CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

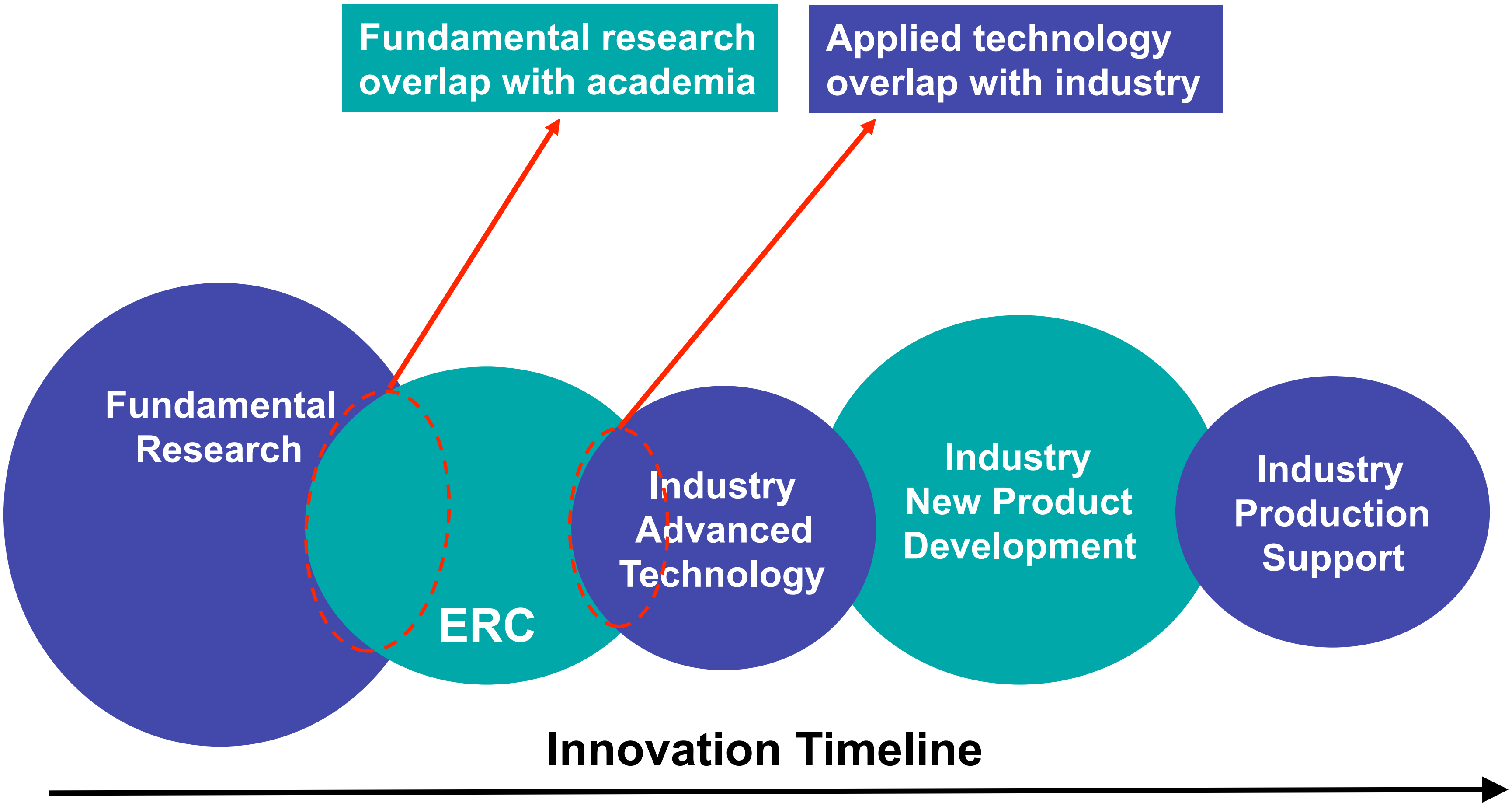
Efficient Transportation with Fluid Power

Georgia Institute of Technology | Milwaukee School of Engineering | North Carolina A&T State University | Purdue University
University of Illinois, Urbana-Champaign | University of Minnesota | Vanderbilt University

Kim Stelson, CCEFP Director
Professor, Mechanical Engineering
University of Minnesota

University of Minnesota | Georgia Institute of Technology | Illinois, University of Illinois at Urbana-Champaign | Purdue University | MSOE | North Carolina A&T State University | Vanderbilt University | National Fluid Power Association NFPA | Science Museum of Minnesota | Project Lead The Way PLTW

