs which annually brings over 150 youth from local middle and high schools to Native American math and science camps and also engages them in after-school and weekend programs and science fairs. These programs provide students with a mix of lab science and field science experiences. Program highlights include an introduction to scientific methods coupled with a focus on Native American culture. During each camp, the CCEFP presents a workshop on hydraulic and pneumatic principles based on fundamental math, science

and physics. Students have hands-on opportunities to test these principles by using a variety of curricula designed by either the CCEFP or gidaa teachers. The same consortium offers a *gidaa odaangiina anaangoog Robotics Program*, which introduces an even greater number of students to basic principles of engineering and related disciplines.

Outcomes:

gidaa STEM Camps		
1. Number of Native American K-12 Students participating in gidaa STEM Camps (since its inception in 2003 by NCED, joint partnership with CCEFP initiated in 2006). 2. Repeat contacts with students.	Number of students	378
	Number of repeat contacts	
	1 Camp	66
	2 Camps	32
	3 Camps	20
	4 Camps	15
	5+ Camps	51

Outcomes:
gidaa students Competing in Local and National Science Fairs

Year	Total gidaa Native American Regional Science Fair entrants	Attended NAISEF	Medals and awards won at NAISEF	NAISEF Grand Award winners sent to compete at Intel ISEF
2005	35	8	7	3
2006	42	16	20	2
2007	46	16	20	1
2008	68	15	30	2
2009	55	13	24	4
2010	58	8	15	2

gidaa odaangiina anaangoog (Shooting for the Stars) Robotics Program
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, NXT Kits, Vex Kits and Textrix kits and software. The *odaangiina anaangoog* Shooting for the Stars Robotics Program enables students in and around Cloquet, 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. This program currently engages students at the elementary, middle and high school levels. A college-level robotics course at Fond du Lac Tribal and Community College is in its third year. Ideally, graduates of *gidaa* and the *gidaa odaangiina anaangoog* Robotics Program will continue their education either at a community college or a four-year university, joining the *giiwed'anang* North Star Alliance (Project C.5) there as active undergraduate members.

Outcomes:

gidaa odaangiina anaangoog Robotics Program			
Number of Students enrolled / demographics	Number of Students		60+
	Male		35
	Female		25
	% from underrepresented groups		65%

giiwed'anang North Star AISES Alliance
To continue support of Native American students in the state, collaborative efforts between the CCEFP, NCED, the Northstar STEM LSAMP Alliance, have led to the formation of the *giiwed'anang* Northstar Alliance of undergraduate AISES and newly formed SACNAS chapters in the state of Minnesota, which includes students from the University of Minnesota (Twin Cities, Morris, and Duluth); Fond du Lac Tribal and Community College, Leech Lake Tribal College, Bemidji State University and St. Cloud University and networks in North Dakota and Wisconsin. The collaboration seeks to deliver academic support for all Native American students in STEM disciplines in Minnesota. The goals of *giiwed'anang* (gee-way-di-nan) are to form relationships between Minnesota AISES and SACNAS undergraduate chapters, provide educational opportunities, academic guidance, open research doors, and bridge the gap between high school, pre- and post-secondary education and industry STEM fields. By networking with Minnesota industry and educational institutions, this alliance fosters fundraising capabilities and professional support and, in so doing, increases the potential for growth in the number of AISES chapters in Minnesota as well as a larger representation of Native Americans in STEM fields and disciplines. Through retreats and related events, the Center is developing personal relationships with the students of *giiwed'anang* and continues to encourage them to participate in research opportunities at CCEFP, NCED and the alliance's universities and colleges.

Outcomes:

giiwed'anang North Star AISES Alliance	Activity	# of students
	Retreat 1, Cloquet, MN: January 2008	8
	Region V AISES Meeting, SD: April 2008	13
	Retreat 2, Cloquet, MN: May 2008	19
	North Star STEM LSAMP Kickoff Meeting: September 2008	10
	Retreat 3, Minneapolis, MN: October 2008	26
	AISES National Conference: November 2008	14
	Retreat 4, Cloquet, MN: February 2009	14
	AISES Region V Annual Meeting: March 2009	13
	AISES National Conference: October 2009	8
	giiwed'anang Presentation at AISES National	20
	Retreat 5, Portland, OR: October 2009	15
	Outreach Activity: gidaa STEM Camp, Cloquet, MN	6
	AISES Professional Chapter: Meeting 1, December 2009	4
	AISES Professional Chapter: Meeting 2, January 2010	4
	AISES Region V Annual Meeting: April 2010	8
	AISES National Conference: November 2010	10
	giiwed'anang Dinner at AISES National: November 2010 (co-sponsored with Northstar LSAMP)	40+
	giiwed'anang Special Presentation: Native Skywalkers at St. Cloud State University (co-sponsored with Northstar LSAMP): November 2011	20+
	Received funding from Minnesota NASA Space Grant Consortium for a Rocket Team	4

Table 7a: Diversity Statistics for ERC faculty and students

	US Citizens or Permanent Residents					Foreign (Temporary Visa Holders)					Citizenship Not Reported				
	Leadership Team [5]	Faculty [6]	Doctoral Students	Masters Students	Undergraduate Students	Leadership Team [5]	Faculty [6]	Doctoral Students	Masters Students	Undergraduate Students	Leadership Team [5]	Faculty [6]	Doctoral Students	Masters Students	Undergraduate Students
Center Total[1]	**11**	**38**	**34**	**27**	**96**	**0**	**4**	**25**	**9**	**4**	**0**	**0**	**0**	**0**	**1**
Women															
Category Total	4	7	5	3	39	0	0	1	2	0	0	0	0	0	0
Center Percent [2]	36%	18%	15%	11%	41%	0%	0%	4%	22%	0%	0%	0%	0%	0%	0%
National Percent [3]	N/A	12.7%	22.9%	21.6%	18.2%	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	5	4	2	51	0	0	2	0	1	0	0	0	0	0
Center Percent [2]	9%	13%	12%	7%	53%	0%	0%	8%	0%	25%	0%	0%	0%	0%	0%
National Percent [3]	N/A	2.7%	2.3%	3.4%	5.9%	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	2	1	0	5	0	0	1	3	1	0	0	0	0	0
Center Percent [2]	0%	5%	3%	0%	5%	0%	0%	4%	33%	25%	0%	0%	0%	0%	0%
National Percent [3]	N/A	3.5%	2.4%	4.2%	9.4%	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	2	1	3	0	0	0	0	0	0	0	0	0	0
Center Percent [2]	0%	0%	6%	4%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
National Percent [3] [4]	N/A	6.0%	3.0%	5.4%	10.4%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

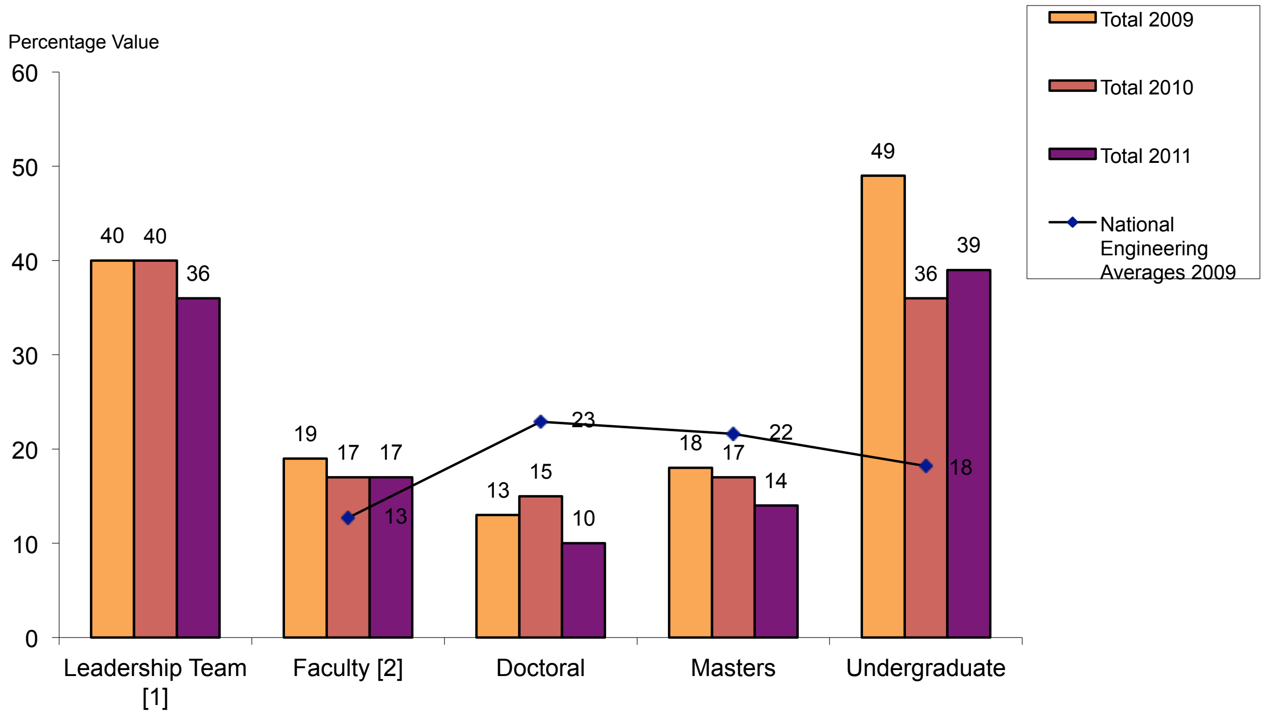
[1] The Center Total includes Men, Women, Gender Not Reported, Persons with Disabilities, Underrepresented Racial Minorities, Hispanic/Latinos
[2] The Center Percentage is based on all U.S. Citizens/permanent residents, foreign personnel and personnel who did not report their citizenship status
[3] The National Percentages are based only on U.S. citizens / permanent residents
[4] All National averages are from 2009 data, except persons with disabilities which is from 2006 data for Faculty and 2008 data for Masters, Doctoral and Undergraduate students.
[5] Leadership Team Includes - Directors, Thrust Leaders, Education Program Leaders, Industrial Liason Officer, Administrative Director, and Research Thrust Management and Strategic Planning
[6] Faculty Includes - Directors, Thrust Leaders, Education Program Leaders, 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 [7]	Total
		UG Non-REU	REU	Graduate		Non-RET	RET			
				Doctoral	Masters					
42	2	74	27	59	36	33	6	0	32	319

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

Figure 7b: Women in the ERC [3]



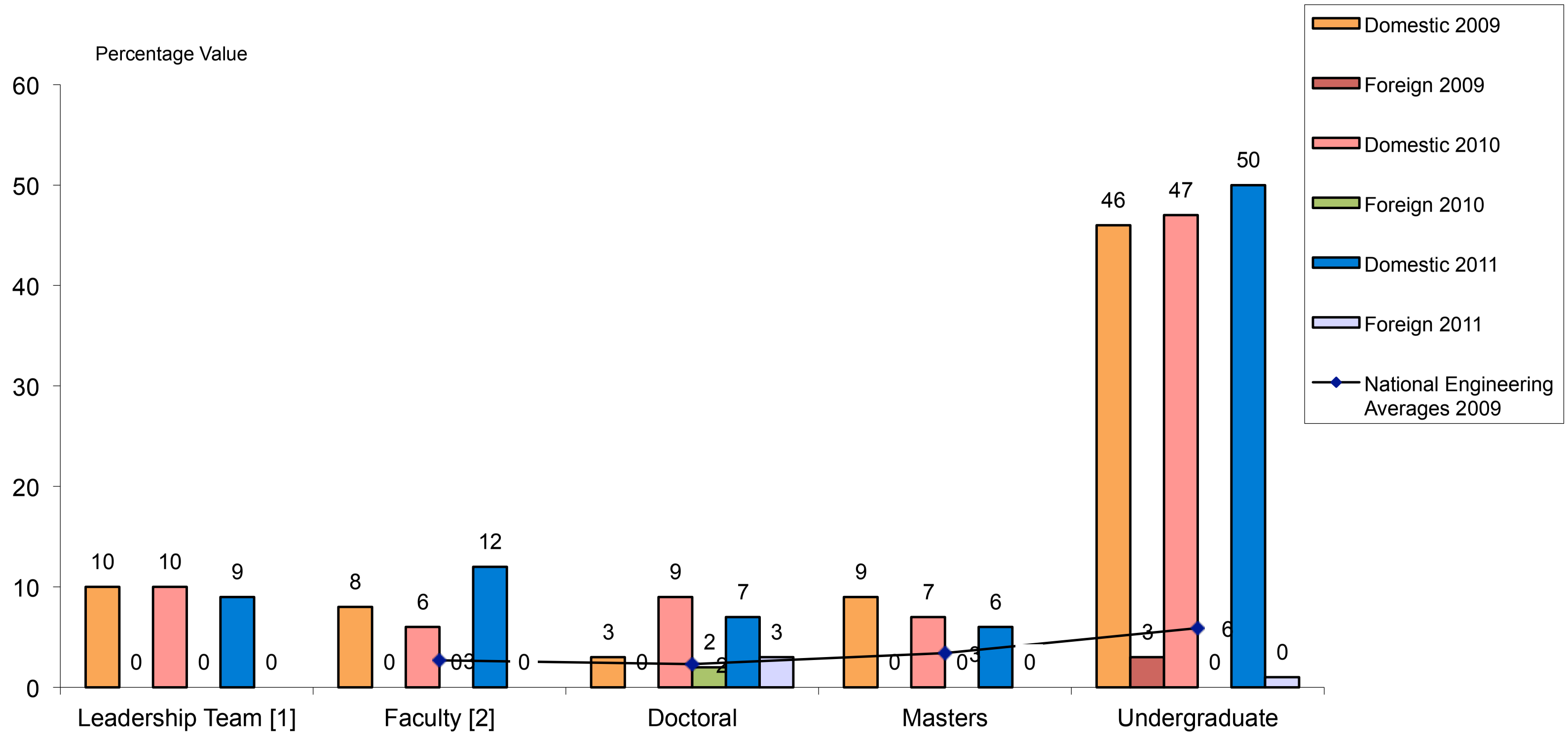
Averages	Faculty	Doctoral	Masters	Undergraduate	Leadership Team
National Engineering Averages 2009	12.7%	22.9%	21.6%	18.2%	N/A
All ERC's 2010	22.17%	23.53%	24.04%	34.71%	31.33%

[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 - Directors, Thrust Leaders, Education Program Leaders, 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] Total counts include personnel regardless of citizenship status

Figure 7c: Underrepresented Racial Minorities in the ERC

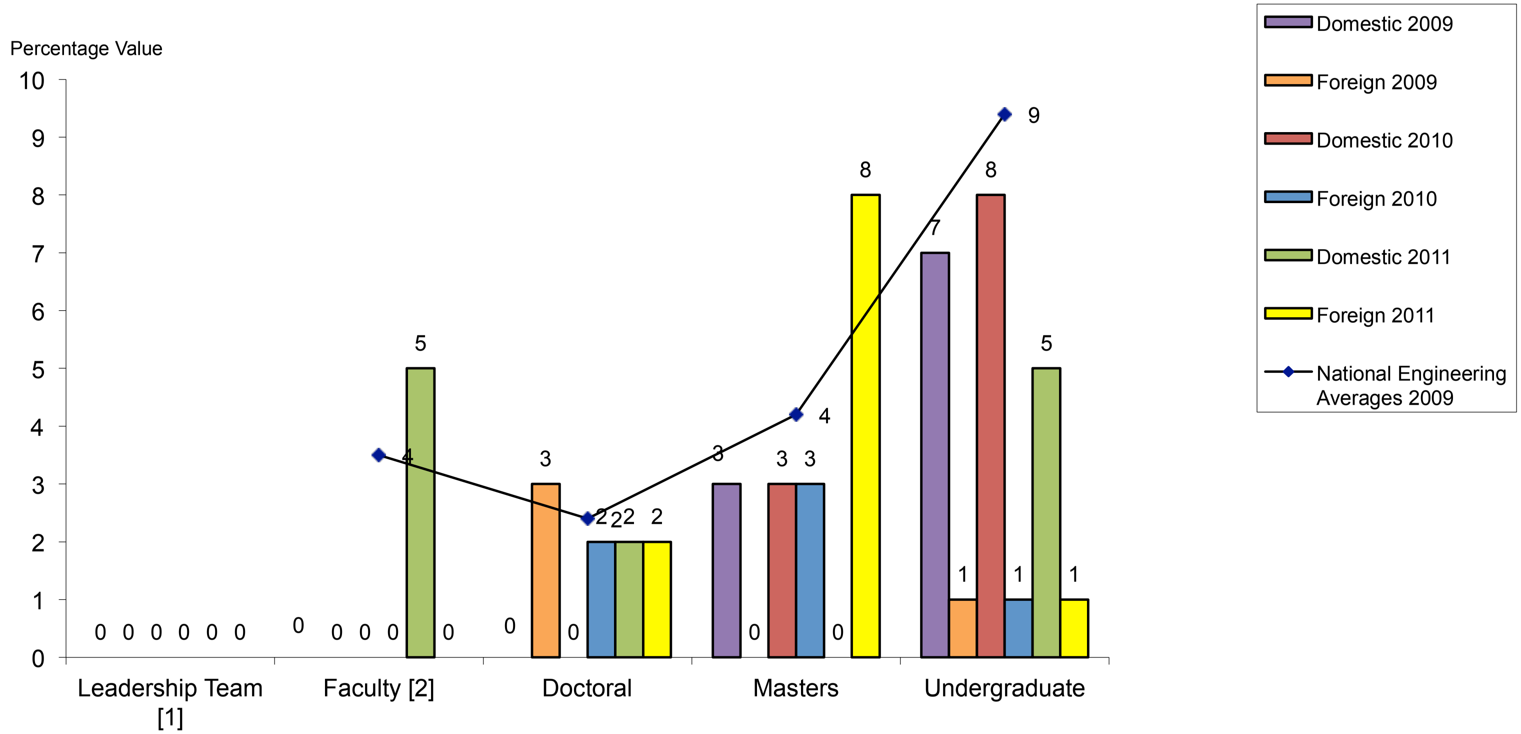


Averages	Faculty	Doctoral	Masters	Undergraduate	Leadership Team
National Engineering Averages 2009	2.7%	2.3%	3.4%	5.9%	20.5%
All ERC's 2010	10.41%	7.7%	10.1%	28.53%	11.45%

[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 - Directors, Thrust Leaders, Education Program Leaders, 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

Figure 7d: Hispanics/Latinos in the ERC

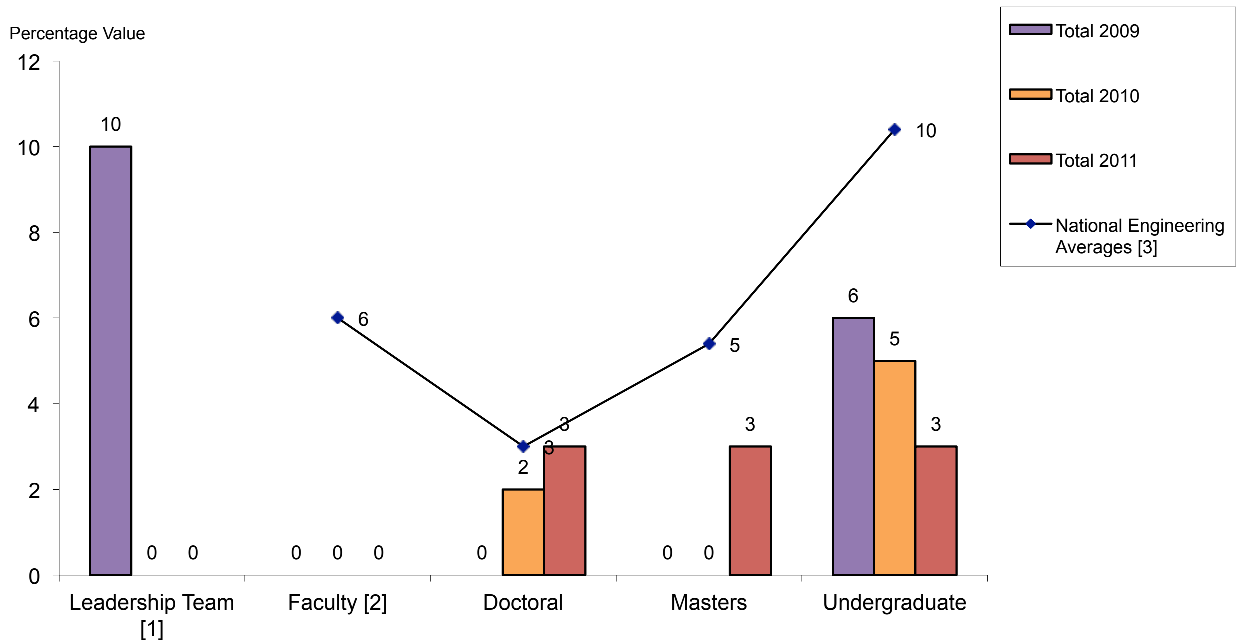


Averages	Faculty	Doctoral	Masters	Undergraduate	Leadership Team
National Engineering Averages 2009	3.5%	2.4%	4.2%	9.4%	N/A
All ERC's 2010	8.37%	7%	12.02%	14.12%	7.23%

[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 - Directors, Thrust Leaders, Education Program Leaders, 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

Figure 7e: Persons with Disabilities in the ERC [4]



Averages	Faculty	Doctoral	Masters	Undergraduate	Leadership Team
National Engineering Averages [3]	6.0%	3.0%	5.4%	10.4%	N/A
All ERC's 2010	1.13%	0.84%	0.48%	0.59%	2.41%

[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 - Directors, Thrust Leaders, Education Program Leaders, 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] National Engineering Average data for disabled personnel reflects 2006 percentages (Faculty), and 2008 percentages (Masters, Doctoral, and Undergraduate students)

[4] Total counts include personnel regardless of citizenship status

Table 7f: Center Diversity, by Institution						
Institution	Women		Underrepresented Racial Minorities [1] [2]		Hispanics [1] [3]	
	#	%	#	%	#	%
Lead Institution						
University of Minnesota	16	23%	14	20%	1	1%
Core Partner						
Georgia Institute of Technology	5	14%	0	0%	1	3%
Purdue University	3	9%	1	3%	1	3%
University of Illinois at Urbana-Champaign	2	11%	1	5%	0	0%
Vanderbilt University	2	17%	1	8%	1	8%
Collaborating Institutions						
Case Western Reserve University	1	100%	0	0%	0	0%
Fond du Lac Tribal and Community College	0	0%	1	50%	0	0%
Illinois Institute of Technology	0	0%	1	50%	0	0%
Milwaukee School of Engineering	4	19%	1	5%	2	10%
Montana State University	1	50%	0	0%	0	0%
North Carolina Agriculture and Technical State University	3	23%	7	54%	0	0%
Science Museum of Minnesota	1	20%	0	0%	0	0%
St. Cloud State University	5	100%	5	100%	0	0%
University of Michigan	0	0%	0	0%	0	0%
University of Minnesota - Morris	4	67%	6	100%	0	0%
University of North Dakota	3	50%	6	100%	2	33%
University of South Florida	0	0%	0	0%	1	100%
Non-ERC Institutions Providing REU Students						
Duke University	0	0%	0	0%	0	0%
Embry-Riddle Aeronautical University	0	0%	0	0%	0	0%
Iowa State University	1	100%	0	0%	0	0%
North Carolina State University	0	0%	1	100%	0	0%
University of Arizona	1	50%	1	50%	0	0%
University of Arkansas	1	100%	0	0%	0	0%
University of Cincinnati	0	0%	1	100%	0	0%
University of Florida	1	50%	0	0%	0	0%
University of Portland	1	100%	0	0%	0	0%
University of Texas at El Paso	0	0%	0	0%	1	100%
Washington State University	0	0%	0	0%	0	0%
Pre-college Partners						
Albrook School	2	50%	0	0%	0	0%
Bemidji High School	1	100%	0	0%	0	0%
Bemidji Middle School	5	83%	1	17%	0	0%
BugONayGeShig School	1	33%	2	67%	0	0%
Cass Lake Middle School	1	50%	0	0%	0	0%
Cloquet High School	0	0%	0	0%	0	0%
Cloquet Middle School	1	100%	0	0%	0	0%
Deer River School	0	0%	1	100%	0	0%
Gibbon, Fairfax, Winthrop School	0	0%	0	0%	0	0%
Lafayette Jefferson High School	0	0%	0	0%	0	0%
Mahnomen High School	1	50%	0	0%	0	0%
McCutcheon High School	0	0%	0	0%	0	0%
Metropolitan Nashville Public School	0	0%	0	0%	0	0%
Naytawaush Charter School	1	100%	1	100%	0	0%

Institution	Women		Underrepresented Racial Minorities [1] [2]		Hispanics [1] [3]	
	#	%	#	%	#	%
Ojibwe School	1	50%	2	100%	0	0%
Ponemah Elementary School	3	100%	1	33%	0	0%
Red Lake Middle School	1	25%	1	25%	0	0%
Robbinsdale Armstrong High School	0	0%	0	0%	0	0%
Rockdale Magnet School for Science and Technology	0	0%	0	0%	0	0%
Smyrna High School	0	0%	0	0%	0	0%
Walker Alternative School	0	0%	0	0%	0	0%

Community College						
Lac Courte Oreilles Ojibwa Community College	0	0%	3	100%	0	0%
Salish Kootenai College	1	17%	6	100%	1	17%

LSAMP						
North Carolina Agricultural And Technical St Univ, Greensboro	1	100%	1	100%	0	0%
Purdue University	0	0%	0	0%	1	100%
Salish Kootenai College, Pablo	1	25%	4	100%	0	0%
University of Minnesota Twin-Cities	6	75%	8	100%	1	13%

[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.

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5.3 MANAGEMENT EFFORT

The CCEFP management approach is now fully implemented with future changes being more evolutionary in nature. An exception has been a major reorganization. The reorganization was undertaken in response to Mike Gust's departure as CCEFP ILO in November 2011. This change gave us an opportunity to rethink some aspects of our organization. We have been working with two human resource experts at the University of Minnesota to carefully consider all aspects of our organizational structure. These were, Mel Mitchell, organizational expert in our university-wide HR department, and Karen Wolterstorff, Chief of Staff for the School of Science and Engineering. Kim Stelson, CCEFP Director has been leading this effort along with Lisa Wissbaum, our Administrative Director, with some additional input from Mike Gust.

Based on this study we have concluded that two new positions are needed in addition to the ILO. These are a Research and Technology Coordinator (RTC) and an External Relations and Communications Coordinator (ERCC). Both of these positions will report to the new ILO. Because of some staffing changes made elsewhere, the overall budget remains little changed. The new management structure is shown on the organization chart, below.

The new structure has several benefits. There will be clearer roles and responsibilities, the research program will be better managed, and we will become a more externally focused organization with higher visibility and better communication with our government and industry partners. These changes will help us greatly as we work toward sustainability.

The new ILO search is now underway. Our plan is to introduce the new ILO at our NSF Site Visit in March. We will delay posting the RTC and ERCC positions until the ILO is in place so that he or she can participate in the recruitment effort. We expect all three of the positions to be filled by the end of May.

New CCEFP Organization Chart

CCEFP uses modern management practices for its key processes such as strategic planning, project selection, budgeting, progress tracking and management communication. These practices are summarized in the table below. All processes have been implemented and continue to be refined and reinforced.

CCEFP Key Operational Processes Summary

Strategic Planning	Project Selection	Budgeting	Progress Updating	Communication
• Annual process that drives and aligns the entire organization.	• Detailed template identifying all critical aspects of the project to assist decision makers. • Section criteria for comparison.	• Budget "rules of thumb" established and utilized for FY2 budgets.	• Focus regular updates within Thrust areas. • Annual summary completed for NSF and industry.	• Include both internal and external communication processes
• Timing needs to meet NSF requirements. Annual review should take place before the next fiscal year begins.	• Need to solicit input from industry and students.	• Simple standardized template created. • Allows room for unique exceptions.	• Simple standardized 4-Up template created.	• Separate management and executive council sessions • Website to be the main portal to the world
• Focused leadership meeting to ensure alignment and develop strategy maps.	• Portfolio Management • Project Management techniques	• Projects budgeted for two years starting in FY5.	• Added Education and Outreach projects to the same format	• Monthly newsletter to targeted e-mail addresses • Regular localized staff meetings

CCEFP Management Practices

Project Selection
Beginning in year four, major revisions to the project selection process were made and a two year funding structure was adopted. At that time, all existing projects were terminated, with any follow-on research requiring a new proposal. For terminated projects, $25,000 of bridge funding was provided as the project transitions to other funding sources.

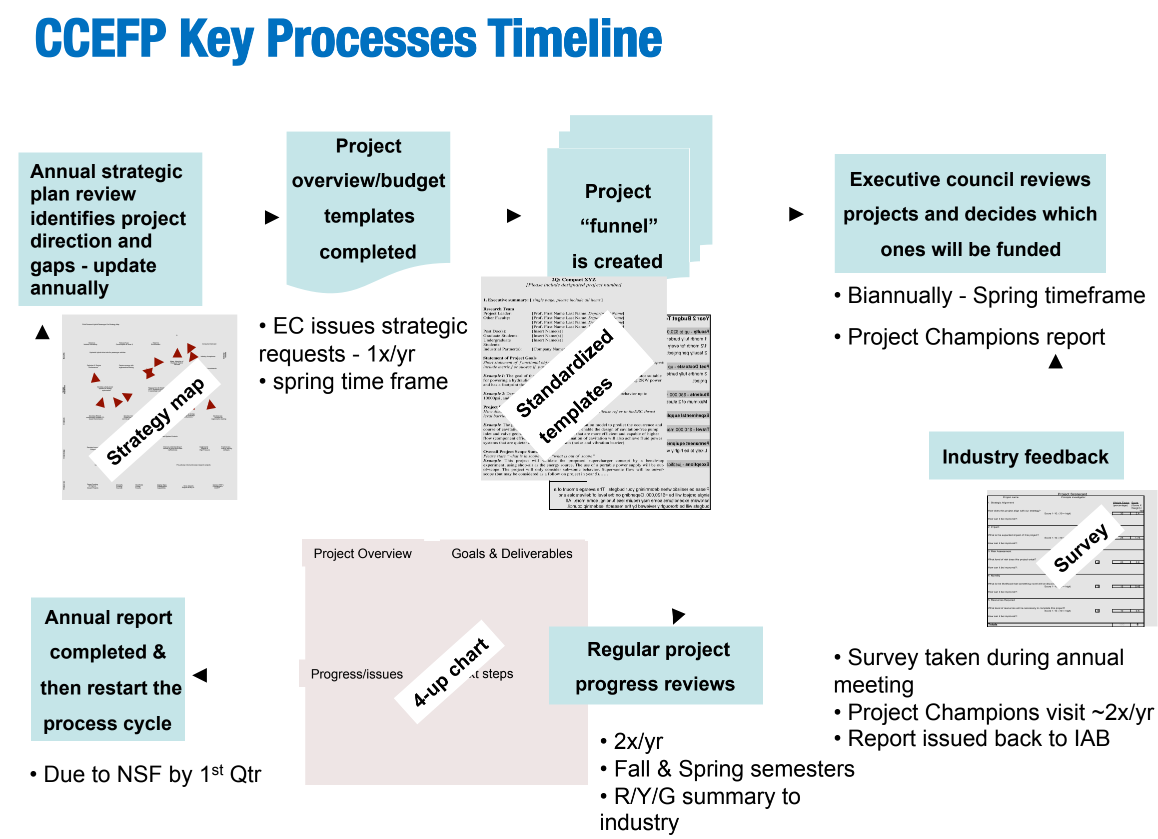
The main elements of the process started in year four and include a center-wide strategic call for proposals, a standardized proposal format, and an extensive evaluation procedure. The strategic call for proposals was a carefully worded three page summary of our strategy that identified research needs necessary to fulfill the strategy. It was widely circulated to both existing and potential new research project leaders along with an updated standardized proposal template. The template was also enhanced to include more focus on the project's research approach, strategic fit, fundamental research content, schedule, deliverables and metrics.

For year five and six funding, a total of thirty-five proposals were received. Of these, budget forecasts allowed for funding of only twenty-four. Five existing projects were terminated, and four new ones were brought into the Center. The non-funded proposals make up a "project funnel" for future consideration when other funding sources are made available.

The CCEFP IAB enthusiastically embraced the new project selection process. They assigned review teams made up of over 30 experts from their organizations to review each and every proposal. Each proposal had at least two industry reviewers. To ensure uniformity, they developed and adopted a standardized review template with fifteen distinct criteria. These criteria were separated into three subgroups: project risk, reward or alignment (strategic fit). The review results were discussed extensively during IAB teleconferences until a final outcome was reached and forwarded to the IAB representatives on the CCEFP Executive Committee (EC). This review process also laid the groundwork for risk-reward portfolio management. A visual representation of the selected fluids projects portfolio is shown in the subsequent Risk-Reward Portfolio for Fluid Related Projects. The x-axis is risk, and the y-axis is reward, while the size of the bubble is strategic alignment.

We are now in the first year of the new two-year funding cycle. In the fall of 2011 a new cycle will begin with updated strategy and call for proposals. The funding decisions for years seven and eight will be decided in early 2012. This will allow sufficient time to recruit graduate students to begin projects in fall 2012. The number of projects is expected to decrease from twenty-four to twenty. This change will be made in recognition that current projects are underfunded delaying progress. Also, NSF funding will decrease in years nine and ten, so the project numbers must begin decreasing in anticipation of this change.

The CCEFP process timeline for project proposals and the standardized review template are summarized in the two images below.



CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

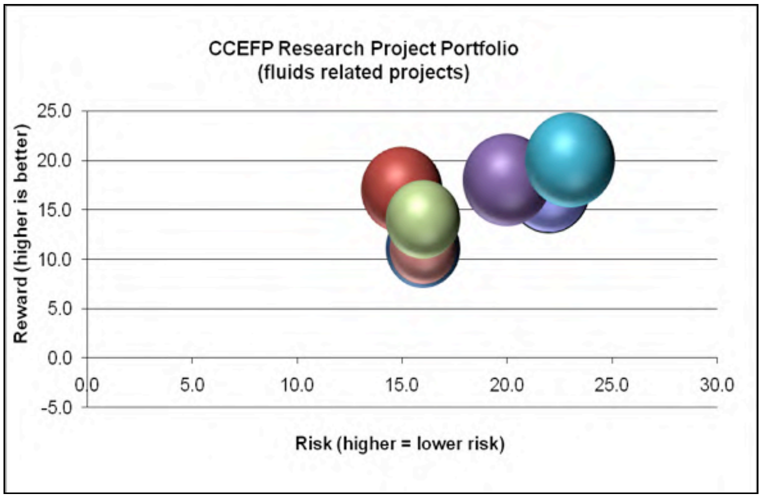
Year 5-6 Proposal Scorecard

Project scores:	**Alignment:**	**15.0**
	Risk:	**15.0**
	Reward:	**15.0**

Proposal number:	x
uation of existing project number:	2.C.x
Project name:	**Advanced Energy Storage Device**
Project PI:	Prof TBD
Brief project description:	The research objective of this proposed work is to extend the current state of knowledge in the use of chemical means for fluid power energy storage. Specifically, this project will seek a low cost, low/no maintenance, high energy density accumulator primarily targeted toward a fluid powered automotive regenerative braking system (hydraulic hybrid).

			Score					
	Scoring Parameter	**Weight (%)**	**1**	**2**	**3**	**4**	**5**	**Enter score (integers only)**
Alignment	Fundamental nature of proj	100%	Largely technology development	Extension of known technology into new space.	Some level of fundamental research apparent	Largely fundamental research (extension of current or past work)	Largely fundamental research (novel direction)	1
	Systems approach	100%	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.	Demonstartion of one or more fluid power systems is planned during this project proposal time	2
	Strategic fit	100%	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	3
	Alignment with test bed	100%	Little or no alignment	Partial alignment, but research not consistent with main focus of test bed	Partial alignment and research is consistent with main focus of test bed	Completely aligned and consistent with scope of test bed	Completely and expands scope of test bed in a manner consistent with Center's goals	4
	Center goals focused	100%	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	100%	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	1
	Deliverables	100%	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	Fullt defined, SMART and competitive benchmarks are part of deliverables	2
	Likelihood of success	100%	Unclear	Moderate - est. 25%	Good - est. 50%	Very good - est. >67%	High - est. >80% (e.g., builds on past successes)	3
	Team assessment	100%	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 processes all critical skillsets for project success	It is apparent that the team processes all critical skillsets for project success	4
	Budget Assessment	100%	It is apparent that the proposed budget is dramatically too high or dramatically insufficient to meet project scope or well outside of specified guidelines	The proposed budget is questionable with respect to project scope or specified guidelines	The proposed budget is adequate	The proposed budget is reasonable based on project scope and specified guideleines	It is apparent that the proposed budget is appropriate to meet project scope and within specified guidelines	5
Reward	Industry participation	100%	No industry partners identified	Potential partners indentified but not yet committed	Letter of support from industry partner	Letter of support and commitment of resources from industry partner	Letters of support and commitment of resources from multiple industry partners	1
	Addressing CCEFP techni	100%	Weak or no link to technical barriers	Addresses one non-transformational technical barrier	Addresses multiple non-transformational technical barrier	Addresses a transformational technical barrier	Addresses multiple technical barriers including at least one transformational barrier	2
	Breadth of applicability	100%	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	3
	External support	100%	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	4
	Original nature of project	100%	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	5

Standardized Review Template



Risk-Reward Portfolio for Fluid Related

Communication
CCEFP must communicate to all its 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.

2010 saw the continuation of our strategy to target specific stakeholder groups for consistent and meaningful communications efforts. 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.