The role of an ERC



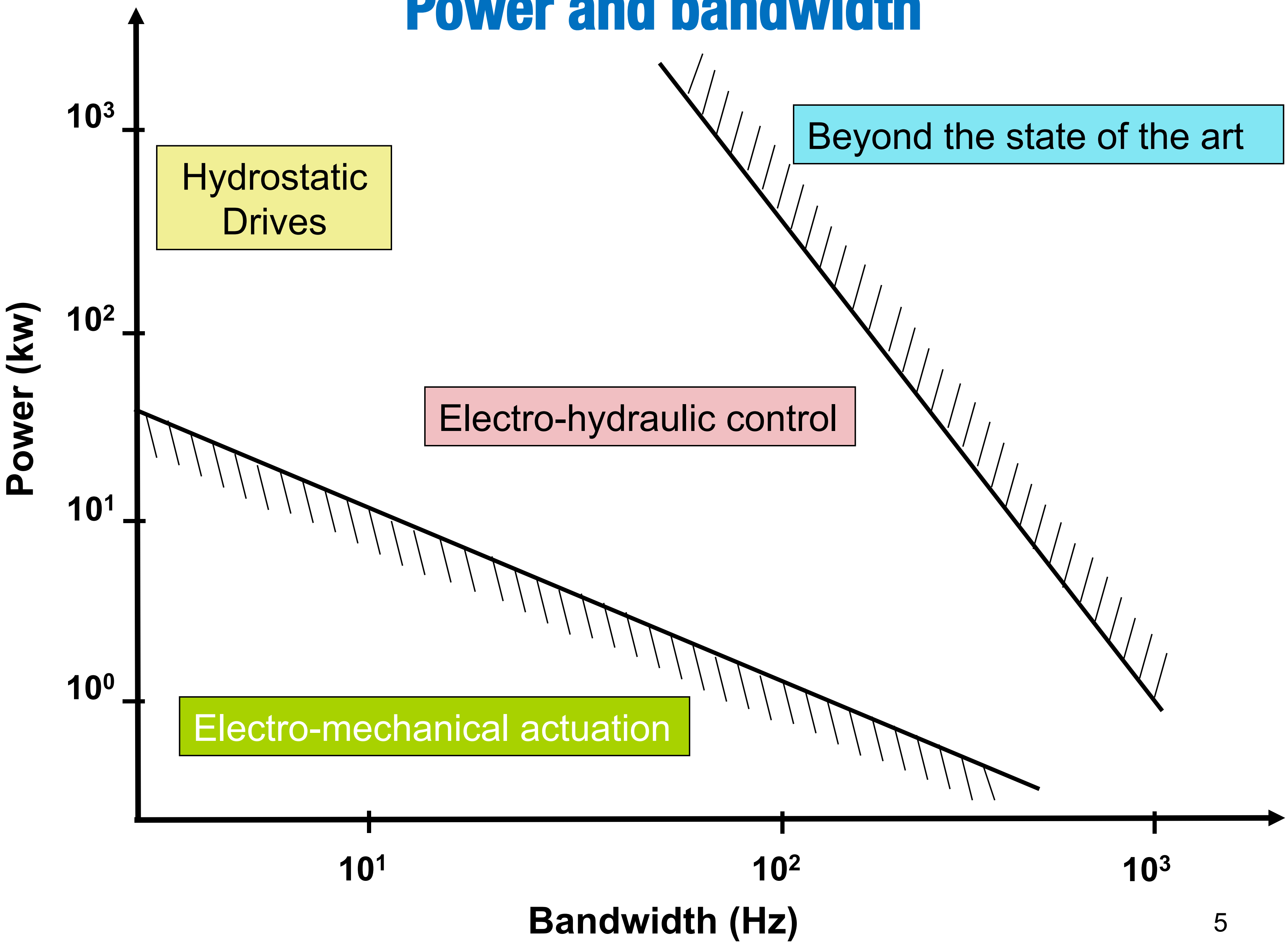
CCEFP Mission

CHANGING THE WAY FLUID POWER IS RESEARCHED, APPLIED AND TAUGHT

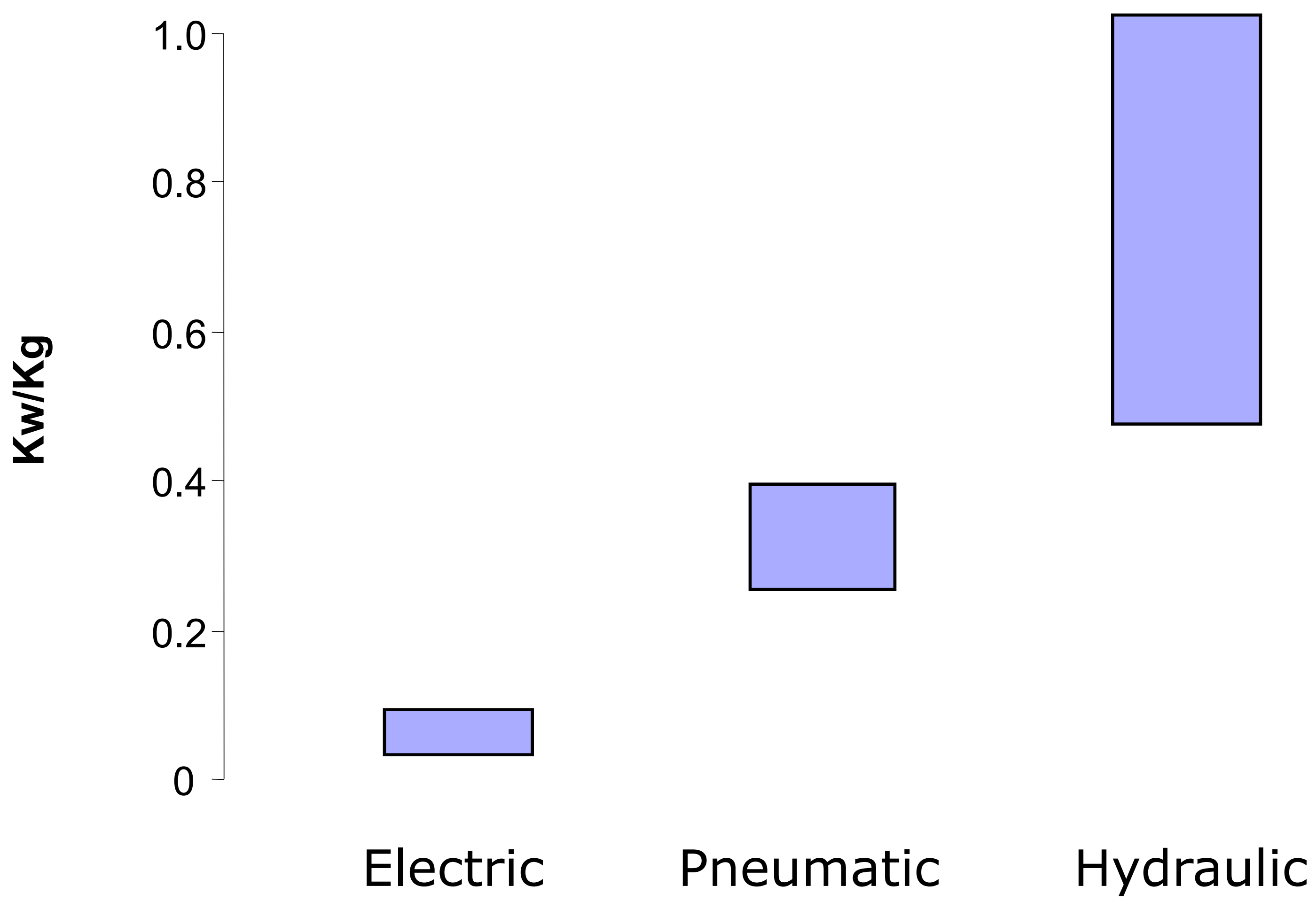
Advantages of fluid power

- Flexible routing
- Bi-directional
- Infinitely variable transmission ratio
- High torque or force
- Load holding without power
- High power and bandwidth
- High power to weight ratio
- Cost effective