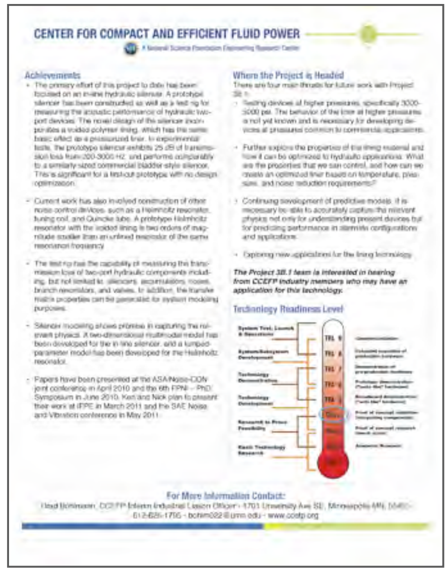
CCEFP efforts to further engage students and faculty have included a formal, online survey tool to provide feedback to Center leadership with regard to meetings, events, project reviews and other operations that require the participation of all members.

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:

Research Project Overviews - In 2010, we have chosen to summarize the key elements of each research project in their own informational and promotional sheets. These Research Project Overview sheets will outline the unmet need, benefit to industry, research personnel, project achievements and technology readiness level (TRL) of each CCEFP project. Not only will these sheets be informative for member industry executives and technologists, but they will also be beneficial to the recruitment of new industry partners. As such they will be made available during the 2011 IFPE show.

Front



Back

Meetings - The CCEFP has two annual meetings: the NSF Site Visit and the CCEFP Annual Meeting. The primary purpose of the Site Visit is for NSF Center review. The primary purpose of the Annual Meeting is to communicate directly with industry. The Site Visits have always been held at the University of Minnesota, and the 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

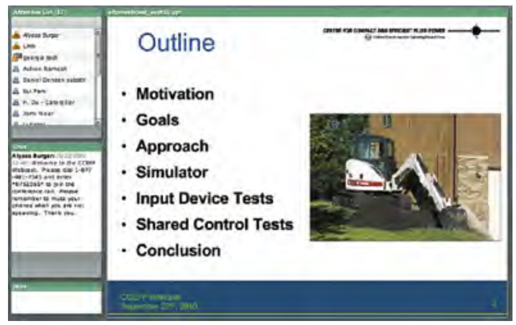
In March 2011, the CCEFP's Site Visit and Annual Meeting will be combined and held in conjunction with the International Exposition for Power Transmission (IFPE) which itself is co-located with the CONEXPO-CON/AGG event in Las Vegas, Nevada. IFPE is the leading international exposition and technical conference dedicated to the integration of fluid power with other technologies for power transmission and motion control applications. IFPE features over 500 exhibits, a renowned technical conference with over 100 presentations from industry and academic experts, and an international audience of nearly 30,000. CONEXPO-CON/AGG showcases the latest equipment, products, services and technologies. Combined, these events represent the largest industry trade show in the world and the Center will have a key role in presenting its research during the event's technical conference, the 52nd National Conference on Fluid Power.

Website - The CCEFP website, www.ccefp.org, was completely redesigned and re-launched in March 2009. The website continues to be the Center's primary means of communicating information to the widest audience and content is updated regularly. A password-protected member's only section allows industry, 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 visually interesting and concise updates on a variety of activities taking place in and around the Center each month. The abbreviated format of the stories enables the reader to see a brief synopsis of each with the option to read more. In this way, readers can stay abreast of the latest news items without having to read through the full articles.

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 list-serve and reaches subscribers in all stake-holder areas including academia, the trade press, industry, K-12 education, and many others both in the U.S. and internationally.

Online Survey Tool - Online surveying has been implemented to assess preferences of faculty, students and industry members prior to planning meetings and/or events at which the full membership will participate, and to gauge attendee satisfaction following such events. In addition, the tool has been used to obtain feedback on various other CCEFP administrative systems already in use, so the leadership can determine methods and frequency of use, preferences, and recommendations from the users before making changes to those systems.

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 100 requests from educators and other interested parties 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, YouTube and TeacherTube. CCEFP will continue to reach out to various audiences using these and other free, ubiquitous online tools whenever appropriate.

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 anywhere 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.


LUBE REPORT
Industry News from LUBES-n-GREASES

Lube Report
February, 2010


OEM Off-Highway
Efficient, Effective, Compact

OEM Off-Highway
November, 2010


IN PURSUIT OF SILENCE

Diesel Progress
December 2010

Sustainability
CCEFP is actively pursuing a plan for the transition to sustainability. We have created a new part-time position, CCEFP External Funding Director, to develop research funding opportunities. Brad Bohlmann has been recently hired for this position. Brad has a solid track record of attracting research funding in his previous position in the Hydraulics Division of Eaton Corporation. He is currently serving as interim ILO while the replacement for Mike Gust is sought.

We have also formed the CCEFP Sustainability Task Force to create a plan to guide us through the transitionThe members of the task force are:

- Kim Stelson, University of Minnesota, Chair
- Andrew Alleyne, University of Illinois, Urbana-Champaign
- Wayne Book, Georgia Institute of Technology
- Tom Bray, Milwaukee School of Engineering
- Mike Gust, University of Minnesota
- Ed Howe, Enfield Technologies
- Monika Ivantysynova, Purdue University
- Joe Kovach, Parker-Hannifin

- Eric Lanke, National Fluid Power Association
- Lonnie Love, Oak Ridge National Laboratory
- Bill Parks, Deltrol Fluid Products

The track record of previous ERCs gives us hope, since most of them have successfully made the transition to sustainability. Previous transitions, however, have always been challenging with difficult choices being made due to the changing funding picture. Most previous ERCs continue their research, but funding for education and outreach was generally more difficult to find. ERCs generally continued operation with a combination of increased industry support and funding from mission-oriented government agencies such as DOD, DOE, NIH, etc. The industry support usually takes the form of increased dues and funding for associated research projects focused on specific member company needs. The key to success is to anticipate and take actions to counteract the transition early since the funding cutoff is so drastic.

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.

During the reporting period, CCEFP's two post-docs were mentored as follows:

Ilker Bayer, University of Illinois at Urbanan-Champaign

Ilker has developed into a principal investigator and directly supervised both graduate and undergraduate students. Ilker took the lead in working with Gates Corporation on nano-texture coatings to substantially improve non-wetting characteristics and Haldex on nano-particle additives that improved their external gear pump efficiency by more than 25%. He helped invent a new type of nanocomposite coating technique and led the efforts on three high-impact journal paper submissions through acceptance.

Dr. Feng Wang, University of Minnesota

Feng Wang is here for two years and he is a Post Doc associate. He did his graduate studies at Zhejiang University and is preparing for an academic career. We are broadening his experience with theoretical and applied studies at both the component and system level. Feng is also collaborating on research with Sauer Danfoss (a CCEFP member company). He has completed a theoretical study of the influence of viscocity and gap size on the efficiency of hydraulic pumps and motors. He has also completed a system level comparison of hydraulic and electric hybrid vehicles. Feng's next project will involve the study of the use of a hydrostatic transmission for wind power, a CCEFP associated project. He meets with Prof. Stelson on a regular basis and has functioned well in opportunities to provide leadership to graduate students.

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.

Financial Tables

Table 8 shows the planned functional budget for Year 5 (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 (38%), Compactness Thrust (28%), Effectiveness Thrust (18%), Test Beds (16%). The percentage distribution of the functional budget is shown in Figure 8a. The major expense is research, shown at 47% of the budget, with funding for education and outreach activities (including REU and RET) at 12%. It is expected that this basic distribution will continue into the future with only minor modifications. In-kind contributions of equipment and software have increased as the Center matures and our methods for tracking those contributions are still improving.

In future years, modest growth is expected in industry funding and in associated projects. Industry funding has remained steady from years 1-5, with almost all promised membership dues received even through the economic downturn. At the end of the reporting year (1/31/11) of year 5, almost all promised membership dues ($689,000) were received. New member company, Case New Holland, joined too recently to be reflected in this year's report, but their new membership shows a path of slow and steady industrial growth in coming years. Associated project funding has continued to grow each year. As shown in Table 9, associated project funding for years 1-4 shows total funds received by CCEFP primary investigators (direct and indirect costs); where year 5 reflects associated project funding, direct costs only. Comparatively, year 5 funding was 29% higher than year 4.

Year 5: $1,885,000 (direct costs only) - Total funding was 2.4 million
Year 4: $1,725,000 (all costs)

Table 8b below shows Year 5 budget distribution by university. The largest recipient of direct cash funding and associated project funding is the lead university with 38%. 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 Direct Costs	Total Cash and Associated Projects	% of Total Direct Cash	% of Total Assoc. Projects
University of Minnesota	$2,206,267	$717,832	$2,924,099	38%	38%
Georgia Tech	$877,199	$265,048	$1,142,246	15%	14%
Milwaukee School of Engineering	$334,676	$220,446	$555,122	6%	12%
North Carolina A & T	$207,229	$0	$207,229	4%	0%
Purdue University	$873,495	$596,121	$1,469,616	15%	32%
UIUC	$590,268	$0	$590,268	10%	0%
Vanderbilt University	$541,421	$85,866	$627,287	9%	5%
Science Museum of Minnesota	$90,000	$0	$90,000	2%	0%
Folsom Technologies International	$98,000	$0	$98,000	2%	0%
Grand Total	$5,818,556	$1,885,313	$7,703,868		

Table 9a shows the funding history of the Center and includes the NSF approved renewal proposal for years 6-10, supplemental funding for a SBIR ERC Collaboration Opportunity Grant (SECO, $199,999), and three students received supplemental graduate student funding (GRS: $44,814, $81,725).

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	5 years	$17,872,339	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	In progress	N/A

Table 9 (at the end of this section) shows the sources of support, and Table 9b below includes the cost sharing by institution. In Year 4, the Center met its cost-share obligation with two of the five institutions meeting or exceeding commitments. The University of Minnesota met its cost-share contribution, but the cash contribution transaction fell in award year 5, therefore it will be shown in the next report.

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	-	$339,537	-
Georgia Tech	$142,995	$267,384	$152,000	-	$130,232	-
MSOE	$0	-	$0	-	$0	-
Purdue	$142,995	$139,404	$152,000	-	$152,557	-
UIUC	$142,995	$210,852	$119,541	-	$92,093	-
Vanderbilt	$94,648	$69,213	$101,333	-	$85,581	-
	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 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 10a, the carry-forward amount of $0 into Year 6 demonstrates that the Center has achieved a more disciplined and steady spending pattern as was predicted after Years 1-3, where carry-forwards were $1.9 million, $1.5 million, and $651,000 respectively.

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	$846,652	$2,018,369
Committed, Encumbered, Obligated funds	$868,000	$2,018,369
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 8: Functional Budget										
Function	Direct Support							Direct Support Total	Associated Projects	Total
	ERC Program	Industry	State	University	Other NSF	Other Government	Other			
1: Efficiency	$863,884	$85,799	$0	$85,800	$0	$0	$0	$1,035,483	$1,089,661	$2,125,144
2: Compactness	$613,700	$76,712	$0	$76,712	$0	$0	$0	$767,124	$580,167	$1,347,291
3: Effectiveness	$391,998	$49,000	$0	$49,000	$0	$0	$0	$489,998	$215,485	$705,483
Test Beds	$348,577	$87,144	$0	$0	$0	$0	$0	$435,721	$0	$435,721
Research Total	$2,218,159	$298,655	$0	$211,512	$0	$0	$0	$2,728,326	$1,885,313	$4,613,639
General & Shared Equipment	$173,145	$0	$0	$0	$0	$0	$0	$173,145	$0	$173,145
New Facilities/ New Construction	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Leadership/ Administration/ Management	$42,000	$181,518	$0	$548,488	$0	$0	$0	$772,006	$0	$772,006
Education Programs (excluding REU and RET Programs)	$306,488	$105,003	$0	$0	$0	$0	$0	$411,491	$0	$411,491
Research Experiences for Teachers Program	$60,000	$0	$0	$0	$0	$0	$0	$60,000	$0	$60,000
Research Experience for Undergraduates Program	$212,500	$0	$0	$0	$0	$0	$0	$212,500	$0	$212,500
Industrial Collaboration/Innovation Program	$0	$16,900	$0	$0	$0	$0	$0	$16,900	$0	$16,900
Center Related Travel	$70,000	$86,924	$0	$40,000	$0	$0	$0	$196,924	$0	$196,924
Residual Funds Remaining	$0	$0	$0	$0	$0	$0	$0	$0	N/A	$0
Indirect Cost	$1,209,432	$0	$0	$0	$0	$0	$0	$1,209,432	N/A	$1,209,432
Total	$4,291,724	$689,000	$0	$800,000	$0	$0	$0	$5,780,724	$1,885,313	$7,666,037

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

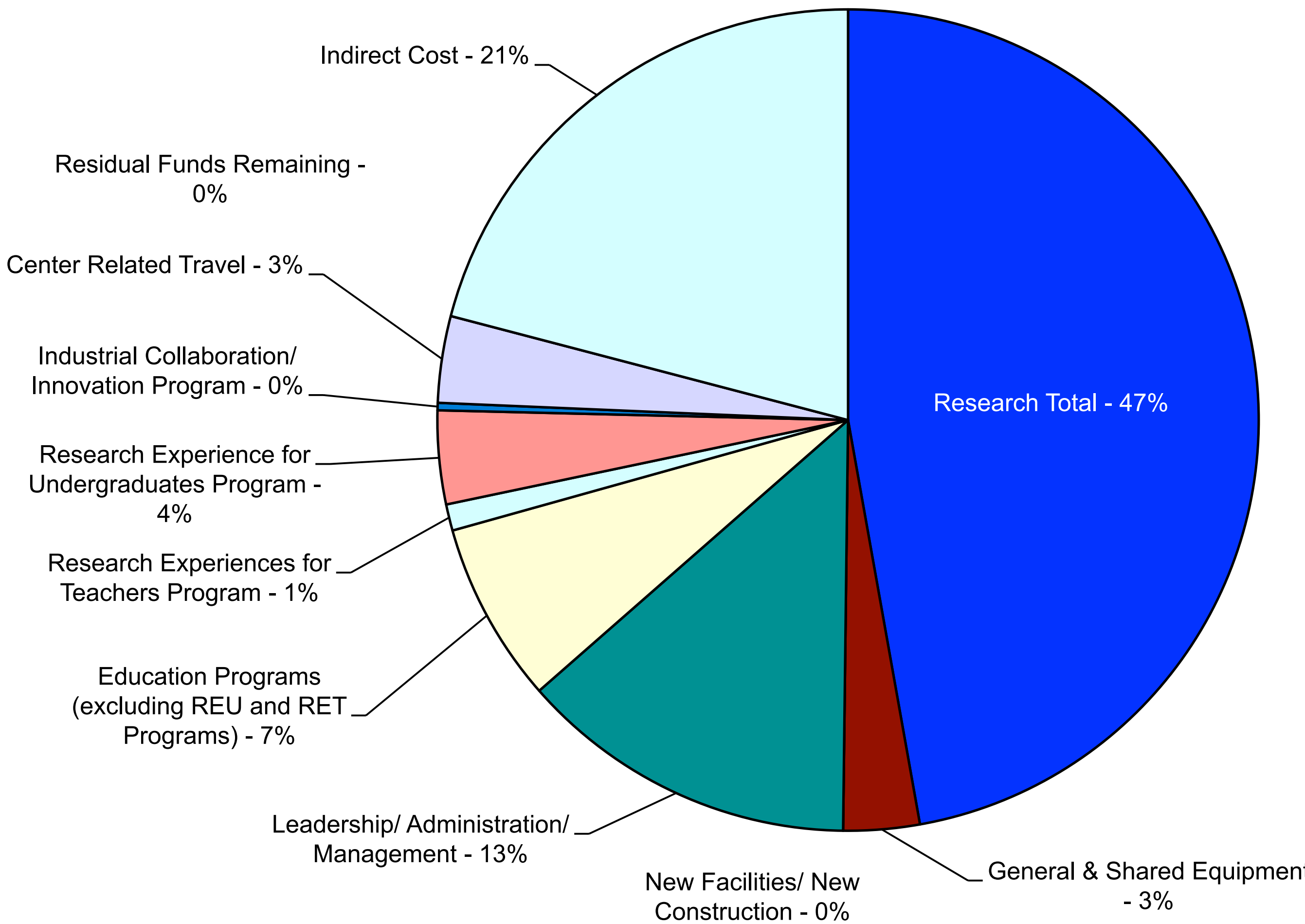


Table 8c
Educational Expenses

	Direct Support	Associated Project Support	Total
Pre-college activities	$35,437.00	$300,000.00	$335,437.00
Curriculum Development	$9,500.00	$0.00	$9,500.00
Student Leadership Council (SLC)	$3,000.00	$0.00	$3,000.00
High School Research Opportunity Program (HSROP)	$0.00	$0.00	$0.00
REU	$212,000.00	$16,000.00	$228,000.00
RET	$57,000.00	$0.00	$57,000.00
Assessment	$45,000.00	$0.00	$45,000.00
Community College activities	$0.00	$0.00	$0.00
Other: Science Museum of Minnesota (public outreach / exhibits)	$90,000.00	$0.00	$90,000.00
Other: Fluid Power Scholars (industry / undergraduate)	$8,800.00	$48,000.00	$56,800.00
Other: giiwed'anang Northstar Alliance (undergraduate Native American STEM students)	$6,500.00	$2,000.00	$8,500.00
TOTAL	$467,237.00	$366,000.00	$833,237.00