Power and bandwidth



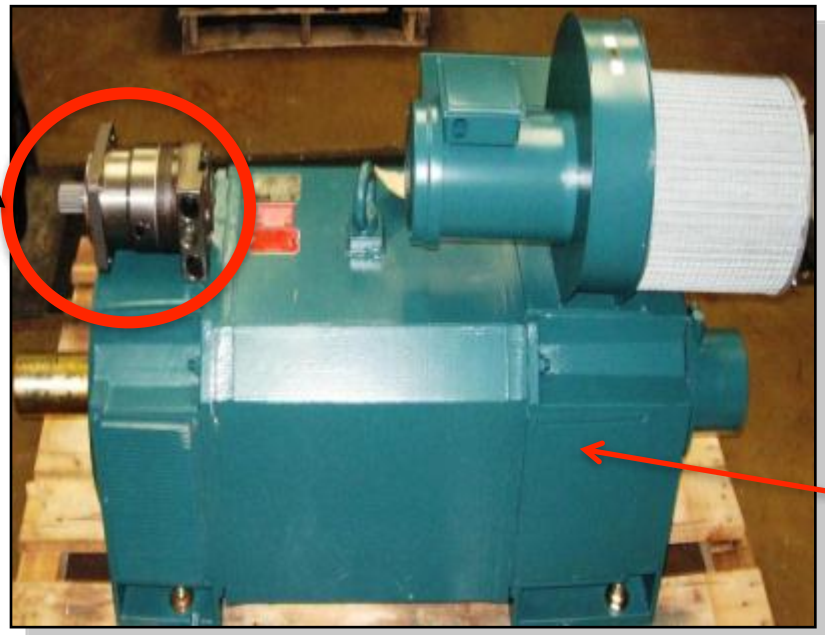
Actuation Power Density



Reference: I. L. Krivts and G. V. Krejnin, *Pneumatic Actuating Systems for Automatic Equipment,* Taylor and Francis, 2006.

Size comparison

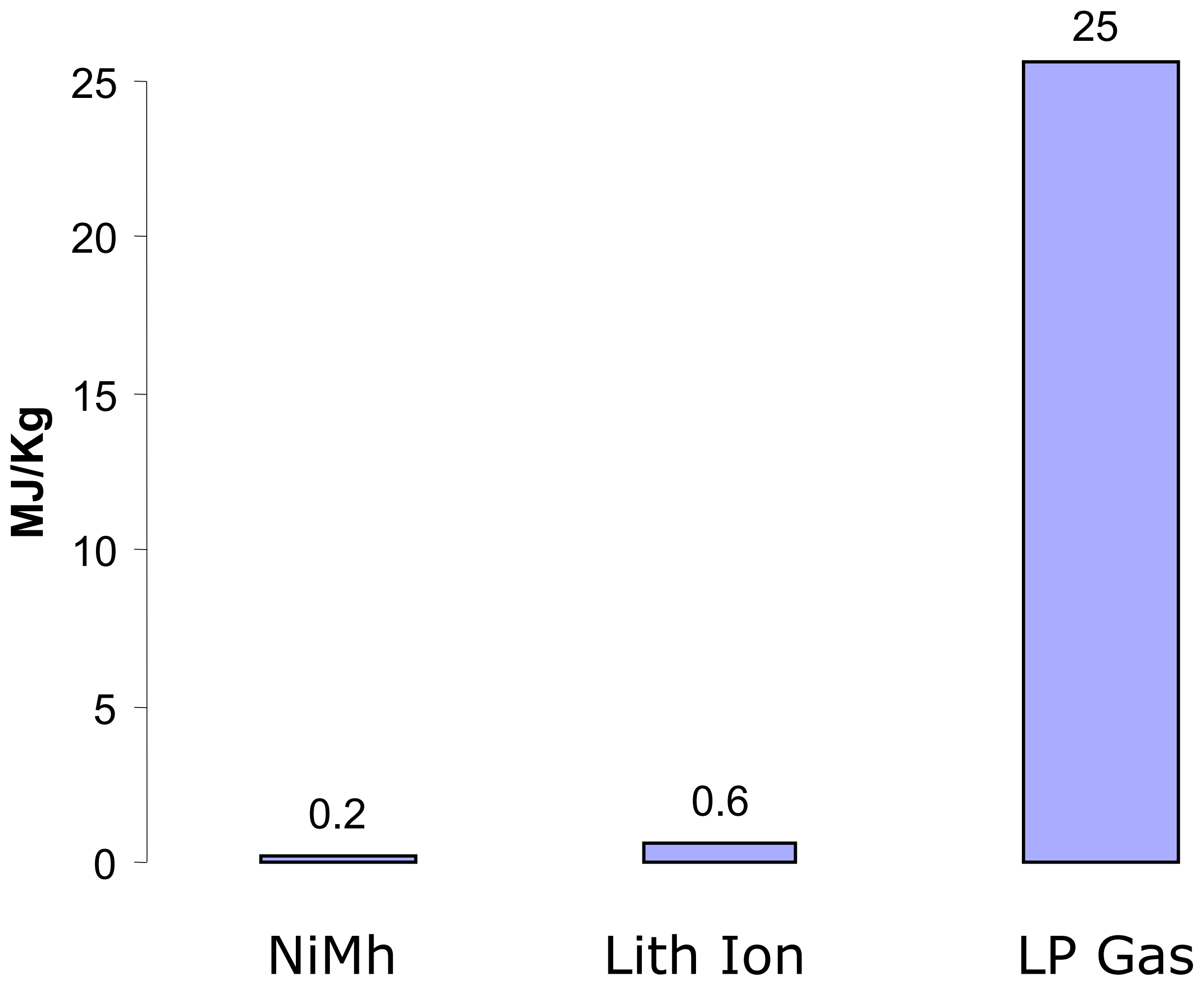
Hydraulic motor



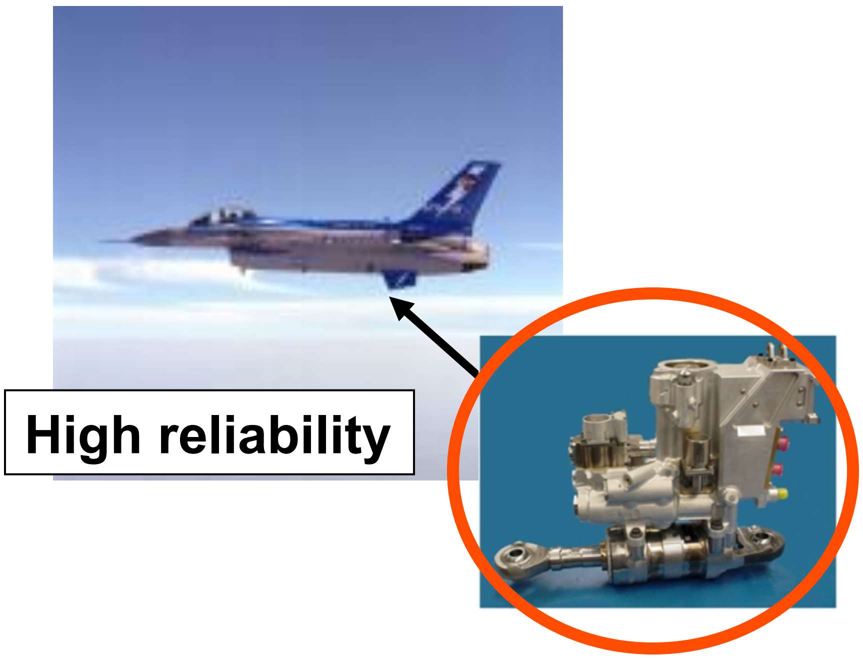
Electric motor

Both motors produce 1200 lb-ft torque at 400 RPM.

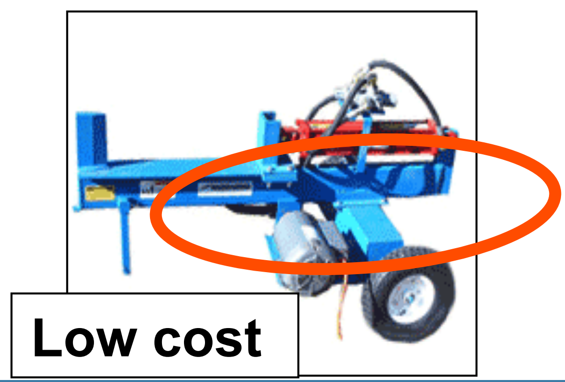
Energy density: Fuels vs. Batteries



“Hidden” fluid power



- “All-electric” airplane
- “Electric” mining shovel
- “Electric” log-splitter



Challenges facing fluid power

- Low efficiency
- Noise
- Leaks
- Low energy storage density
- Lack of familiarity

CCEFP Vision Statement

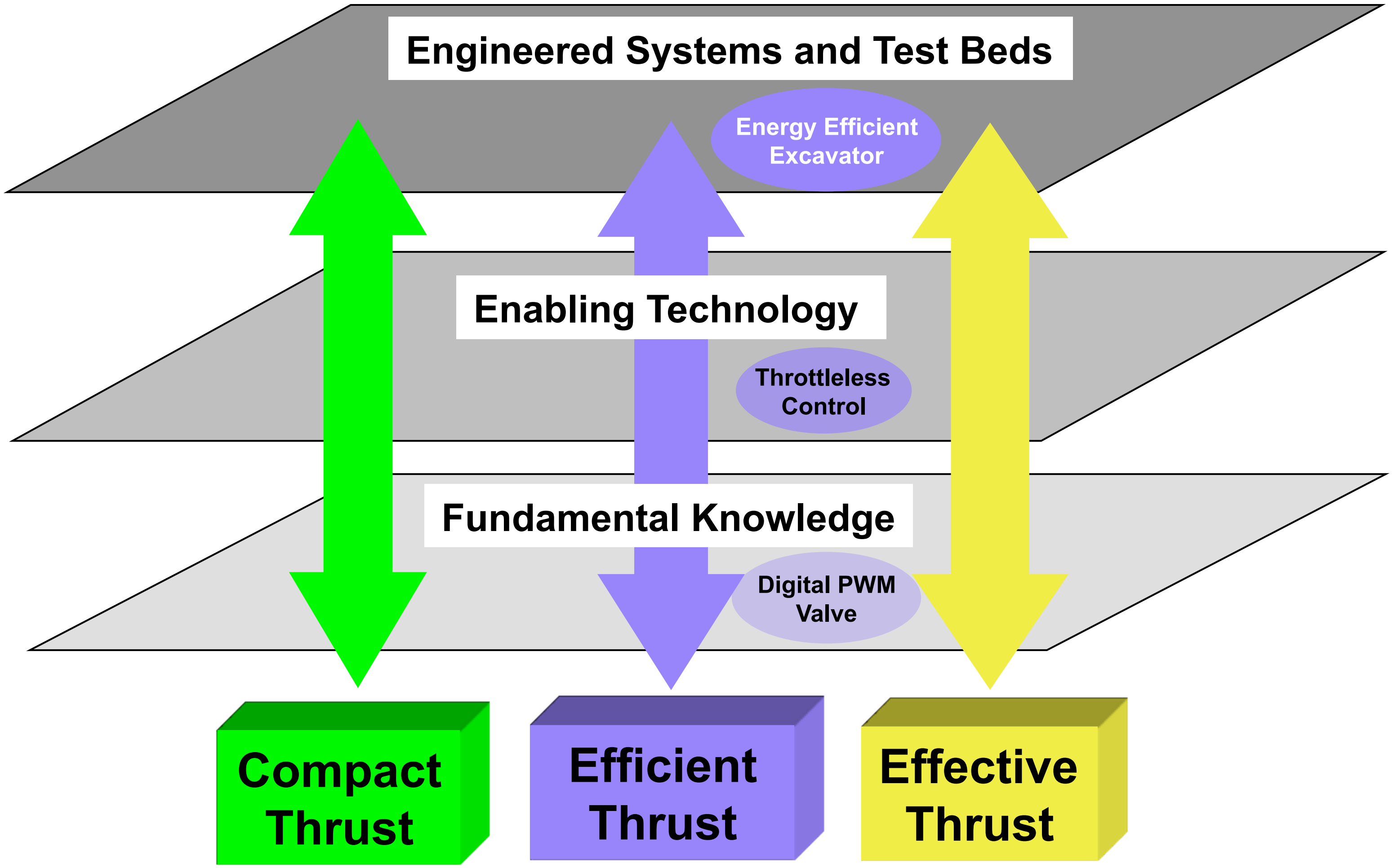
Making fluid power <u>compact</u>, <u>efficient</u> and <u>effective</u>