Table 9: Sources of Support									
Sources of Support	Early Cumulative Total [1]	June 01, 2006 - May 31, 2007	June 01, 2007 - May 31, 2008	June 01, 2008 - May 31, 2009	Jun 01, 2009 - May 31, 2010	Jun 01, 2010 - May 31, 2011			Cumul. Total [2]
						Rec'd.	Prom.	Total	
Unrestricted Cash									
NSF ERC Base Award	$0	$1,946,020	$3,250,000	$3,500,000	$3,750,000	$4,010,000	$0	$4,010,000	$16,456,020
U.S. Industry	$0	$50,793	$633,000	$591,500	$579,415	$571,500	$36,500	$608,000	$2,462,708
Foreign Industry	$0	$60,000	$60,000	$141,000	$108,000	$81,000	$0	$81,000	$450,000
State	$0	$0	$0	$0	$0	$0	$0	$0	$0
U.S. University	$0	$313,763	$650,000	$831,646	$913,885	$800,000	$0	$800,000	$3,509,294
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other Source.	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL Unrestricted Cash	**$0**	**$2,370,576**	**$4,593,000**	**$5,064,146**	**$5,351,300**	**$5,462,500**	**$36,500**	**$5,499,000**	**$22,878,022**
Restricted Cash									
NSF ERC Program Special Purpose Awards and Supplements	$0	$0	$65,801	$59,133	$44,814	$281,724	$0	$281,724	$451,472
U.S. Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
State	$0	$0	$0	$0	$0	$0	$0	$0	$0
U.S. University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign University	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (Not ERC Program)	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other U.S. Government (Not NSF)	$0	$0	$0	$0	$0	$0	$0	$0	$0
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other Source.	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL Restricted Cash	**$0**	**$0**	**$65,801**	**$59,133**	**$44,814**	**$281,724**	**$0**	**$281,724**	**$451,472**
Residual Funds									
NSF/ERC Program [2]	$0	$1,023,980	$279,300	$696,322	$316,642	$0	$0	$0	N/A
U.S. Industry [2]	$0	$587,207	$599,662	$484,959	$297,485	$0	$0	$0	N/A
Foreign Industry [2]	$0	$0	$0	$0	$0	$0	$0	$0	N/A
State [2]	$0	$0	$0	$0	$0	$0	$0	$0	N/A
U.S. University [2]	$0	$298,502	$127,439	$281,567	$232,525	$0	$0	$0	N/A
Foreign University [2]	$0	$0	$0	$0	$0	$0	$0	$0	N/A
Other NSF (Not ERC Program) [2]	$0	$0	$49,656	$0	$0	$0	$0	$0	N/A
Other U.S. Government (Not NSF) [2]	$0	$0	$0	$0	$0	$0	$0	$0	N/A
Foreign Government [2]	$0	$0	$0	$0	$0	$0	$0	$0	N/A
Other Source. [2]	$0	$0	$0	$0	$0	$0	$0	$0	N/A
TOTAL Residual Funds [2]	**$0**	**$1,909,689**	**$1,056,057**	**$1,462,848**	**$846,652**	**$0**	**$0**	**$0**	**N/A**
Associated Projects									
U.S. Industry	$0	$457,629	$620,235	$663,806	$1,098,877	$379,599	$0	$379,599	$3,220,146
Foreign Industry	$0	$0	$0	$0	$0	$0	$0	$0	$0
State	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other NSF (not ERC program)	$0	$113,333	$28,833	$99,326	$99,051	$157,667	$0	$157,667	$498,210
Other US Government (not NSF)	$0	$653,318	$150,000	$734,017	$527,447	$640,749	$0	$640,749	$2,705,531
Foreign Government	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other (specify source)	$0	$5,000	$20,000	$141,620	$0	$675,298	$0	$675,298	$841,918
Foreign University	$0	$0	$0	$0	$0	$32,000	$0	$32,000	$0
TOTAL Associated Projects	**$0**	**$1,229,280**	**$819,068**	**$1,638,769**	**$1,725,375**	**$1,885,313**	**$0**	**$1,885,313**	**$7,297,805**
TOTAL Cash Support, All Sources [3]	**$0**	**$4,280,265**	**$5,714,858**	**$6,586,127**	**$6,242,766**	**$5,744,224**	**$36,500**	**$5,780,724**	**$23,329,494**
Value of Equipment									
U.S. Industry	$0	$159,000	$75,000	$350,402	$0	$90,000	$0	$90,000	$674,402
TOTAL Value of In-Kind Equipment	**$0**	**$159,000**	**$75,000**	**$350,402**	**$0**	**$90,000**	**$0**	**$90,000**	**$674,402**
Value of New Facilities in Existing Buildings									
U.S. University	$0	$57,591	$193,000	$375,000	$0	$0	$0	$0	$625,591
TOTAL Value of New Facilities in Existing Buildings	**$0**	**$57,591**	**$193,000**	**$375,000**	**$0**	**$0**	**$0**	**$0**	**$625,591**
Value of Visiting Personnel									
U.S. Industry	$0	$0	$0	$22,500	$0	$63,862	$0	$63,862	$86,362
U.S. University	$0	$0	$0	$16,200	$0	$0	$0	$0	$16,200
Foreign University	$0	$10,000	$39,500	$10,000	$0	$0	$0	$0	$59,500
Other Assets									
TOTAL Value of Visiting Personnel	**$0**	**$10,000**	**$39,500**	**$48,700**	**$0**	**$63,862**	**$0**	**$63,862**	**$162,062**
U.S. Industry	$0	$0	$0	$0	$0	$57,927	$0	$57,927	$57,927
Other Source.	$0	$0	$0	$0	$169,032	$0	$0	$0	$169,032
TOTAL Value of Other Assets Donated	**$0**	**$0**	**$0**	**$0**	**$169,032**	**$57,927**	**$0**	**$57,927**	**$226,959**
TOTAL In-Kind Support, All Sources	**$0**	**$226,591**	**$307,500**	**$774,102**	**$169,032**	**$211,789**	**$0**	**$211,789**	**$1,689,014**
Percent Non-ERC Program Cash	**N/A**	**17.91**	**28.83**	**30.53**	**29.68**	**25.29**	**100.00**	**25.76**	**27.53**
Grand Total (Cash + In-Kind)	**$0**	**$4,506,856**	**$6,022,358**	**$7,360,229**	**$6,411,798**	**$5,956,013**	**$36,500**	**$5,992,513**	**$30,293,754**

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

[2] 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.

[3] 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.

Table 10: Annual Expenditures and Budgets

Expenses Proposed and Residual Budget	Early Cumulative Total [1]	June 01, 2006 - May 31, 2007 Expend.	June 01, 2007 - May 31, 2008 Expend.	June 01, 2008 - May 31, 2009 Expend.	Jun 01, 2009 - May 31, 2010 Expend.	Jun 01, 2010 - May 31, 2011 Budget	Proposed Budget - Next Award Year
Salaries							
Faculty	$0	$219,229	$357,473	$477,455	$484,549	$396,274	**$396,274**
Postdocs	$0	$106,172	$196,473	$115,001	$67,797	$51,620	**$51,620**
Students	$0	$384,120	$1,023,697	$836,231	$1,049,477	$1,208,267	**$1,208,267**
Research Staff	$0	$17,301	$248,840	$121,572	$232,601	$81,281	**$81,281**
Administration/Management	$0	$304,473	$405,473	$497,013	$448,895	$498,518	**$498,518**
Other Salaries	$0	$21,262	$99,529	$22,275	$120,594	$61,250	**$61,250**
Total Salaries	$0	$1,052,557	$2,331,485	$2,069,547	$2,403,913	$2,297,210	**$2,297,210**
Fringe Benefits	$0	$224,701	$493,148	$541,702	$591,497	$809,740	**$809,740**
Salaries and Fringe Benefits Total	$0	$1,277,258	$2,824,633	$2,611,249	$2,995,410	$3,106,950	**$3,106,950**
Other Expenses							
General Operating Expenses	$0	$291,244	$794,583	$407,483	$622,847	$762,675	**$862,675**
Facilities	$0	$0	$1,000	$0	$0	$0	**$0**
Major Isolated Expenses	$0	$0	$31,000	$0	$0	$55,000	**$45,000**
Equipment	$0	$99,085	$450,188	$187,609	$95,831	$173,145	**$73,145**
Indirect Costs	$0	$646,310	$1,165,595	$1,080,129	$1,262,004	$1,529,153	**$1,529,153**
Other	$0	$56,679	$219,162	$344,713	$188,744	$153,801	**$153,801**
Total Other Expenses	$0	$1,093,318	$2,661,528	$2,019,934	$2,169,426	$2,673,774	**$2,663,774**
Residual Funds Remaining	$0	$1,909,689	$1,056,057	$1,312,927	$0	$0	**$0**
TOTAL Expenditures & Budgets	$0	$4,280,265	$6,542,218	$5,944,110	$5,164,836	$5,780,724	**$5,770,724**
Prior Award Year Residual Funds spent in Current Award Year							
ERC Program	$0	$0	$1,023,980	$279,300	$279,300	$0	**$0**
Other NSF	$0	$0	$0	$0	$0	$0	**$0**
Other Federal	$0	$0	$0	$0	$0	$0	**$0**
Industry	$0	$0	$587,207	$1,250,042	$1,250,042	$0	**$0**
Other	$0	$0	$297,496	$756,115	$0	$0	**$0**
Prior Award Year Residual Funds spent in Current Award Year	$0	$0	$1,908,683	$2,285,457	$1,529,342	$0	**$0**

[1] For Centers in operation for more than 5 years

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

Organization	June 01, 2008 - May 31, 2009				Jun 01, 2009 - May 31, 2010				Jun 01, 2010 - May 31, 2011 Received			
	Fees and Contributions	Sponsored Projects	Associated Projects	In-Kind Support	Fees and Contributions	Sponsored Projects	Associated Projects	In-Kind Support	Fees and Contributions	Sponsored Projects	Associated Projects	In-Kind Support
Member Organizations												
AAA Products International	$1,000	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Afton Chemical Corp.	$10,000	$0	$0	N/A	$10,000	$0	$0	$0	$10,000	$0	$0	$0
Air Logic	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0
Bimba Manufacturing Compa	$6,000	$0	$0	N/A	$6,000	$0	$0	$2,300	$6,000	$0	$0	$200
Bobcat	$15,000	$0	$0	N/A	$15,000	$0	$0	$5,000	$15,000	$0	$0	$0
Bosch Rexroth Corporation	$50,000	$0	$0	N/A	$50,000	$0	$0	$0	$50,000	$0	$5,000	$9,000
Caterpillar, Inc.	$50,000	$0	$0	N/A	$50,000	$0	$0	$0	$50,000	$0	$76,797	$0
Command Controls Corpora	$500	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Deere & Company	$15,000	$0	$86,887	N/A	$0	$0	$76,024	$0	$0	$0	$0	$0
Delta Computer Systems, In	$5,000	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Deltrol Fluid Products	$5,000	$0	$0	N/A	$5,000	$0	$0	$0	$5,000	$0	$0	$0
Donaldson Company	$12,000	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Eaton Corporation	$50,000	$0	$0	N/A	$50,000	$0	$50,000	$0	$50,000	$0	$0	$0
Enfield Technologies	$5,000	$0	$0	N/A	$5,000	$0	$0	$0	$5,000	$0	$0	$0
Evonik RohMax USA	$10,000	$0	$0	N/A	$10,000	$0	$0	$2,500	$10,000	$0	$0	$0
Exxon Mobil	$0	$0	$0	N/A	$30,000	$0	$0	$0	$40,000	$0	$0	$0
Festo Corporation	$40,000	$0	$0	N/A	$40,000	$0	$0	$0	$12,000	$0	$0	$0
Fluid Power Educational Fou	$1,000	$0	$0	N/A	$0	$0	$0	$0	$1,000	$0	$0	$0
G.W. Lisk Company	$15,000	$0	$0	N/A	$15,000	$0	$0	$0	$15,000	$0	$0	$0
Gates Corporation	$40,000	$0	$0	N/A	$40,000	$0	$0	$0	$40,000	$0	$0	$0
Hagglunds Drives, Inc.	$6,000	$0	$0	N/A	$6,000	$0	$0	$0	$6,000	$0	$0	$0
Haldex Hydraulics Corporati	$6,000	$0	$0	N/A	$6,000	$0	$0	$0	$6,000	$0	$0	$0
Heco Gear, Inc.	$2,000	$0	$0	N/A	$2,000	$0	$0	$0	$2,000	$0	$0	$0
Hedland Flow Meters	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$4,592
High Country Tek, Inc.	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0
Hoowaki, LLC	$0	$0	$0	N/A	$0	$0	$0	$0	$1,000	$0	$0	$0
Husco International, Inc.	$40,000	$0	$20,000	N/A	$40,000	$0	$0	$0	$40,000	$0	$5,000	$0
Hydac Corporation	$5,000	$0	$0	N/A	$5,000	$0	$0	$0	$5,000	$0	$0	$2,400
Hydraquip Corporation	$6,000	$0	$0	N/A	$6,000	$0	$0	$0	$6,000	$0	$0	$0
INA USA Corporation	$1,000	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$0
International Fluid Power So	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0
Kepner Products, Co.	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0
Linde Hydraulics Corp.	$5,000	$0	$0	N/A	$5,000	$0	$0	$0	$5,000	$0	$1,000	$0
Master Pneumatic-Detroit, In	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0
Mead Fluid Dynamics	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$0	$0	$0	$0
Mico, Inc.	$1,000	$0	$0	N/A	$0	$0	$0	$0	$1,000	$0	$0	$0
Moog, Inc.	$15,000	$0	$0	N/A	$15,000	$0	$0	$0	$15,000	$0	$0	$0
MTS Systems Corporation	$15,000	$0	$0	N/A	$0	$0	$0	$0	$15,000	$0	$0	$0
National Fluid Power Associ	$50,000	$12,000	$0	N/A	$50,000	$0	$71,067	$0	$50,000	$0	$71,067	$0
National Tube Supply Comp	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0
Netshape Technologies	$15,000	$0	$0	N/A	$11,250	$0	$0	$0	$7,500	$0	$0	$0
Nexen Group, Inc.	$1,000	$0	$0	N/A	$0	$0	$0	$0	$1,000	$0	$0	$0
Parker Hannifen Corporation	$50,000	$0	$278,878	N/A	$50,000	$0	$0	$0	$0	$0	$0	$0
Parker Hannifin Corporation	$0	$0	$0	N/A	$0	$0	$0	$0	$50,000	$0	$0	$36,000
PHD, Inc.	$6,000	$0	$0	N/A	$6,000	$0	$0	$0	$6,000	$0	$0	$0
PIAB Vacuum Products	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0
Poclain Hydraulics	$15,000	$0	$0	N/A	$6,000	$0	$0	$0	$6,000	$0	$0	$0
Quality Control Corporation	$1,000	$0	$0	N/A	$1,000	$0	$0	$0	$1,000	$0	$0	$0

Organization	June 01, 2008 - May 31, 2009				Jun 01, 2009 - May 31, 2010				Jun 01, 2010 - May 31, 2011 Received			
	Fees and Contributions	Sponsored Projects	Associated Projects	In-Kind Support	Fees and Contributions	Sponsored Projects	Associated Projects	In-Kind Support	Fees and Contributions	Sponsored Projects	Associated Projects	In-Kind Support
RB Royal Industries, Inc.	$2,000	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Ross Controls	$5,000	$0	$0	N/A	$5,000	$0	$0	$0	$5,000	$0	$0	$0
Sauer-Danfoss	$50,000	$0	$118,041	N/A	$50,000	$0	$0	$8,500	$50,000	$0	$8,000	$70,837
Shell Global Solutions	$12,000	$0	$0	N/A	$12,000	$0	$0	$0	$0	$0	$0	$0
Simerics, Inc.	$0	$0	$0	N/A	$0	$0	$0	$0	$1,000	$0	$0	$0
Sun Hydraulics	$15,000	$0	$0	N/A	$15,000	$0	$0	$0	$15,000	$0	$0	$832
Sun Source	$12,000	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Takako Industries	$0	$0	$0	N/A	$0	$0	$0	$0	$1,000	$0	$0	$0
Tennant	$12,000	$0	$0	N/A	$12,000	$0	$0	$0	$12,000	$0	$0	$0
The Lubrizol Corporation	$0	$0	$0	N/A	$0	$0	$0	$0	$5,000	$0	$0	$0
The Toro Company	$12,000	$0	$0	N/A	$12,000	$0	$0	$0	$12,000	$0	$0	$0
Trelleborg Sealing Solutions	$30,000	$0	$0	N/A	$6,000	$0	$0	$0	$6,000	$0	$0	$0
Veljan Hydrair Private Limite	$5,000	$0	$0	N/A	$5,015	$0	$0	$0	$5,000	$0	$0	$0
Total Members	**$741,500**	**$12,000**	**$503,806**	**N/A**	**$666,265**	**$0**	**$197,091**	**$18,300**	**$652,500**	**$0**	**$166,864**	**$123,861**
Non-Member Organization												
Casappa S.p.A.	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$37,962	$0
DARPA	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$115,884	$0
Deere & Co.	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$48,252	$0
Deere & Company	$0	$0	$0	N/A	$0	$0	$0	$0	$15,000	$0	$72,450	$0
Dynasonics	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$2,535
Environmental Protection Ag	$0	$0	$279,109	N/A	$0	$0	$0	$0	$0	$0	$0	$0
ERC unnamed industry mem	$0	$0	$0	N/A	$0	$0	$78,000	$0	$0	$0	$0	$0
Ford	$0	$0	$0	N/A	$0	$0	$0	$30,000	$0	$0	$0	$101,000
Funded by: Sauer-Danfoss,	$0	$0	$0	N/A	$0	$0	$803,786	$0	$0	$0	$0	$0
Funding Sources (7) kept co	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$395,345	$0
John Deere, HUSCO Interna	$0	$0	$0	N/A	$0	$0	$20,000	$50,000	$0	$0	$0	$0
Laboratoire de Mecanique; I	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$57,276	$0
National Defense Science ar	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$13,320	$0
National Defense Science ar	$0	$0	$0	N/A	$0	$0	$0	$70,732	$0	$0	$0	$0
National Institutes of Health	$0	$0	$0	N/A	$0	$0	$599,447	$0	$0	$0	$41,625	$0
National Science Foundation	$0	$0	$0	N/A	$0	$0	$99,051	$0	$0	$0	$640,109	$0
NSF	$0	$0	$99,326	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Oak Ridge National Laborato	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$10,656	$0
Parker Hannifen Foundation	$0	$0	$91,620	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Phillips Health Care	$0	$0	$150,000	N/A	$0	$0	$0	$0	$0	$0	$0	$0
Precision Associates	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$925
Purdue Research Park Trask	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$37,576	$0
Sentrinsic, LLP	$0	$0	$10,000	N/A	$0	$0	$0	$0	$0	$0	$0	$0
The Martin Company	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$36,630	$0
The Timken Company	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$45,288	$0
Total Oil Company	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$13,903	$0
U.S. Army Research Office	$0	$0	$454,908	N/A	$0	$0	$0	$0	$0	$0	$0	$0
United Technologies Resear	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$57,706	$0
University of Minnesota Med	$0	$0	$50,000	N/A	$0	$0	$0	$0	$0	$0	$0	$0
University of Minnesota, Inst	$0	$0	$0	N/A	$0	$0	$50,000	$0	$0	$0	$0	$0
University of MN; IonE and I	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$45,832	$0
University of Stuttgart/Germa	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$31,968	$0
Vanderbilt University	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$16,667	$0
Vex Robotics	$0	$0	$0	N/A	$0	$0	$0	$0	$0	$0	$0	$300
Total Non-Members	**$0**	**$0**	**$1,134,963**	**N/A**	**$0**	**$0**	**$1,650,284**	**$150,732**	**$15,000**	**$0**	**$1,718,449**	**$104,760**
Total	**$741,500**	**$12,000**	**$1,638,769**	**N/A**	**$666,265**	**$0**	**$1,847,375**	**$169,032**	**$667,500**	**$0**	**$1,885,313**	**$228,621**

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5.4 RESOURCES AND UNIVERSITY COMMITMENT

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

Due to economic hardships experienced by CCEFP universities, no major infrastructure projects were completed in the last reporting period. Faculty hiring was also affected by the economic situation. The commitment to hire twelve CCEFP faculty members remains unchanged, but may be delayed. CCEFP has hired six faculty to date: Jiang (NCAT), Martini (PU), Sun (UM), Ueda (GT), Vacca (PU) and Webster (VU).

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, one at Minnesota and one at Illinois. 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. 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.

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SUMMARY PROPOSAL BUDGET

YEAR 6

FOR NSF USE ONLY

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

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

0.	First Name	M	Last Name	Title	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF
1.	Kim	A	Stelson	Dr.	0.00	0.00	2.00	31,642	
2.	Perry		Li	Dr.	0.00	0.00	2.50	22,231	
3.	William		Durfee	Dr.	0.00	0.00	1.50	20,786	
4.	Thomas		Chase	Dr.	0.00	0.00	1.00	10,470	
5.	David		Kittelson	Dr.	0.00	0.00	1.00	15,533	
6.	Zongxuan		Sun	Dr.			1.00	11,103	
(6 PERSONNEL (1-6)								**111,765**	

Item	CAL	ACAD	SUMR	Funds Requested By Proposer	Funds Granted by NSF
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00		
2. (1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	12.00	0.00	0.00	$106,080	
3. (9) GRADUATE STUDENTS	12.00			$208,818	
4. (3) UNDERGRADUATE STUDENTS	12.00			$31,200	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)					
6. (2) OTHER	12.00			$134,062	
TOTAL SALARIES AND WAGES (A+B)				**$591,925**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				$197,111	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				**$789,036**	

D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000)				
	HydraulicHybrid Vehicle Test Bed	20000		
TOTAL EQUIPMENT		20000	**$20,000**	
E. TRAVEL	1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)		$36,000	
	2. FOREIGN		$6,000	
F. PARTICIPANT SUPPORT COSTS				
1. STIPENDS	REU/RET participants during summer 2011: 3 University of Minnesota students ($4000 each) and 2 RET Teachers ($6000 each)	$24,000		
2. TRAVEL	REU/RET participants during summer 2011: 3 students at UMN ($1,500 each) and 2 RET Teachers ($1000 each)	$6,500		
3. SUBSISTENCE	REU participants during summer 2011: 3 students at UMN ($1,950 each)	$5,849		
4. OTHER	REU/RET costs: Housing costs for 3 REU students at UMN ($2000 each); 2 RET Teachers ($1500 each) for supplies equip, other at UMN	$9,000		
(5) TOTAL NUMBER OF PARTICIPANTS		$45,349	**$45,349**	
G. OTHER DIRECT COSTS				
1. MATERIALS AND SUPPLIES			$20,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION			$10,000	
3. CONSULTANT SERVICES				
4. COMPUTERS SERVICES			$0	
5. SUBAWARDS			$2,241,000	
6. OTHER				
TOTAL OTHER DIRECT COSTS			**$2,271,000**	
H. TOTAL DIRECT COSTS (A THROUGH G)			**$3,167,385**	

I. INDIRECT COSTS (SPECIFY RATE AND BASE)

Name of indirect cost item			Amount	Rate	
GRA student fringe, no IDC	$69,536	**exempt idc**	**826,615**	49.50%	$832,615
REU/RET reduced overhea	24000	**charge idc**	6000		
Equipment has no IDC	20000	**exempt idc**			

	Funds Requested By Proposer	Funds Granted by NSF
TOTAL INDIRECT COSTS	**$832,615**	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)	**$4,000,000**	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.D.7.j.)	$0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)	$4,000,000	
M. COST SHARING: PROPOSED LEVEL — AGREED LEVEL IF DIFFERENT $	$800,000	

PI/PD NAME	DATE	FOR NSF USE ONLY
Kim A. Stelson	2/9/11	INDIRECT COST RATE VERIFICATION

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APPENDIX I

Glossary of Acronyms and Special Terms

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
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

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
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
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
VaNTH…………	Multidisciplinary ERC consisting of Vanderbilt, Northwestern and Texas-Harvard/MIT
W ………………	watt

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APPENDIX II

Agreements and Certifications

Engineering Research Center for Compact and Efficient Fluid Power Membership Agreement

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

WHEREAS, Lead University will operate the Center in cooperation with six other universities, namely, University of Illinois at Urbana-Champaign, Purdue University, Vanderbilt University, Georgia Institute of Technology, Milwaukee School of Engineering and North Carolina Agricultural and Technical University (hereinafter, each university individually is "University", and the seven universities collectively are "Universities").

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

The parties hereby agree to the following terms and conditions:

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

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

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

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

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

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

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

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

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

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

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

I. Pursuant to 35 U.S.C. § 200 *et seq.* (the "Bayh-Dole Act"), the University or Universities whose researchers are inventors under U.S. Patent law (the "Inventing University") shall have the right to retain title to all patents developed from this work, subject to the rights of the U.S. Government as set forth in the Bayh-Dole Act and regulations. The provisions of Part 730, "Intellectual Property", of the NSF Grants Policy Manual shall also govern rights and responsibilities regarding intellectual property created with NSF funding. If any Member exercises its rights under Paragraph K of this Agreement, the Inventing University or Inventing Universities shall exercise its right to retain title.

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

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

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

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

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

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

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

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

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

P. CONTACTS for this Agreement are as follows:

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

Q. This Agreement is the complete and exclusive statement of the understanding between the Parties regarding the subject matter hereof, and it supersedes all prior written or contemporaneous communications.

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

REGENTS OF THE UNIVERSITY OF MINNESOTA **on behalf of** **The Engineering Resource Center**	**MEMBER**
Name Kevin McKoskey, CRA Senior Associate Director	Name
Title	Title
Date: ______________________	Date: ______________________

NGEDOCS: 1150312.9

CCEFP INDUSTRY MEMBERSHIP LIST

Private Sector Firms

Afton Chemical Corp.
Air Logic
Bimba Manufacturing Co.
Bobcat Co.
Bosch Rexroth Corp.
Caterpillar Inc.
Deltrol Fluid Products
Eaton Corp.
Enfield Technologies
Evonik RohMax USA, Inc.
Exxon Mobil
Festo Corp.
G.W. Lisk Co., Inc.
Gates Corp.
HÃgglunds Drives Inc.
Haldex Hydraulics Corp.
HECO Gear, Inc.
Hedland Flow Meters (Racine Federated)
High Country Tek, Inc.
Hoowaki, LLC
HUSCO International, Inc.
HYDAC Corp.
Hydraquip Corp.
Kepner Products Co.
Linde Hydraulics Corp.
Master Pneumatic-Detroit, Inc.
MICO, Inc.
Moog Inc.
MTS Systems Corp.
National Fluid Power Assoc.
National Tube Supply Co.
Netshape Technologies, Inc.
Nexen Group, Inc.
Parker Hannifin Corp.
PHD, Inc.
PIAB Vacuum Products
Poclain Hydraulics
Quality Control Corp.
Ross Controls
Sauer-Danfoss
Simerics
Sun Hydraulics Corp.
Takako Industries
Tennant Co.
The Lubrizol Corporation
The Toro Co.
Trelleborg Sealing Solutions U.S. Inc.
Veljan Hydrair Pvt. Ltd.

Non-Private Sector Firms

Fluid Power Educational Foundation
International Fluid Power Society
Ralph Rivera (individual)

Industrial/Practioner Members That Will Provide Support by the End of the Current Award Year

Donaldson Company
R.T. Dygert International
Shell Global Systems

CERTIFIED BY AOR

Kevin McKoskey
Senior Associate Director
Sponsored Projects Administration

Table 9b - Cost Sharing by Institution

Institution	Award Year 1 (FY07) Committed	Award Year 1 (FY07) Actual	Award Year 2 (FY08) Committed	Award Year 2 (FY08) Actual	Award Year 3 (FY09) Committed	Award Year 3 (FY09) 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

Institution	Award Year 4 (FY10) Committed	Award Year 4 (FY10) Actual	Award Year 5 (FY11) Committed	Award Year 5 (FY11) Actual	Award Year 6 (FY12) Committed	Award Year 6 (FY12) Actual
U. of Minnesota	$226,367	$187,032	$242,667	-	$339,537	-
Georgia Tech	$142,995	$267,384	$152,000	-	$130,232	-
MSOE	$0	$0	$0	-	$0	-
Purdue	$142,995	$139,404	$152,000	-	$152,557	-
UIUC	$142,995	$210,852	$119,541	-	$92,093	-
Vanderbilt	$94,648	$69,213	$101,333	-	$85,581	-

Institution	Award Year 7 (FY13) Committed	Award Year 7 (FY13) Actual	Award Year 8 (FY14) Committed	Award Year 8 (FY14) Actual	Cumulative Commitment
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

CERTIFIED BY AOR

Kevin McKoskey
Senior Associate Director
Sponsored Projects Administration

Table 10a: Unexpended Residual in the Current Award and Proposed Award Year

	Previous Award Year to Current Award Year	Current Award Year to Proposed Award Year
Total Unexpended Residual Funds	$846,652	$2,018,369
Committed, Encumbered, Obligated funds	$868,000	$2,018,369
Residual Funds Without Specified Use	$0	$0

CERTIFIED BY AOR

Kevin McKoskey
Senior Associate Director
Sponsored Projects Administration

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

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

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

The following is the University of Minnesota's response.

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

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

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

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

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

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

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

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

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

The following are links to the:

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

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

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

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

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

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

Administrative

UNIVERSITY OF MINNESOTA
BOARD OF REGENTS POLICY

INSTITUTIONAL CONFLICT OF INTEREST
Adopted: June 10, 2005

INSTITUTIONAL CONFLICT OF INTEREST

SECTION I. SCOPE.

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

SECTION II. DEFINITIONS.

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

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

SECTION III. GUIDING PRINCIPLES.

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

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

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

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

SECTION IV. RESERVATION OF AUTHORITY.

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

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

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

SECTION V. ASSURANCE, DELEGATION OF AUTHORITY, AND REPORTING.

The president or delegate shall:

(a) implement an oversight process and administrative policies and procedures to address institutional conflict of interest and to identify situations in which institutional conflict of interest may arise;
(b) recommend and implement plans to manage, reduce, or eliminate institutional conflict of interest;
(c) develop and present conflict of interest plans to the Board for review and action as required under Section IV;
(d) ensure that individuals covered by this policy who act on behalf of the institution adhere to these policies and procedures, follow applicable conflict management plans, and do not engage in activities in which there is an actual conflict of interest; and
(e) report to the Board annually all institutional conflict of interest matters that do not meet the thresholds identified in Section IV.

SECTION VI. DISCLOSURES.

Subd. 1. Regents. Regents shall file a financial disclosure statement annually and report conflicts of interest as required by Board of Regents Policy: *Code of Ethics.*

Subd. 2. University Officials. University officials shall, upon appointment and annually on September 30 thereafter, file a financial disclosure statement with the president or delegate, disclosing significant economic interests and how those interests may relate to their institutional responsibilities. Such disclosure shall be made in addition to any reporting requirement for individual conflicts of interest.

Subd. 3. Department/Unit Heads. Annually and under circumstances described in administrative policy, department/unit heads shall disclose relevant financial and business interests by filing a *Report of External Professional Activities*.

Subd. 4. Other Individuals. The president or delegate may designate other individuals who shall file a financial disclosure statement.

SUPERSEDES: FINANCIAL DISCLOSURE FOR SENIOR UNIVERSITY OFFICIALS, DATED NOVEMBER 10, 1995.

CERTIFIED BY AOR

Kevin McKoskey, CRA
Senior Grants Manager
Office of Sponsored Projects Administration

OMB No. 0990-0263
Approved for use through 1/31/2012

Protection of Human Subjects
Assurance Identification/IRB Certification/Declaration of Exemption
(Common Rule)

Policy: Research activities involving human subjects may not be conducted or supported by the Departments and Agencies adopting the Common Rule (56FR28003, June 18, 1991) unless the activities are exempt from or approved in accordance with the Common Rule. See section 101(b) of the Common Rule for exemptions. Institutions submitting applications or proposals for support must submit certification of appropriate Institutional Review Board (IRB) review and approval to the Department or Agency in accordance with the Common Rule.

Institutions must have an assurance of compliance that applies to the research to be conducted and should submit certification of IRB review and approval with each application or proposal unless otherwise advised by the Department or Agency.

1. Request Type	2. Type of Mechanism	3. Name of Federal Department or Agency and, if known, Application or Proposal Identification No.
[] ORIGINAL [X] CONTINUATION [] EXEMPTION	[X] GRANT [] CONTRACT [] FELLOWSHIP [] COOPERATIVE AGREEMENT [] OTHER:______	National Science Foundation #0540834

4. Title of Application or Activity	5. Name of Principal Investigator, Program Director, Fellow, or Other
Assessment of gait using novel fluid-power assistive ankle-foot-orthoses (AFOs)	**Kim Stelson, Sc.D. (Minnesota)** **Elizabeth Hsiao-Wecksler, Ph.D.**

6. Assurance Status of this Project *(Respond to one of the following)*

[X] This Assurance, on file with Department of Health and Human Services, covers this activity:
Assurance Identification No. FWA00008584, the expiration date March 08, 2013 IRB Registration No. **00000018**

[ ] This Assurance, on file with *(agency/dept)*______, covers this activity.
Assurance No.______, the expiration date ______ IRB Registration/Identification No.______ *(if applicable)*

[ ] No assurance has been filed for this institution. This institution declares that it will provide an Assurance and Certification of IRB review and approval upon request.

[ ] Exemption Status: Human subjects are involved, but this activity qualifies for exemption under Section 101(b), paragraph______.

7. Certification of IRB Review (Respond to one of the following IF you have an Assurance on file)

[X] This activity has been reviewed and approved by the IRB in accordance with the Common Rule and any other governing regulations.
by: [ ] Full IRB Review on (date of IRB meeting) ______ or [X] Expedited Review on June 21,2010
[ ] If less than one year approval, provide expiration date ______

[ ] This activity contains multiple projects, some of which have not been reviewed. The IRB has granted approval on condition that all projects covered by the Common Rule will be reviewed and approved before they are initiated and that appropriate further certification will be submitted.

8. Comments

IRB#08710 Assessment of gait using novel fluid-power assistive ankle-foot-orthoses (AFOs)

9. The official signing below certifies that the information provided above is correct and that, as required, future reviews will be performed until study closure and certification will be provided.	10. Name and Address of Institution
11. Phone No. *(with area code)* **(217) 333-2670** 12. Fax No. *(with area code)* **(217) 333-0405** 13. Email: **irb@illinois.edu**	***University of Illinois at Urbana-Champaign*** ***Institutional Review Board*** ***528 E. Green Street, Suite 203*** ***Champaign, IL 61820***
14. Name of Official ***Sue Keehn***	15. Title **Director, Institutional Review Board**
16. Signature Sue Keehn	17. Date 6/21/10

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APPENDIX III

Table 7: Personnel

Table 7: ERC Personnel

Personnel Type	Total	Gender			Citizenship Status: Race: U.S. citizens and permanent residents only							Citizenship Status	Ethnicity: Hispanic			Disability
		Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
All Institutions																
Total [1]	**311**	**228**	**82**	**1**	**51**	**5**	**15**	**154**	**12**	**4**	**23**	**49**	**8**	**5**	**0**	**9**
Leadership/Administration																
Directors	3	3	0	0	0	0	0	2	1	0	0	0	0	0	0	0
Thrust Leaders	3	2	1	0	0	0	1	2	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Education Program Leaders	3	1	2	0	0	0	0	3	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
Staff	6	4	2	0	1	0	1	3	0	0	1	0	0	0	0	1
Subtotal	**17**	**11**	**6**	**0**	**1**	**0**	**2**	**12**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**
Research under Strategic Research Plan																
Senior Faculty	25	23	2	0	0	0	1	19	5	0	0	0	0	0	0	0
Junior Faculty	10	9	1	0	1	0	0	4	1	0	0	4	1	0	0	0
Research Staff	13	13	0	0	0	0	0	9	1	0	0	3	0	0	0	1
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	2	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Total Doctoral Students	59	53	6	0	0	0	4	24	2	0	4	25	1	1	0	2
Total Master's Students	36	31	5	0	0	0	2	23	2	0	0	9	0	3	0	1
Total Undergraduate Students	31	19	12	0	9	1	1	16	0	1	0	2	1	0	0	0
Other Visiting College Students	2	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**178**	**152**	**26**	**0**	**10**	**1**	**8**	**95**	**11**	**1**	**4**	**47**	**3**	**4**	**0**	**4**
Curriculum Development and Outreach																
Senior Faculty	3	2	1	0	0	0	0	3	0	0	0	0	0	0	0	0
Junior Faculty	3	2	1	0	3	0	0	0	0	0	0	0	1	0	0	0
Research Staff	9	5	4	0	2	0	0	7	0	0	0	0	0	0	0	1
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	43	24	18	1	26	1	2	9	0	3	1	1	3	0	0	1
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**58**	**33**	**24**	**1**	**31**	**1**	**2**	**19**	**0**	**3**	**1**	**1**	**4**	**0**	**0**	**2**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	25	17	8	0	0	3	3	17	1	0	0	1	0	1	0	2
LSAMP REU Students	2	1	1	0	0	0	1	0	0	0	1	0	1	0	0	0
Subtotal	**27**	**18**	**9**	**0**	**0**	**3**	**4**	**17**	**1**	**0**	**1**	**1**	**1**	**1**	**0**	**2**
Pre-College (K-12)																
Teachers (RET)	6	6	0	0	0	0	0	6	0	0	0	0	0	0	0	0

Personnel Type	Total	Gender			Citizenship Status								Ethnicity: Hispanic			Disability
					Race: U.S. citizens and permanent residents only							Other Non-U.S.	US/Perm	Temp	Not Reported	
		Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	Not Provided					
Teachers (non-RET)	33	15	18	0	9	0	0	8	0	0	16	0	0	0	0	0
Subtotal	**39**	**21**	**18**	**0**	**9**	**0**	**0**	**14**	**0**	**0**	**16**	**0**	**0**	**0**	**0**	**0**
University of Minnesota - Lead Institution																
Total [1]	**71**	**55**	**16**	**0**	**7**	**1**	**1**	**36**	**4**	**3**	**2**	**19**	**0**	**1**	**0**	**2**
Leadership/Administration																
Directors	2	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0
Thrust Leaders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Education Program Leaders	3	1	2	0	0	0	0	3	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
Staff	6	4	2	0	1	0	1	3	0	0	1	0	0	0	0	1
Subtotal	**13**	**8**	**5**	**0**	**1**	**0**	**1**	**9**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**
Research under Strategic Research Plan																
Senior Faculty	7	7	0	0	0	0	0	6	1	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Research Staff	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Doctoral Students	18	17	1	0	0	0	0	4	1	0	1	12	0	0	0	0
Total Master's Students	13	11	2	0	0	0	0	9	0	0	0	4	0	1	0	0
Total Undergraduate Students	2	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**43**	**40**	**3**	**0**	**0**	**0**	**0**	**20**	**4**	**0**	**1**	**18**	**0**	**1**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	3	2	1	0	0	0	0	3	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	3	1	2	0	1	0	0	2	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	13	8	5	0	5	1	0	3	0	3	0	1	0	0	0	1
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**19**	**11**	**8**	**0**	**6**	**1**	**0**	**8**	**0**	**3**	**0**	**1**	**0**	**0**	**0**	**1**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Teachers (non-RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of Illinois at Urbana-Champaign - Core Partner																
Total [1]	**19**	**17**	**2**	**0**	**0**	**0**	**1**	**10**	**2**	**0**	**1**	**5**	**0**	**0**	**0**	**1**
Leadership/Administration																
Directors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thrust Leaders	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Education Program Leaders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Administrative Director	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Staff	0	0	0	0	0	0	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**
Research under Strategic Research Plan																
Senior Faculty	4	3	1	0	0	0	1	2	1	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Total Doctoral Students	7	7	0	0	0	0	0	5	1	0	1	0	0	0	0	1
Total Master's Students	5	4	1	0	0	0	0	2	0	0	0	3	0	0	0	0
Total Undergraduate Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**18**	**16**	**2**	**0**	**0**	**0**	**1**	**9**	**2**	**0**	**1**	**5**	**0**	**0**	**0**	**1**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Purdue University - Core Partner																
Total [1]	**33**	**30**	**3**	**0**	**0**	**0**	**1**	**21**	**0**	**0**	**1**	**10**	**0**	**1**	**0**	**0**
Leadership/Administration																
Directors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thrust Leaders	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Education Program Leaders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Administrative Director	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research under Strategic Research Plan																