- **Compact** means smaller and lighter for the same function.
- **Efficient** means saving energy.
- **Effective** means clean, quiet, safe and easy-to-use.

➢ **Major goals**

1. Doubling fuel efficiency in current applications.
2. Expand fluid power use in transportation.
3. Create portable, un-tethered human-scale fluid power applications.
4. Ubiquity - fluid power that can be used anywhere.

Thrusts and Systems approach



In an NSF ERC, research must be validated on test bed systems

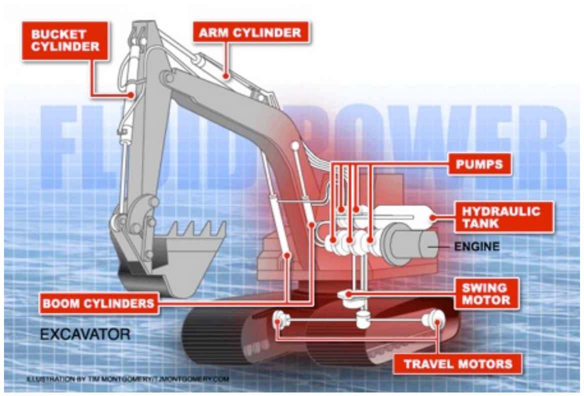
CCEFP Locations

Department of Energy Fluid Power Energy Study

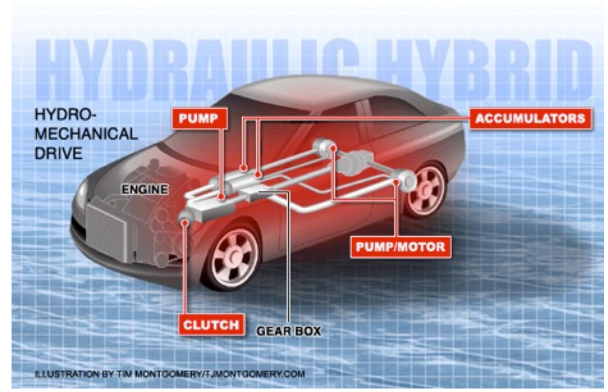
- DOE funded survey of 18 industry partners led by:
  - Lonnie Love (Oak Ridge National Lab and CCEFP Scientific Advisory Board)
  - Eric Lanke and Peter Alles (NFPA)

- Conclusions:
  - Fluid power transmits 2.3 - 3.0% of the energy consumed in the US
  - Average fluid power efficiency is 21%
  - Improvements in fluid power efficiency can have a significant impact on energy use.