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Senior Faculty	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0
Junior Faculty	3	2	1	0	0	0	0	2	0	0	0	1	0	0	0	0
Research Staff	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	12	12	0	0	0	0	0	5	0	0	1	6	0	1	0	0
Total Master's Students	8	8	0	0	0	0	1	7	0	0	0	0	0	0	0	0
Total Undergraduate Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	2	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Subtotal	**28**	**26**	**2**	**0**	**0**	**0**	**1**	**16**	**0**	**0**	**1**	**10**	**0**	**1**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	5	4	1	0	0	0	0	5	0	0	0	0	0	0	0	0
Subtotal	**5**	**4**	**1**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Georgia Institute of Technology - Core Partner																
Total [1]	**36**	**31**	**5**	**0**	**0**	**0**	**0**	**26**	**1**	**0**	**0**	**8**	**1**	**0**	**0**	**3**
Leadership/Administration																
Directors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thrust Leaders	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Education Program Leaders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Administrative Director	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research under Strategic Research Plan																
Senior Faculty	8	8	0	0	0	0	0	8	0	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Research Staff	3	3	0	0	0	0	0	1	0	0	0	2	0	0	0	1
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	12	10	2	0	0	0	0	8	0	0	0	4	1	0	0	1
Total Master's Students	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Total Undergraduate Students	8	6	2	0	0	0	0	6	0	0	0	1	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**33**	**29**	**4**	**0**	**0**	**0**	**0**	**23**	**1**	**0**	**0**	**8**	**1**	**0**	**0**	**2**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	3	2	1	0	0	0	0	3	0	0	0	0	0	0	0	1
Subtotal	**3**	**2**	**1**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Vanderbilt University - Core Partner																
Total [1]	**12**	**10**	**2**	**0**	**0**	**1**	**0**	**8**	**0**	**0**	**1**	**2**	**0**	**1**	**0**	**0**
Leadership/Administration																
Directors	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Thrust Leaders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Thrust Management and Strategic Planning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industrial Liaison Officer (ILO)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Education Program Leaders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Administrative Director	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research under Strategic Research Plan																
Senior Faculty	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Junior Faculty	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Research Staff	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	4	3	1	0	0	0	0	2	0	0	1	1	0	0	0	0
Total Master's Students	2	1	1	0	0	0	0	1	0	0	0	1	0	1	0	0
Total Undergraduate Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**11**	**9**	**2**	**0**	**0**	**0**	**0**	**8**	**0**	**0**	**1**	**2**	**0**	**1**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Milwaukee School of Engineering - Collaborating Institutions																
Total [1]	**21**	**17**	**4**	**0**	**1**	**0**	**0**	**19**	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**1**
Research under Strategic Research Plan																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0
Research Staff	6	6	0	0	0	0	0	6	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	5	4	1	0	0	0	0	4	0	0	0	1	0	1	0	1
Total Undergraduate Students	9	6	3	0	0	0	0	9	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**21**	**17**	**4**	**0**	**1**	**0**	**0**	**19**	**0**	**0**	**0**	**1**	**1**	**1**	**0**	**1**
North Carolina Agriculture and Technical State University - Collaborating Institutions																
Total [1]	**13**	**10**	**3**	**0**	**0**	**0**	**6**	**0**	**4**	**0**	**0**	**3**	**0**	**0**	**0**	**0**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Research under Strategic Research Plan																
Senior Faculty	3	3	0	0	0	0	0	0	3	0	0	0	0	0	0	0
Junior Faculty	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	6	4	2	0	0	0	4	0	0	0	0	2	0	0	0	0
Total Master's Students	2	2	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Total Undergraduate Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**12**	**10**	**2**	**0**	**0**	**0**	**5**	**0**	**4**	**0**	**0**	**3**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	0	1	0	0	0	1	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**
Science Museum of Minnesota - Collaborating Institutions																
Total [1]	**5**	**4**	**1**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	5	4	1	0	0	0	0	5	0	0	0	0	0	0	0	1
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**5**	**4**	**1**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
St. Cloud State University - Collaborating Institutions																
Total [1]	**5**	**0**	**5**	**0**	**4**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
Research Staff	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	0	3	0	2	0	1	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**5**	**0**	**5**	**0**	**4**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Illinois Institute of Technology - Collaborating Institutions																
Total [1]	**2**	**2**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Case Western Reserve University - Collaborating Institutions																
Total [1]	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Montana State University - Collaborating Institutions																
Total [1]	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	2	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of South Florida - Collaborating Institutions																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
University of Michigan - Collaborating Institutions																
Total [1]	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Fond du Lac Tribal and Community College - Collaborating Institutions																
Total [1]	**2**	**2**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	2	2	0	0	0	0	1	1	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	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**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
University of Minnesota - Morris - Collaborating Institutions																
Total [1]	**6**	**2**	**4**	**0**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	6	2	4	0	6	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**6**	**2**	**4**	**0**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of North Dakota - Collaborating Institutions																
Total [1]	**6**	**3**	**3**	**0**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	6	3	3	0	6	0	0	0	0	0	0	0	2	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**6**	**3**	**3**	**0**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**
Washington State University - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of Florida - Non-ERC Institutions Providing REU Students																
Total [1]	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	2	1	1	0	0	0	0	2	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**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
University of Portland - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	0	1	0	0	0	0	1	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**
University of Texas at El Paso - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**
University of Arkansas - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1
Subtotal	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
Iowa State University - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	0	1	0	0	0	0	1	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**
University of Arizona - Non-ERC Institutions Providing REU Students																
Total [1]	**2**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	2	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Duke University - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
University of Cincinnati - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Embry-Riddle Aeronautical University - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
North Carolina State University - Non-ERC Institutions Providing REU Students																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
NSF REU Site Award Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ERC's Own REU Students	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Albrook School - Pre-college Partners																
Total [1]	**4**	**2**	**2**	**0**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	4	2	2	0	0	0	0	4	0	0	0	0	0	0	0	0
Subtotal	**4**	**2**	**2**	**0**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Cloquet High School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	1	1	0	0	0	0	0	1	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**
Cloquet Middle School - Pre-college Partners																
Total [1]	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	1	0	1	0	0	0	0	1	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**
Gibbon, Fairfax, Winthrop School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Teachers (non-RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Personnel Type	Total	Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	Disability
Lafayette Jefferson High School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Teachers (non-RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Ojibwe School - Pre-college Partners																
Total [1]	**2**	**1**	**1**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	2	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Robbinsdale Armstrong High School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Teachers (non-RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Smyrna High School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Teachers (non-RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Metropolitan Nashville Public School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Teachers (non-RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
McCutcheon High School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Teachers (non-RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Rockdale Magnet School for Science and Technology - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	1	1	0	0	0	0	0	1	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**
Bemidji Middle School - Pre-college Partners																
Total [1]	**6**	**1**	**5**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	6	1	5	0	1	0	0	0	0	0	5	0	0	0	0	0
Subtotal	**6**	**1**	**5**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**5**	**0**	**0**	**0**	**0**	**0**
Red Lake Middle School - Pre-college Partners																
Total [1]	**4**	**3**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	4	3	1	0	1	0	0	0	0	0	3	0	0	0	0	0
Subtotal	**4**	**3**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**
Cass Lake Middle School - Pre-college Partners																
Total [1]	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	2	1	1	0	0	0	0	0	0	0	2	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
BugONayGeShig School - Pre-college Partners																
Total [1]	**3**	**2**	**1**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	3	2	1	0	2	0	0	0	0	0	1	0	0	0	0	0
Subtotal	**3**	**2**	**1**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Mahnomen High School - Pre-college Partners																
Total [1]	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	2	1	1	0	0	0	0	0	0	0	2	0	0	0	0	0
Subtotal	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Naytawaush Charter School - Pre-college Partners																
Total [1]	**1**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	1	0	1	0	1	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**
Deer River School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	1	1	0	0	1	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**
Ponemah Elementary School - Pre-college Partners																
Total [1]	**3**	**0**	**3**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	3	0	3	0	1	0	0	0	0	0	2	0	0	0	0	0
Subtotal	**3**	**0**	**3**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
Bemidji High School - Pre-college Partners																
Total [1]	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	1	0	1	0	0	0	0	1	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**
Walker Alternative School - Pre-college Partners																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Pre-College (K-12)																
Teachers (RET)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Teachers (non-RET)	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
Salish Kootenai College - Community College																
Total [1]	**6**	**5**	**1**	**0**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	2	2	0	0	2	0	0	0	0	0	0	0	1	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Personnel Type	Total	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	Not Provided	Other Non-U.S.	US/Perm	Temp	Not Reported	
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	4	3	1	0	4	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**6**	**5**	**1**	**0**	**6**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
Lac Courte Oreilles Ojibwa Community College - Community College																
Total [1]	**3**	**3**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Curriculum Development and Outreach																
Senior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Junior Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Research Staff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Visiting Faculty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Industry Researchers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Post Docs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Master's Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Undergraduate Students	3	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Other Visiting College Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**3**	**3**	**0**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
North Carolina Louis Stokes Alliance for Minority Participation (North Carolina Agricultural And Technical St Univ, Greensboro) - (LSAMP)																
Total [1]	**1**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
ERC REU Students																
LSAMP REU Students	1	0	1	0	0	0	1	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**
Louis Stokes Alliance for Minority Participation (LSAMP) Indiana (Purdue University) - (LSAMP)																
Total [1]	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**
ERC REU Students																
LSAMP REU Students	1	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Subtotal	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**
The All Nations Louis Stokes Alliance for Minority Participation (Salish Kootenai College, Pablo) - (LSAMP)																
Total [1]	**4**	**3**	**1**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Research under Strategic Research Plan																
LSAMP Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAMP Masters Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAMP Undergraduate Students	4	3	1	0	4	0	0	0	0	0	0	0	0	0	0	0
Subtotal	**4**	**3**	**1**	**0**	**4**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
North Star STEM Alliance (University of Minnesota Twin-Cities) - (LSAMP)																
Total [1]	**8**	**2**	**6**	**0**	**5**	**1**	**1**	**1**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**
Research under Strategic Research Plan																
LSAMP Doctoral Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LSAMP Masters Students	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Personnel Type	Total	Gender			Citizenship Status								Ethnicity: Hispanic			Disability
					Race: U.S. citizens and permanent residents only							Other Non-U.S.	US/Perm	Temp	Not Reported	
		Male	Female	Gender Not Reported	AI/AN	NH/PI	B/AA	W	A	More than one race reported, minority	Not Provided					
LSAMP Undergraduate Students	8	2	6	0	5	1	1	0	0	1	0	0	1	0	0	0
Subtotal	**8**	**2**	**6**	**0**	**5**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**

[1] If ERC Personnel were entered at the individual level the Total 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

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

Task Force Reports

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SYSTEMS ENGINEERING TASK FORCE: FINAL REPORT

Systems Engineering Task Force:
Chris Paredis (Chair)
Michael Goldfarb
Craig Klocke
Perry Li
Rick Sporrer

1/18/2011

EXECUTIVE SUMMARY

This report provides an overview of the Systems Engineering activities within the Center for Compact and Efficient Fluid Power.

Fluid Power plays an important role in transmitting, storing and transforming energy in a broad range of systems. It is the CCEFP's mission to innovate current fluid power technologies into compact, efficient and effective sources of energy transmission. This mission poses significant systems engineering challenges because an improvement towards one of the main goals (compactness, efficiency or effectiveness) may well compromise one of the other goals. Successful completion of the Center's mission therefore requires a systematic, consistent and comprehensive consideration of all the relevant goals. The discipline of Systems Engineering (SE) provides a theoretical foundation for achieving this.

To help facilitate the application of SE principles and methods within the CCEFP, a task force has been established. The Systems Engineering Task Force (SETF) consists of academic and industry members with a theoretical and practical background in SE. The key recommendations of the task force address three main activity areas: SE education, the use of SE in center research projects and test beds, and the use of SE principles for managing the research project portfolio.

Education: The SETF proposes six levels of increasing awareness and proficiency in SE, and recommends specific target levels for different groups within the CCEFP. To achieve these targets, it recommends that a series of center-wide tutorials and seminars be organized, raising general awareness of SE concepts and methods. Several additional educational activities should be targeted towards the test-bed groups to provide more detailed information on the application of Model-Based Systems Engineering methods and tools. Most of these recommendations have already been implemented.

Research: The SETF recommends SE models, methods and tools be consistently applied in all test beds and projects that have a systems focus. This recommendation has been implemented in part. It has resulted in a tighter collaboration between project 2E, which is most focused on (Model-Based) Systems Engineering, and the test beds. The test beds have made a concerted effort to adopt a broad all-encompassing perspective in their system analyses. More advanced approaches for Model-Based Systems engineering being developed in project 2E are being applied and demonstrated in TB-3.

Management: The SETF recommends that a systematic approach be deployed for evaluating and selecting projects in the CCEFP's portfolio. This recommendation has been implemented and has resulted in a spreadsheet that the management committee uses to evaluate projects according to a comprehensive set of criteria addressing risk, reward and the alignment with CCEFP objectives.

1. INTRODUCTION

1.1. What is Systems Engineering?

"Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle."
(http://www.incose.org/practice/fellowsconsensus.aspx)

SE has its early roots at Bell Telephone Laboratories in the 1940s with the initial major applications during World War II [2]. It developed into an established discipline in the 1960s with the Apollo Program as one of its hallmark achievements. More recently, in 1990, a professional organization of systems engineers was founded: the International Council on Systems Engineering (INCOSE).

A key aspect of the SE discipline is the systems view — an all-encompassing view covering all concerns, all engineering disciplines, and all life-cycle phases. The goal of the SE process is to identify a system alternative that leads to outcomes that are most preferred, taking all these views and concerns into consideration. Finding the best system alternative is not only difficult because so many different concerns need to be considered, but also because of the uncertainty involved in our predictions of the outcomes. Selecting the alternative that leads to the most preferred outcomes under uncertainty is studied in decision theory. SE should therefore be based on decision theory. Decision theory provides the foundation for multi-objective design optimization, uncertainty modeling, quantitative risk management, and predictive mathematical modeling — all areas of importance in SE.

In addition to making decisions about the system, SE also encompasses the process of doing so. Systems Engineers must make decisions about how to decompose the solution of complex problems into manageable tasks, in which order to perform these tasks, and how to allocate resources to the tasks. This is particularly important for the engineering of large, complex systems.

To aid in the management of all the information and knowledge associated with the SE tasks, a recent trend has been to move from traditional documents towards computer-interpretable models — Model-Based Systems Engineering (MBSE). The MBSE approach is quickly reaching maturity with the introduction and wide-spread adoption of the Systems Modeling Language: OMG SysML™. Within the CCEFP, researchers are investigating how to best use the SysML to capture, organize, and (re-)use information and knowledge about fluid-power systems to facilitate the design of such systems.

1.2. Why is Systems Engineering relevant to the CCEFP?

Fluid-power systems are inherently multidisciplinary. They are tightly integrated with mechanical structures, mechanisms, and increasingly also with electronics and embedded controls. In addition, there are typically multiple concerns involved. For instance, when selecting a pump for a particular fluid-power system, one cares about displacement, physical size, mass, cost, efficiency, noise, leakage, etc. All these different concerns need to be considered in the design of the system. The fluid-power domain is therefore a prime candidate for the application of SE.

In addition, the fluid-power circuits have the advantage that they are easily decomposed into components, connected to each other through well-defined interfaces. A system architecture for a fluid-power system can thus be thought of as a configuration of fluid-power components. This makes the fluid-power domain a good domain for investigating new methods and tools for exploring and optimizing system architecture.

With the adoption of electro-hydraulics, the number of viable system architectures has increased significantly, and the knowledge regarding which of these candidate architectures is best suited for a particular problem is currently lacking. If system designers do not fully understand the complexity and emergent behavior of the system under development, they might overlook important design details and relationships. Such mistakes can compromise stakeholder objectives and lead to costly design iterations or system failures. It is thus important to develop a systematic approach for synthesizing and analyzing fluid-power systems in a broad range of different use contexts.

1.3. What are the Systems Engineering opportunities in the CCEFP?

Given that the fluid-power domain is well suited for applying and improving SE methods and tools, what are the specific opportunities for SE related activities within the CCEFP? The SETF recognizes opportunities in the areas of education, research and center management.

Education. Practicing engineers and researchers in the fluid power domain often have a strong background in control systems theory. These engineers are specialists in describing the dynamic behavior of systems, which is an important part of the performance characterization of fluid-power systems. However, SE is much broader. There is a significant opportunity to educate the practitioners of fluid power on how to expand their systems perspective to include the modeling of any information and knowledge associated with the SE process: objectives, functions, preferences, uncertainties, etc. This will help the fluid-power engineers to make better design decisions, and hence improve the overall quality of future fluid power systems.

Research. Given that fluid-power systems and the corresponding design problems exhibit all the key characteristics of SE problems, the CCEFP is well-positioned to make a contribution to the state of knowledge and practice not only in fluid power, but also in SE. In particular in the test beds, there is an opportunity to apply novel SE methods and tools.

Management. As an organization, the CCEFP itself can be considered as a system that needs to be designed. When making decisions about the Center, multiple objectives need to be considered: contributions to the state of knowledge in fluid power; outreach to industry and the general public, transfer of technology, etc. For the Center to be successful, a portfolio of projects needs to be selected that addresses all these objectives. The selection of this project portfolio is an example of decision making under uncertainty with respect to multiple objectives. There is an opportunity to apply SE principles to this selection process.

2. THE SYSTEMS ENGINEERING TASK FORCE

To help take advantage of the opportunities outlined in the previous section, the CCEFP has created the Systems Engineering Task Force, consisting of five members representing the different stakeholders within the Center.

2.1. Who is part of the task force?

Chris Paredis (Chair) — Associate Professor in the G.W. Woodruff School of Mechanical Engineering at Georgia Tech, and Associate Director of the Model-Based Systems Engineering Center at Georgia Tech.

Michael Goldfarb — H. Fort Flowers Professor of Mechanical Engineering in the Department at Vanderbilt University, and Director of the Center for Intelligent Mechatronics.

Craig Klocke — Global Leader for Propel Systems at Sauer-Danfoss

Perry Li — Professor in the Department of Mechanical Engineering at the University of Minnesota and Deputy Director of the CCEFP.

Rick Sporrer — Director of Technical Services at Sauer-Danfoss

2.2. What is the charge of the task force?

The charge of the Systems Engineering Task Force as specified by the CCEFP Management Committee is:

Provide an overall recommendation for CCEFP activity in the area of Systems Engineering:

- *Cover both research and education in systems engineering*
- *Make a recommendation for how systems engineering should be used as a management tool in the Center*

2.3. What are the actions taken by the task force?

The SETF has taken actions to improve SE practices within the CCEFP in three areas: education, research, and management. The following actions were identified and addressed by the SETF:

- Develop a consensus of what is meant by Systems Engineering
- Educate the CCEFP membership on the concepts of Systems Engineering
- Develop a common Systems Engineering approach and tool suite
- Apply this approach in the test beds
- Apply this approach in the management of the CCEFP project portfolio

The details of these actions and the corresponding outcomes are provided in the subsequent sections of this report.

3. SYSTEMS ENGINEERING EDUCATION

3.1. What are the needs for education within the CCEFP?

The CCEFP encompasses a broad range of stakeholders with different levels of need and interest in SE. The stakeholders who are most involved in SE are the participants in test-bed projects. By the very nature of the test-beds, the focus is on system-level integration of components and technologies and on the system-wide analysis and assessment of these technologies. In addition to the test-beds, there are individual research projects that focus on or would benefit from a systems-perspective. For instance, project 1A.1 on Integrated Algorithms for Optimal Energy Use in Mobile Fluid Power Systems, or project 2E on Model-Based Systems Engineering for Efficient Fluid Power. Finally, SE could also be applied to the management of the portfolio of center projects.

To encourage and facilitate the application of SE within the CCEFP, it is important that the different stakeholders can communicate clearly and unambiguously about SE ideas, methods and tools. It is therefore important to develop a common framework and vocabulary with which all CCEFP stakeholders are familiar. Beyond this common foundation, it is important to cater to the different educational needs with targeted initiatives. Of course, ideally, all stakeholders would be experts in SE, but practically, it is not realistic to expect everybody to invest the time and effort equivalent to several graduate-level courses to reach this level of expertise. Instead, targeted initiatives that quickly fill in the gaps in knowledge and expertise are desirable.

To help guide the development of these educational initiatives, the SETF identified several levels of proficiency and awareness in Systems and specified target levels of proficiency for each of the groups of stakeholders within the CCEFP. The six levels of proficiency and awareness are:

1. **Awareness of a high-level SE process:** what is SE?; the SE process from problem formulation to concept generation, analysis and evaluation.
2. **Ability to identify and express clear objectives and associated attributes/metrics:** Value-focused design; requirements versus objectives; combining multiple objectives.
3. **Ability to generate and analyze concepts from a systems perspective:** concept generation; system architecture; generation and solution of analysis models.
4. **Ability to perform trade-space exploration and optimization:** defining a SE problem in terms of optimization; tools for design space exploration and optimization.
5. **Ability to take uncertainty into account:** probabilities as beliefs about future events; predictive modeling; preferences under uncertainty.
6. **Ability to apply Model-Based SE approaches:** formal representation of SE information and knowledge; modeling languages and formalisms for SE.

The following groups of stakeholders were considered, each with an associated target of proficiency and awareness of SE concepts, methods and tools:

Group of CCEFP Stakeholders	Target level of proficiency
Everybody	2
Test-Beds	3 – 4
Project with SE Emphasis	4 or above
Center Management	3 + 5

- **All CCEFP members:** to facilitate unambiguous communications about SE ideas, methods and tools, the SETF recommends that all CCEFP members attain proficiency at levels 1 and 2.
- **Members working on test-beds:** for researchers involved in the development of test-beds within the CCEFP, a minimum understanding is needed of how to compare different alternatives from a systems perspective. Ideally, a systematic exploration and optimization of the alternatives would be achieved. The SETF therefore recommends a proficiency level of 3 to 4.
- **Members working on projects with a strong systems emphasis:** for researchers involved in project with a strong systems emphasis, it is important to have a sound understanding of all the issues involved in the generation of system alternatives, the prediction of the performance of these alternatives (considering uncertainty), and the selection of the most preferred system alternative. The SETF therefore recommends a proficiency level of 4 or above (depending on the specific context of the project).
- **Center management:** for the management team involved in developing a coherent portfolio of research projects, it is important to understand how to analyze and compare different portfolios with each other, considering the significant uncertainty involved in predicting the outcomes of individual research projects. The SETF therefore recommends a proficiency level of 3 with the inclusion of level 5.

To help the stakeholders reach these levels of proficiency, the SETF has taken the actions detailed in the next section.

3.2. What actions have been undertaken to address these needs?

3.2.1. Seminars

To establish a common understanding of the basic concepts and terminology in SE, the SETF organized two webcast seminars in the fall of 2009, and a live seminar at the CCEFP Annual Conference in June of 2010:

- *Introduction to Systems Engineering* (Webcast on September 23, 2009): The focus of this seminar was on basic concepts of systems engineering. What is Systems Engineering? What is the systems perspective? What is the relation between SE and decision making? What is the V-Model for Systems Engineering? How to refine a system concept through concept generation, analysis and evaluation? How does uncertainty play a role in Systems Engineering?
- *Defining Objectives and Measures of Effectiveness in Systems Engineering* (Webcast on October 21, 2009): The focus of this seminar was on the formulation of objectives for SE problems. Why should we focus on Value? What is an objective? What is an attribute or measure of effectiveness? What are fundamental and means objectives? How are they different from each other? How to elicit objectives? How to measure the extent to which objectives are met? How to express preferences with respect to multiple objectives?
- *Model-Based Systems Engineering in the CCEFP* (Seminar presented at the CCEFP Annual Conference, Purdue University, June 15, 2010): The focus of this seminar was on introducing the CCEFP community to basic concepts of Model-Based Systems Engineering (MBSE). What is Systems Engineering? What is MBSE? Why is MBSE important? What is SysML? How is MBSE applied within the CCEFP? What are the future challenges and opportunities for MBSE?

All three seminars were well attended both by researchers in the CCEFP and by industry members (>50 attendees per seminar). They clearly responded to a need for information about SE.

3.2.2. Application demonstrations in testbeds and projects

To make sure the concepts that were introduced in the seminars would also be applied in the test beds, the SETF recommended additional targeted instruction for the test-bed researchers. The members of project 2E have guided the researchers in TB-4 (Rescue Robot) and TB-6 (Foot Orthosis) through the initial SE process of eliciting the objectives, quantifying these objectives in measures of effectiveness and defining test cases for measuring the measures of effectiveness. The results of this objectives elicitation process have been modeled in SysML.

In addition, the members of project 2E have been involved in the further application of SE ideas in TB-3 (Hybrid Vehicle). Since some of these ideas are still in the research stage, the transfer of these ideas to the CCEFP researchers involved in the other test-beds will occur after the proper demonstration in TB-3. The next steps in the application of a thorough SE approach to TB-3 are the definition of a comprehensive evaluation criterion, uncertainty quantification for the corresponding predictive models, comprehensive comparison with the leading competing approaches, and finally system optimization considering uncertainty and risk. A more detailed overview of these steps is provided in Section 4.4.

To support the comprehensive evaluation of alternatives using a formal, model-based approach, an REU-student developed a convenient analysis tool for MBSE. The tool combines the formal representation of models in the SysML tool, MagicDraw® by No Magic, with the efficient solving of these models using the simulation integration framework, ModelCenter® by Phoenix Integration. Analysis models, represented using SysML parametric diagrams, can be formally related in SysML to descriptive models of the system architecture with corresponding requirements and specifications. These analysis models can be automatically mapped to ModelCenter, where they can be executed possibly in combination with optimization, uncertainty quantification, or design-of-experiment tools. Finally, the results of the analyses are mapped back to SysML, where they can be stored as the rational for SE decisions. More information is available at: http://www.srl.gatech.edu/research/MBSE/md2mc/. This tool will facilitate the use of formal analysis models in the test beds.

3.2.3. New Course: Model-Based Systems Engineering

To help the researchers in the CCEFP with acquiring expertise in Model-Based Systems Engineering, a new course has been introduced at Georgia Tech in the fall of 2010. The course is called: “ME/ISyE 4803: Model-Based Systems Engineering.” It is a senior-level course in which the students learn about the Model-Based Systems Engineering process and how it can be supported using the Systems Modeling Language (OMG SysML™). In its first offering, 42 students were enrolled from both Mechanical Engineering and Industrial and Systems Engineering (30 undergraduate and 12 graduate students). The course was well-received by the students and resulted in several excellent student projects in which simple systems engineering problems were solved supported by SysML models.

The next step is to make the course contents available to the researchers in the CCEFP. A condensed version of this course is already available offered through the Georgia Tech Executive Education program, so that CCEFP industry members have access to this knowledge and expertise. It is divided into a two-course cycle:

- SysML 101: Model-Based Engineering Using SysML: Essentials for Understanding SysML Models (http://www.pe.gatech.edu/courses/model-based-engineering-using-sysml-essentials-understanding-sysml-models-sysml-101)
- SysML 102: Model-Based Engineering Using SysML: Hands-On Essentials for Creating SysML Models (http://www.pe.gatech.edu/courses/model-based-engineering-using-sysml-hands-essentials-creating-sysml-models-sysml-102)

Both short courses are part of the Georgia Tech Systems Engineering Certificate Professional Education Program (http://www.pe.gatech.edu/defense-technology/defense-technology-certificates/systems-engineering-certificate). The courses are currently being offered four times per year.

4. SYSTEMS ENGINEERING RESEARCH

4.1. Review of the Current State of the Art in Systems Engineering

Since the early days of Systems Engineering in the 1940s and 50s, the discipline has made a lot of progress. For a long time, the focus was (and still is to a large extent) very much on the SE process: What are the activities one should perform in each of the phases of the systems life cycle? For instance, the INCOSE Systems Engineering Handbook provides a detailed discussion of the following processes [11]:

1. Stakeholder Requirements Definition Process
2. Requirements Analysis Process
3. Architectural Design Process
4. Implementation Process
5. Integration Process
6. Verification Process
7. Transition Process
8. Validation Process
9. Operation Process
10. Maintenance Process
11. Disposal Process

In addition, process models, such as the V-model [8], were introduced and are currently commonly used to guide the SE process. However, so far all these process models have been qualitative in nature, and except for system analysis and simulation [1], few quantitative tools have been in use. For instance, risk management has always been an important part of the management process in traditional SE. However, risk was characterized in a very qualitative manner, usually using a color-coded risk matrix (low=green, medium=yellow, high=red), with the probability level (of the risk occurring) on the horizontal axis and the impact or consequence level on the vertical axis [9]. Such a risk matrix may be useful for elicitation purposes, but it is too vague to support the comparison of system alternatives involving complex tradeoffs.

Without a strong emphasis on quantitative methods, SE was limited to documentation and glorified project management [6, 19]. More recently this focus on project management and documentation has shifted in two important ways. First, a view of systems engineering as decision making has been advocated [12, 22, 25]. Decision making clearly is a key characteristic of SE. The goal of the SE process is to identify a system alternative that leads to outcomes that are most preferred, taking into consideration a comprehensive, all-encompassing view of the system. This decision-based perspective has the advantage that it provides a strong theoretical, mathematical foundation, including probability theory, utility theory, decision theory, and game theory. The decision-based perspective is complemented by value-focused thinking [13]. This focus on value has recently been emphasized in engineering design and systems engineering as Value-Driven Design [3-4].

A second recent shift in SE methodology has been the capture of SE information and knowledge in formal, computer-based models rather than only (voluminous) documents. This new approach is called Model-Based Systems Engineering (MBSE) [7]. In MBSE, modeling languages with formal syntax and semantics have been created to enable the representation of SE information and knowledge in an unambiguous and computer-interpretable fashion. Two prominent examples of MBSE languages are OPM and OMG SysML™ [5, 10, 24].

4.2. Model-Based Systems Engineering

In terms of Systems Engineering, within the CCEFP, the focus has been on Model-Based Systems Engineering. The MBSE approach pursued within the Center builds on the Systems Modeling Language (OMG SysML™) developed by the Object Management Group [24]. SysML is a general-purpose information modeling language that allows system designers to create and manage models of physical systems using well-defined, visual constructs. The knowledge captured in a SysML model is intended to support the specification, analysis, design, verification and validation of a complex system.

The specification of the SysML language reuses a subset of UML 2.0 and extends it where necessary. Adopted in November 1997, the Unified Modeling Language [21] is a visual language for specifying, constructing, and documenting the artifacts of software, business models, and other applicable systems. It is a general-purpose modeling language that can be used with all major object and component methods. The language is commonly used during the development of large-scale, complex software for various domains and implementation platforms.

The SysML profile was developed to extend UML for increased support of SE projects. The *«block»* is the basic unit of structure in SysML and can be used to represent hardware, software, facilities, personnel, or any other system element. A block definition diagram describes the system hierarchy and system or component classifications. The internal block diagram describes the internal structure of a system in terms of its parts, ports, and connectors. In addition, behavior diagrams include the use-case diagram, activity diagram, sequence diagram, and state machine diagram. A use-case diagram provides a high-level description of functionality that is achieved through interaction among systems or system parts. The activity diagram represents the flow of data and control between activities. A sequence diagram represents the interaction between collaborating parts of a system. The state machine diagram describes the state transitions and actions that a system or its parts perform in response to events. Finally, parametric diagrams represent constraints on system property values such as performance, reliability, and mass properties, and serve as a means to integrate the specification and design models with engineering analysis models.

4.3. Current use of Model-Based Systems Engineering Research in the CCEFP

Within the CCEFP, researchers are investigating how to best use the SysML to capture, organize, and (re-)use information and knowledge about fluid-power systems to facilitate the design of such systems [15, 17-18, 23]. In addition, MBSE methods are being developed in which this formal knowledge is applied towards the efficient exploration of architectures of fluid-power systems [14, 16, 20, 23].

These new models and methods are also being used in several test-beds within the CCEFP. For instance, in the rescue robot test bed, the requirements have been broken down into detailed requirements and corresponding test cases, as is illustrated in the figures below. The research ideas developed in project 2E are gradually being introduced into the test beds, first in TB-3 followed by the other test beds. A detailed list of steps and milestones is provided in the next section

ID	Name	Text
1	Victim Survivability	The system shall maximize the survivability of victims in a collapsed and/or burning building.
1.1	Availability	The availability of the system shall be maximized.
1.2	Usability	The Usability of the system shall be maximized.
1.3	Capability	The capability of the system shall be maximized.
1.3.1	Find Victims	The system shall be able to find and identify victims.
1.3.2	On-Site Assistance	The system shall provide on-site assistance to victims.
1.3.2.2	Provide Support	The system shall provide support to victims in peril.
1.3.2.2.1	Pressure Relief	The system shall be able to lift debris to alleviate pressure on the victim.
1.3.2.2.1.1	Lifting	The system shall be able to lift obstacles and victims
1.3.2.2.1.1.1	Lift Obstacle	The system shall be able to lift obstacles
1.3.2.2.1.1.2	Lift Victim	The system shall be able to lift victims
1.3.2.2.2	Medical Services	The system shall be able to provide limited medical services to victims (e.g. defibrillator).
1.3.2.3.1	Pulse	The system shall report the victim's pulse.
1.3.3	Retrieve Victims	The system shall be capable of retrieving victims.
1.3.4	Provide Information	The system shall provide pertinent information to rescuers.
1.3.4.1	Victim Location	The system shall report the location of victims.

Figure 1: A few examples of requirements modeled in SysML for the rescue robot

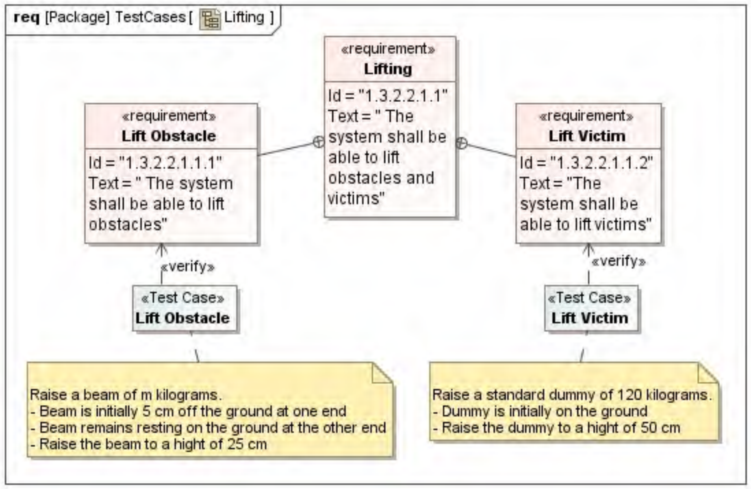

Figure 2: A few examples of test cases linked to requirements in SysML

4.4. Next steps in the use of Model-Based Systems Engineering in the CCEFP

To support the development of the test beds, the SE models, methods and tools developed in project 2E will be applied in the test beds. This process will start with TB-3 and consists of the following steps:

1) **Development of a comprehensive evaluation criterion**: A key characteristic of value-focused systems engineering is that system alternatives are compared with each other based on a single, comprehensive evaluation criterion. This evaluation criterion should take on a system-wide perspective and account for all the aspects that may influence the value of the system. Project 2E is developing such a comprehensive evaluation criterion for the hydraulic hybrid.
Target Completion Date: March 2011.

2) **Uncertainty quantification**: The comprehensive evaluation criterion cannot be evaluated with certainty. In fact, some factors contributing to the criterion are likely to be quite uncertain. It is therefore important to quantify the uncertainty in the models so that an assessment can be made as to whether the uncertainty is sufficiently small or whether it is cost-effective to collect additional data in order to reduce the uncertainty further.
Target Completion Date: June 2011.

3) **Comparison with leading competing alternatives**: To verify the competitiveness of the test beds and to justify their further development, we need to compare them to the leading competing alternatives. This requires modeling the competing alternatives according to the same comprehensive evaluation criterion. For a fair comparison, uncertainty must be taken into account also. The aversion for risk will be modeled by mapping the evaluation criterion onto a utility function.
Target Completion Date: August 2011.