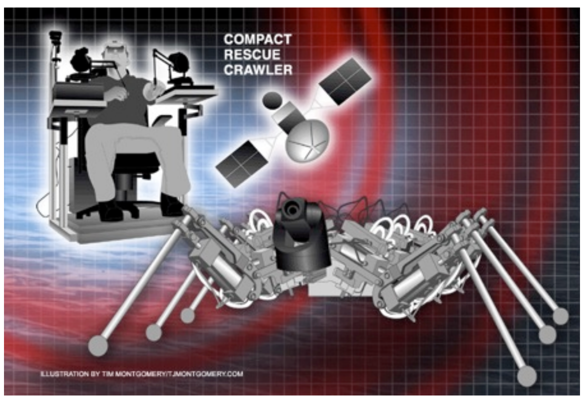
CCEFP Test Beds



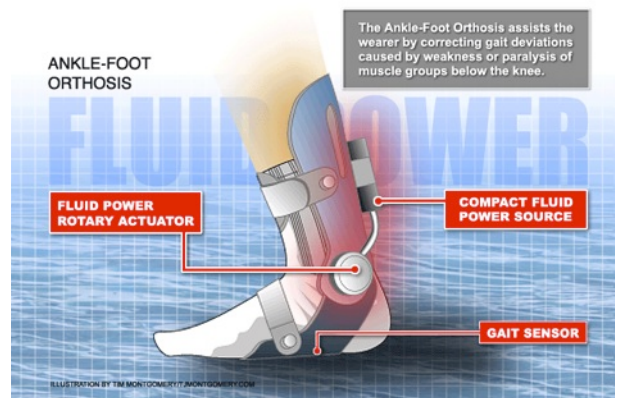
Test Bed 1: Mobile Heavy Equipment



Test Bed 3: Hybrid Passenger Vehicles

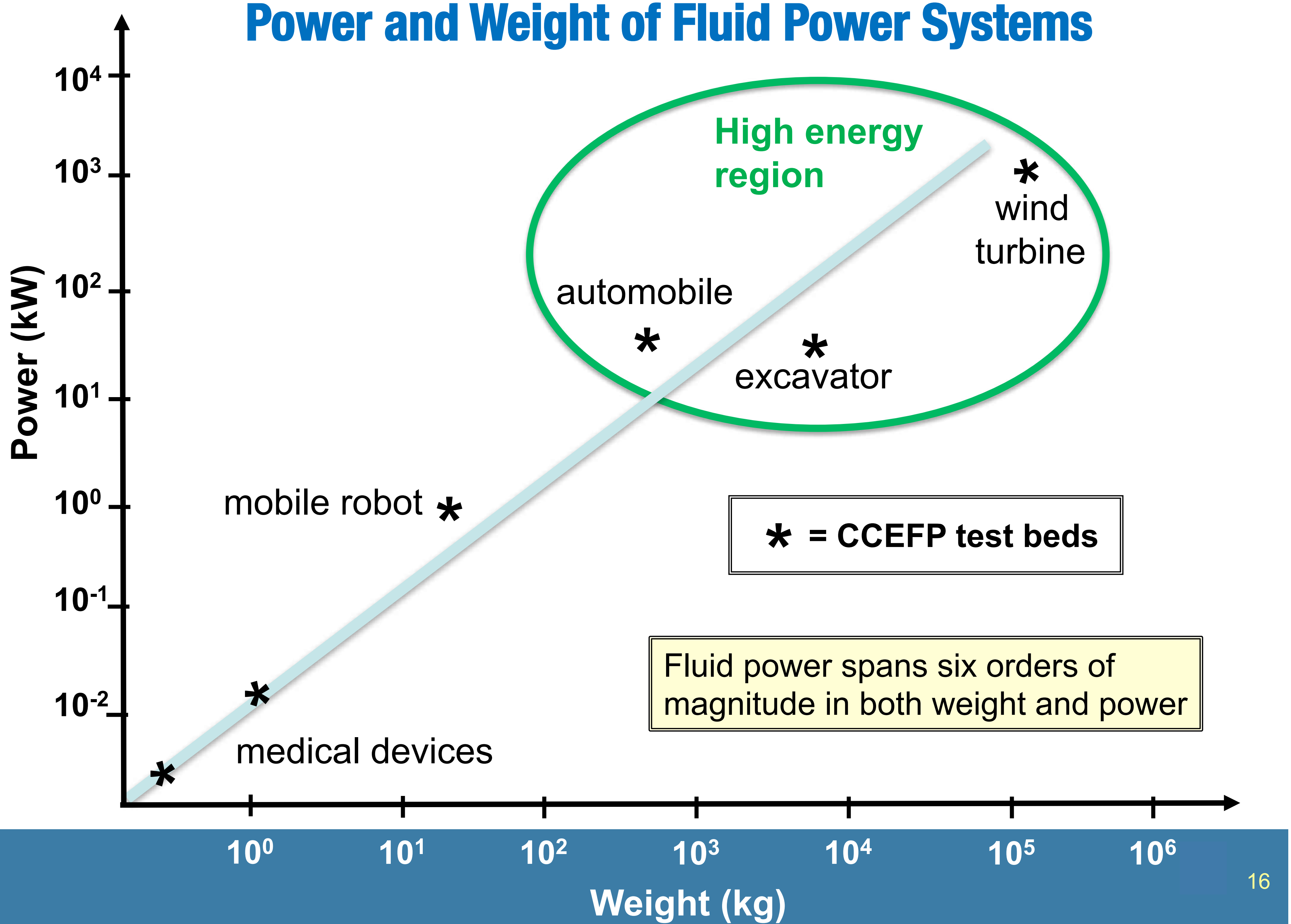


Test Bed 4: Mobile Human Scale Equipment



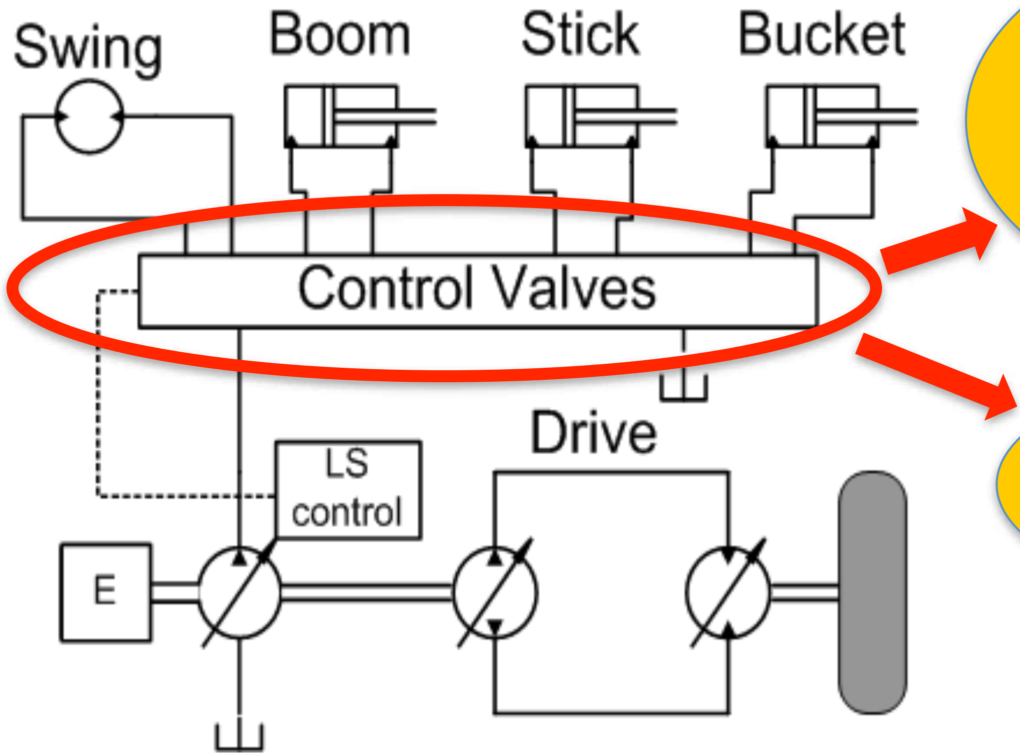
Test Bed 6: Human Assist Devices

Power and Weight of Fluid Power Systems



Existing application: heavy mobile equipment

Current technology barrier



40+ % energy consumption due to throttling

No energy recovery

Today: Hydraulic resistances used for motion control

Test Bed 1: Excavator

Excavator Test Bed has been fitted with variable displacement pumps

Displacement Controlled Fluid Power Systems for Off-Highway Vehicles

40+% fuel savings!