4) **System optimization considering uncertainty and risk**: To determine the best alternative while taking into account a comprehensive systems view, the system will be optimized across the space of system alternatives based on the comprehensive evaluation criterion considered under uncertainty. Given the computational expense involved in solving an optimization problem under uncertainty across a large space of system configurations, this step is the most challenging and the most uncertain at this point.
Target Completion Date: August 2011.

The execution of these four steps will result in a thorough evaluation, comparison and optimization of the different alternatives being considered in TB-3. It will also serve as a comprehensive case-study that can be emulated in the other test beds.

5. SYSTEMS ENGINEERING AS A MANAGEMENT TOOL

Systems Engineering is an approach that can be applied not only to the development of physical systems, but to any problem for which a systems perspective is important. In the context of the CCEFP, this also includes the management of the CCEFP itself. For instance, an important decision for the CCEFP is to choose a portfolio of research projects that meets the Center's objectives best. Such a portfolio must take into account the project potential for advancing the state of knowledge, advancing the state of the art in fluid-power technology, etc.

To help the center management evaluate the project proposals in a systematic fashion, the SETF has recommended using a comprehensive set of metrics organized by three categories: 1) alignment with CCEFP goals, 2) potential risks, and 3) potential rewards. Mike Gust developed a spreadsheet to support such an approach. As is shown in the Figure below, the spreadsheet allows each member of the project selection committee to score each project according to the three top-level criteria based on more detailed evaluation metrics. The scores can then be aggregated by each of the three categories and summarized in an overview sheet to be used in the project selection process.

Although the spreadsheet requires numerical scores for each of the evaluation metrics, one must be careful in the interpretation of the aggregated results. Each evaluation metric is qualitatively assessed using a score between 1 and 5 based on brief textual descriptions indicating the meaning of each numerical value. These numerical values are then aggregated in a weighted sum across all the members of the committee. The resulting scores for alignment, risk and reward can serve as an initial filter to distinguish the best projects from the worst, but it should not be used to directly a decision-making criterion.

Instead the SETF has recommended that the management committee use the assessment results to guide the discussion of the individual projects in which discrepancies between scores from individual committee members can be reconciled and additional considerations can be included. Additional considerations may for instance include potential overlap or synergy between different projects.

The spreadsheet and corresponding assessment methodology has been used for the selection of projects in years 5 and 6 of the CCEFP. Although there is room for refinement of the tool, it has definitely improved the effectiveness of the decision-making process.

CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Project scores:	
Alignment:	4.50
Risk:	3.75
Reward:	3.70

Year 5-6 Proposal Scorecard

Proposal number: 2
Conituation of existing 2.C.2
Project name: **Advanced Strain Energy Accumulator**
Project PI: Prof Eric Barth
Brief project description: The research objective of this proposed work is to extend the current state of knowledge in the use of strain energy storing materials for the engineering design of compact energy storage devices. Specifically, this project will seek a low cost, low/no maintenance, high energy density accumulator primarily targeted toward a fluid powered automotive regenerative braking system (hydraulic hybrid).

	Scoring Parameter	Weight (%)	Score: 1	Score: 2	Score: 3	Score: 4	Score: 5	Enter score (integers only)
Alignment	Fundamental nature of project	15%	Largely technology development	Extension of known technology into new space.	Some level of fundamental research apparent	Largely fundamental research (extension of current or past work)	Largely fundamental research (novel direction)	4
Alignment	Systems approach	10%	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.	Demonstartion of one or more fluid power systems is planned during this project proposal time	3
Alignment	Strategic fit	30%	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	5
Alignment	Alignment with test bed	15%	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	30%	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	15%	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	3
Risk	Deliverables	15%	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	Fullt defined, SMART and competitive benchmarks are part of deliverables	4
Risk	Likelihood of success	40%	Unclear	Moderate - est. 25%	Good - est. 50%	Very good - est. >67%	High - est. >80% (e.g., builds on past successes)	3
Risk	Team assessment	15%	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 pocesses all critical skillsets for project success	It is apparent that the team pocesses all critical skillsets for project success	5
Risk	Budget Assessment	15%	It is apparent that the proposed budget is dramatically too high or dramatically insufficient to meet project scope or well outside of specified guidelines	The proposed budget is questionable with respect to project scope or specified guidelines	The proposed budget is adequate	The proposed budget is reasonable based on project scope and specified guideleines	It is apparent that the proposed budget is appropriate to meet project scope and within specified guidelines	5
Reward	Industry participation	30%	No industry partners identified	Potential partners indentified but not yet committed	Letter of support from industry partner	Letter of support and commitment of resources from industry partner	Letters of support and commitment of resources from multiple industry partners	2
Reward	Addressing CCEFP technical barrier(s)	30%	Weak or no link to technical barriers	Addresses one non-transformational technical barrier	Addresses multiple non-transformational technical barrier	Addresses a transformational technical barrier	Addresses multiple technical barriers including at least one transformational barrier	5
Reward	Breadth of applicability	10%	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	3
Reward	External support	10%	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	20%	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	5

Figure 3: Example of the project evaluation tool used for selecting CCEFP projects

6. SUMMARY AND RECOMMENDATIONS

In this report, the Systems Engineering Task Force of the CCEFP assesses the current state of practice of SE within the Center, and has provides recommendations for further application and improvements of SE practices:

1) **Education:** The SETF proposes six levels of increasing awareness and proficiency in SE, and recommends specific target levels for different groups within the CCEFP. To achieve these targets, it recommends that a series of center-wide tutorials, seminars, and targeted activities for test beds be organized.

2) **Research:** The SETF recommends SE models, methods and tools be consistently applied in all test beds and projects that have a systems focus. The recommended SE best practices include the definition of a comprehensive evaluation criterion, uncertainty quantification for the

corresponding predictive models, comprehensive comparison with the leading competing approaches, and finally system optimization considering uncertainty and risk.

3) **Management:** The SETF recommends that a systematic approach be deployed for evaluating and selecting projects in the CCEFP's portfolio according to a comprehensive set of criteria addressing risk, reward, and the alignment with CCEFP objectives.

These recommendations have already been implemented to a large extent, as is outlined in this report. The level of awareness and proficiency in SE has increased significantly through a series of seminars and tutorials. The portfolio of CCEFP research projects for years 5 and 6 has been selected with the aid of a spreadsheet that allowed members of the Management Committee to score individual project according to risk, reward, and alignment with CCEFP objectives. Finally, Model-Based Systems Engineering methods and tools have been used in all of the test beds to develop comprehensive evaluation criteria. A value-focused evaluation approach is currently being developed for TB-3. This is still an ongoing activity that ties in closely with the research activities in project 2E.

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HUMAN-MACHINE INTERFACE TASK FORCE: FINAL REPORT

Human-Machine Interface Task Force:
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1/18/2011

1. Statement of Task Goals

During the 2009 NSF Site Visit, the NSF Review Team made the following comments regarding the weakness of the human-machine interface (HMI) research within the Center for Compact and Efficient Fluid Power (CCEFP):

- "Failure to integrate human performance into the system analysis up-front"
- "The human factors effort should be a consistent aspect of the systems approach to the research efforts and not an afterthought."

In response to these concerns, the Ad Hoc Human-Machine Interface Task Force was established with the following goals:

1) To form a framework that guides test beds towards up-front integration of human factors into system analysis and design for improved human performance and
2) To develop plans that identify and address the significant human factors research issues related to current and future fluid power systems.

2. Vision of the HMI Task Force

The HMI Group set up its vision is as follows:

> "*Human interaction with fluid power will capitalize on and compliment the inherent superior capabilities of a human operator to accomplish a wide range of tasks and activities while providing a safe, intuitive, productive and comfortable work environment. This will be enabled through an understanding of the human component in its motor, sensory and cognitive aspects and their dynamic interaction in the system. Existing systems as well as future system concepts will be thereby enabled to perform efficiently and effectively with reduced training time."*

3. HMI Research in Support of the CCEFP Strategic Plans

Within CCEFP, HMI research has been broadly addressed by projects 3A.1 and 3A.3, as well as by the ankle-foot orthosis, TB6, in the narrow context of rehabilitation and assistive technology. The research teams have been challenged to incorporate design features that enhance human performance into the overall system, thereby reducing barriers to effective operation. The HMI Task Force provides recommendations for HMI research activities within the Center to refocus HMI research efforts and to enhance their impact on the effectiveness of fluid power systems. Some of the major HMI barriers to effective overall fluid-power systems are identified as follows:

1) Safety hazards
2) Long training time
3) Challenging goals for productivity improvement
4) Physical and mental overload
5) Negative user attitudes towards design changes
6) Unfamiliarity of HMI principles by system designers

3.1 Potential HMI research

Bearing in mind the goal of overcoming the above-mentioned barriers with CCEFP research, the following potential HMI research issues have been identified:

1) Establishing appropriate design and testing paradigms for HMI features on fluid power systems of various power levels and sizes, from excavators to ankle-foot orthoses;
2) Analyzing the effects of HMI design options on operator attitudes and performance;
3) Analyzing the changes in operator skill requirements, required training time as well as physical and mental performance brought forth by technology changes (state-of-the-art technology, unconventional power sources);
4) Exploring any potential effects on human performance and productivity due to technological enhancements (e.g.: eliminating valves in pump-controlled excavators).
5) Establishing standard metrics for productivity improvements for better HMI designs. What are the appropriate metrics for measuring productivity improvement? What is the relationship between productivity and HMI?
6) Analyzing effects of interface modalities in human performance:

a. How much/how strong should haptic feedback be?
b. What is the best way to present environment on visual displays?
c. How to resolve potential conflict among modalities (haptic, visual and auditory) and its negative impact on productivity

7) Analyzing human performance in automated and remote systems:
   a. Human trust in automated systems
   b. What problems are associated with vigilance (especially in lengthy operations)?
   c. Situation awareness of the supervisory or remote operator
8) Identifying control placement and configuration for minimized physical stresses
9) Shortening the learning curve and improving the level of satisfaction for operators (practically new experience, unconventional controls, young application domain):
   a. Design of interfacing hardware and software components that support the cognitive tasks and motor skills of the human operator
   b. Identification of usability trade-offs where needed
   c. Research to develop effective training methods and also to identify human trust in system
10) Understanding and establishing cost saving components by implementing outcomes of HMI research

3.2 Description and explanation of task approaches

The outline of the task approaches is as follows:

1) Test bed engineers, HMI experts, and our industrial partners work synergistically to identify needs for HMI research specific to fluid power within each test bed;
2) The four test beds are ranked according to the scope and impact of their HMI research needs in order to prioritize resources allocated to HMI research activities among the test beds (Due to limited resources HMI research at the Center should be focused on top-ranked test beds.);
3) Task analysis studies are conducted on the top-priority test beds to systematically identify areas within the test beds that demand intense HMI efforts.

Front-end task analysis is conducted for top priority test beds. This analysis provides a systematic illustration of user interactions with the system as well as a system or test-bed-specific context for implementing fundamental ergonomic principles. The analysis is essentially an ordered sequence of tasks and subtasks that identify the user(s), operations, environment, starting and goal states, and requirements for task completion. The outcomes of a task analysis study include: (1) operator behaviors required to perform the task, (2) system states that occur when the task is performed and (3) a mapping of the operator (task) behaviors onto the system states.

Results from test-bed-specific task analyses help systematically identify potential HMI research studies in CCEFP. Each study is evaluated according to its potential impacts on the test bed's success in meeting its own goals and fulfilling the Center’s mission.

The general rules for recommending HMI research activities are summarized below:

- All research activity must stay within the scope of test bed design goals and the Center mission.
- Research problems, which are specific to fluid power, are top priority.
- Industry experts are to be engaged in research-related decision making.
- Center management will help guide the prioritizing of HMI research areas, while considering factors such as resource constraints.

4. HMI Research Approaches

The HMI Task Force has identified the HMI research needs within all four test beds, where Test Bed 1 (excavator) has the widest range of HMI issues that are specific to fluid power. The needs mainly focus on replacement options for mechanical (hydraulic) control, which leads to HMI research in various areas. Some examples of this research include: establishing appropriate testing paradigms for HMI design features; analyzing the effects of HMI design options on operator attitudes; analyzing the changes in operator skill requirements brought forth by HMI components; and establishing standard metrics for productivity improvements from better HMI designs. HMI research also needs to explore any potential effects on human performance and productivity from the elimination of valves in pump-controlled excavators.

For Test Bed 3 (highway vehicle), all HMI features remain the same as in regular vehicles. This finding means that there are no HMI issues that are specific to fluid power. Therefore, no HMI research is needed for this test bed at this time.

For Test Bed 4 (rescue robot), HMI research should focus on both the navigation of the robot and its task performance. HMI should investigate the enhancement of human control of the multi-articulated fluid power driven robot operated at a distance from the controlling human. It is important to understand that a fluid power rescue robot has significant force and power, therefore placing it in a new category of rescue machines that possess new abilities to lift and move. Because of this fact, HMI research is needed to establish the control strategies and HMI methodologies that are best for this new class of machines.

For Test Bed 6 (ankle-foot orthosis), HMI research emphasizes effects on human performance of design factors such as size, weight and mass distribution of the orthosis as well as potential effects on performance from noise, emission and leakage. HMI research is also needed to explore effective control methods that work with different gait impairment and/or different walking conditions (e.g., even vs. uneven ground).

Based on the HMI research needs identified for all of the test beds, the priorities for receiving HMI research efforts are as follows:

1) Test Bed 1 (excavator)
2) Test Bed 4 (rescue robot)
3) Test Bed 6 (orthosis)
4) Test Bed 3 (highway vehicle)

Therefore, it is recommended that Test Bed 1 and Test Bed 4 should be the main focus of HMI research efforts.

4.1 Approaches by research teams at North Carolina A&T State University

Research teams at North Carolina A&T State University (NCAT) have conducted the following research to meet the CCEFP's goals:

1) Modeling operator performance for fluid power systems
   a. Using discrete event simulation to model excavator operator performance (Hughes & Jiang, 2010)
   b. Using Human Performance Modeling Tool to Predict Fluid Powered Rescue Robot Operator Performance (Lee, et al. 2009)
   c. Development of an integrative framework to model operator performance for fluid power systems (Hughes, 2009, 2010)
   d. Development of Digital Human Model to Evaluate Excavator Operator Performance (Liu, et al., 2009)
2) User centered design in fluid power systems
   a. A user-centered design for the rescue robot with Fluid Power (Delpish, et al. 2007)
   b. Development of a User-Centered Framework for Rescue Robot Interface Design (Delpish, et al. 2010)
3) Assessment of usability and HMI impact on user behavior
   a. Investigation of Operator Behavior Using Haptic Controlled Backhoe Simulator (Osafo-Yeboah, et al., 2008)
   b. Usability Evaluation of a Haptically Controlled Backhoe Excavator Simulation (Osafo-Yeboah, et al., 2009)
   c. Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback (Osafo-Yeboah, et al., 2010)
4) Trust Measurement for Fluid Powered Rescue Robots
   a. Development of an Instrument to Measure Operator Trust for Fluid Powered Rescue Robots (Jenkins, et al., 2009)

   b. Application of Eye Tracking in Measuring Trust in Human Robotic Interaction (Jenkins, et al., 2010)

4.2 Approaches by research teams at Georgia Tech

Research teams at Georgia Tech (GT) have conducted the following research to meet the CCEFP's goals:

1) Implementation and effectiveness of intuitive excavator controls with haptic feedback
   a. Creation of excavator simulator program used by GT and NCAT (Elton)
   b. Equip Bobcat cab with simulation input and display (Elton, Huggins)
   c. Equip John Deere backhoe with haptic controls, biodynamic feed through (Kontz, Humphreys, Huggins)
   d. Create software for shared control (Enes)
   e. Software, circuit and test bed for stable displacement control of single rod cyliders (Wang, Huggins)
2) Experimentation on interface design
   a. Coordinated control of excavators improves efficiency of soil removal (Elton)
   b. Shared control makes novices perform like experts (Enes)
   c. Biodynamic feed through can be reduced with control intervention (Humphreys)
   d. Singular perturbation analysis for simplified modeling of hydraulic circuits (Wang)
   e. Circuit analysis explaining susceptibility to limit cycles, ways to avoid (Wang)
3) Rescue robot test bed implementation
   a. Creation of an operator interface workbench with legged mobility (Gueriero, Zhu) (supplemented by Vanderbilt's 4 legged version)
   b. Test facility for alternative pneumatic teleoperation control (Gueriero)
   c. Simulation of robot dynamics driven by workbench (Kim)
4) Research on Test Bed 4
   a. Facilitate research by UMN and NCAT
   b. Control studies (Gueriero)
   c. Gait planning with human operator directing (Kim)
   d. Balance dictated movement constraints (Daepp, Chipalkatty)
   e. Behavior simulation with pneumatic drives (Daepp)

4.3 Research Benefits (Estimating value of enhanced user interfaces.)

Based on research results and reasonable estimates of the usage of mobile fluid power, we can make rough estimates of the value of improved interfaces. Only the most direct advantages are listed here, and several assumptions are made. It is also worthwhile to note that there are other tremendous cost saving benefits due to reduced fatigue, improved work environment, changed workload etc., but these benefits are not listed here.

Cost benefits to excavators: In terms of energy, operator experiments by Mark Elton [1] showed that for excavator tasks, an improvement of 18% in fuel efficiency per unit of soil moved resulted from the shift from joysticks to intuitive coordinated control. Based on an estimation by Lonnie Love of the Department of Energy, the outcome of this research results in saving over 112 million gallons per year solely in excavators if this change were achieved for all such devices. His estimation is as follows:

- 125,000 excavators actively used in U.S.
- utilization (average usage: 1,092 hours/year; average fuel consumption: 5.73 gallons/hour; and 80% to hydraulics)

Furthermore, the improvement of productivity in soil moved per unit time was 18%. Assuming that an operator is paid $40/hr, a savings of nearly $983M would result each year. The value of the combined savings of fuel and time would result in saving over 112M gallons and a saving in wages of almost $983M per year. An alternative approach, taken in the studies by Aaron Enes, [2] showed that blended shared control with standard joystick interfaces resulted in a reduction of task completion time for a trenching task between 5% and 20%. If a 10% reduction of task time were extended to all mobile hydraulics as estimated above, the savings due to this increase in productivity would result in a savings of $546M each year.

5. Recommendations

A considerable amount of HMI research in the areas recommended by the HMI Task Force has already been conducted through the combined efforts of Georgia Tech and North Carolina A&T State University research teams (projects 3A.1 and 3A.3), including the task analyses for Test Beds 1 and 4. Results are included in respective project reports. However, the research teams should strengthen their collaborative relationship with the CCEFP's industrial partners including John Deere, Caterpillar and Bobcat. Georgia Tech has regularly shared their experiences and ideas with John Deere, but it is still limited and it is highly encouraged they build a strong relationship with all member companies.

Finally, the HMI research teams should engage in the following additional activities more regularly:

1) Organized webcast training sessions on human factors and HMI so all of the Center research team members and the Center industry partners have more complete knowledge about integrating human performance into system analysis up-front.
2) Serving as Ergonomic consultants and as experts on integrating human performance into system analysis.

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