- Displacement control eliminates losses in throttling valves
- 40% fuel savings verified in field tests at Caterpillar
- Hybridization, energy efficient fluids and improved human machine interface will save even more energy
- The technology is simpler, lighter, cheaper, and more efficient than competing designs

Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Project Goals:

- Develop fluid power hybrid power trains for ***passenger vehicles***
- Drive / integrate CCEFP research projects
- Acceleration: 0-60mph in 8 seconds (0.37g) ***(High power density)***
- Fuel economy: 70 mpg under federal cycles ***(High efficiency)***
- Package size: compatible with vehicles such as Honda Civic, Ford Focus, etc. ***(Compact)***

Generation I: Polaris Ranger ATV

- Polaris Ranger all terrain vehicle
- Downsized diesel engine (~ 20kW)
- UMN-designed input coupled hydro-mechanical power-split architecture
- Modular transmission design
- Hybridized with composite accumulators
- Full engine management

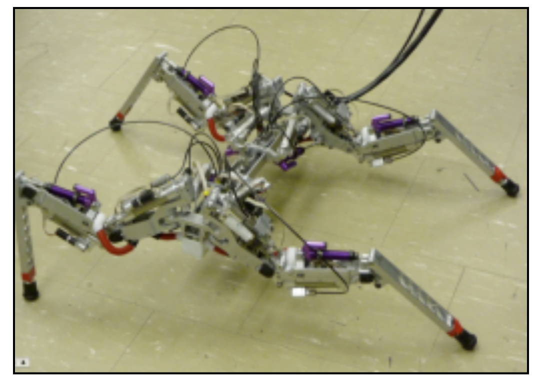
Generation II: Ford F150

- Ford F150 full-size pickup truck
- Hydro-mechanical transmission from *Folsom Technology International (FTI)*
- Output coupled power-split
- Originally intended to be a continuous variable transmission (CVT)
- Will hybridize with composite accumulators

Test Bed 4: Compact Rescue Robot

- Current electric rescue robots cannot rescue and are only used for surveillance
- Fluid power is needed to generate the required force and power
- Multi-axis coordinated control and remote human-machine interface required

Defense, underwater exploration, first responders, etc.



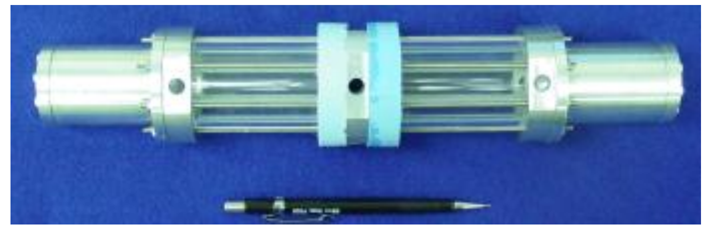
Test Bed 4 is transitioning to a patient transfer device for use in hospitals and nursing homes.

Compact Power Supplies

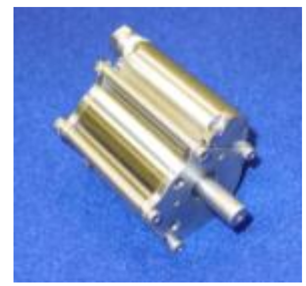
- Candidate power supplies for rescue robot
  - Electric Drive (ED)
  - IC engine and hydraulics
  - Hot Gas Vane Motor
  - Free Piston Engine Compressor (FPEC)

- Weight comparison
  - 3 hour run time: FPEC weighs 50% less than ED
  - 10 hour run time: FPEC weighs 70% less than ED

Pneumatic FPE



~1 Kw



Chemo-fluidic

Test Bed 6: Orthosis

- Weight comparison: FP solution is lighter if pressure is greater than 250 psi (17 bar)
- Migrating from pneumatics to hydraulics
- Near term solution: battery-driven pump powering miniature hydraulics
- Long term solution: 10 W free-piston engine compressor



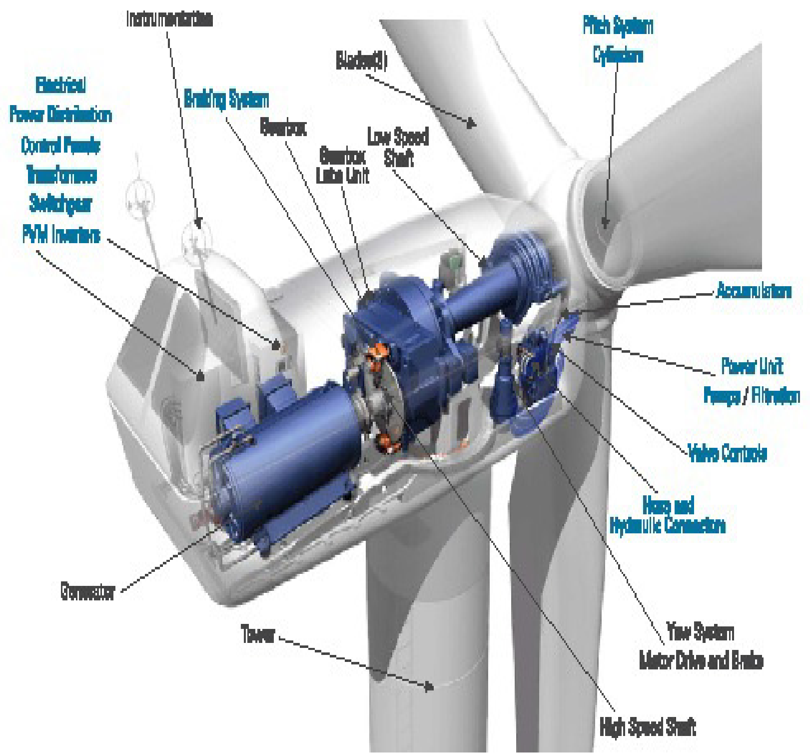
HCCI Pneumatic FPE

New market opportunity!

National Renewable Energy Laboratory
Innovation for Our Energy Future

U.S. DEPARTMENT OF ENERGY

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

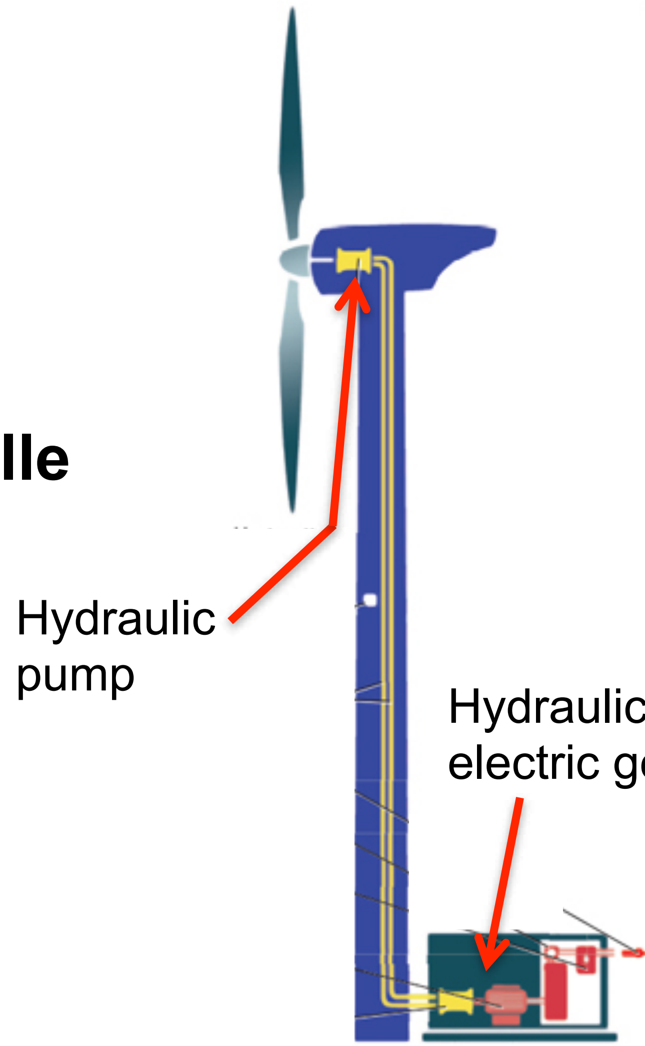


- **Gearbox reliability is a significant problem** (Replacement costs for a 2 MW failure can exceed $500,000 and 1 week downtime .)
- **Continuously variable transmission (CVT) can extract more energy**
- **$ per delivered kW-hr is the key metric**

A hydrostatic transmission has the potential to improve reliability and increase efficiency

HST wind turbine with ground based generator

- **Reduces installed cost**
- **Reduces maintenance cost**
- **Increases availability**
- **Reduces weight in the nacelle**

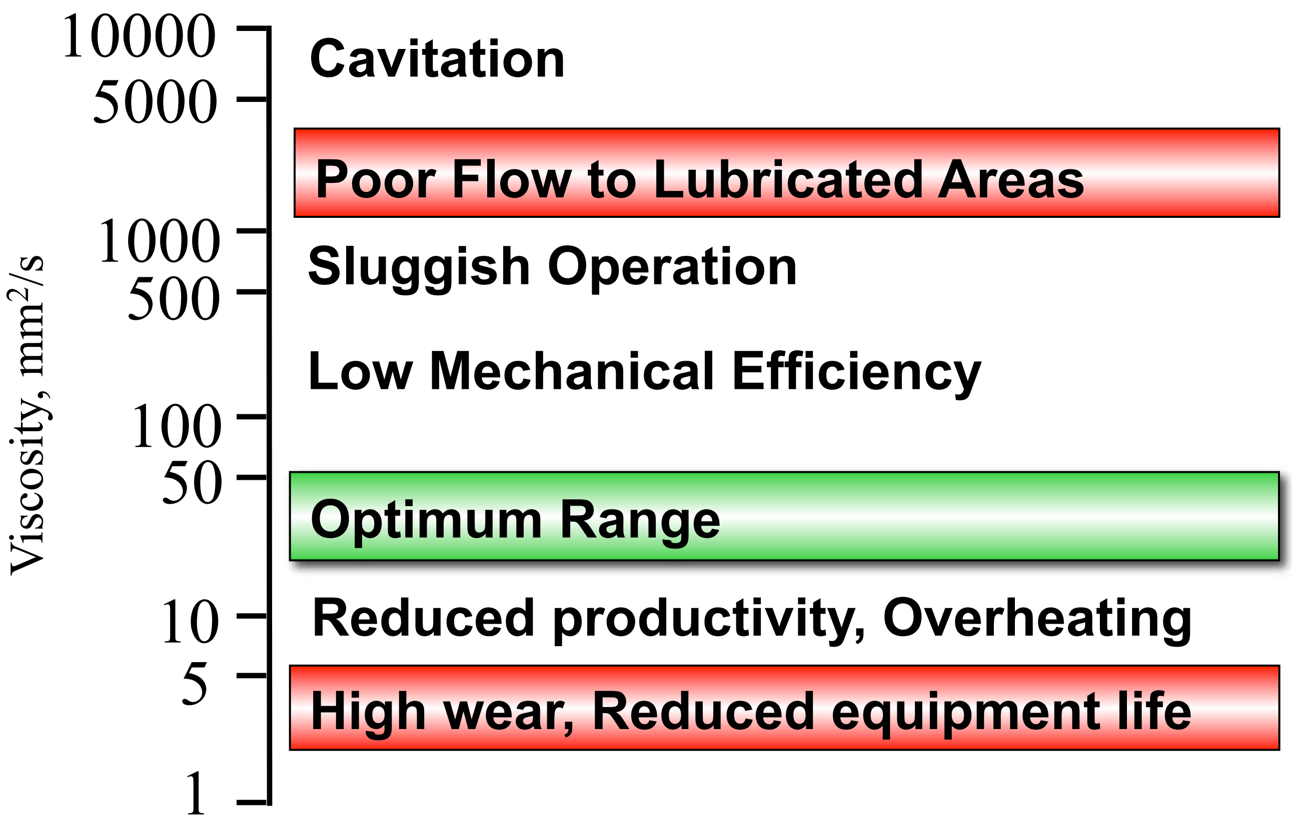


Open Accumulator for Wind Power Energy Storage

- Approach
  - Compressed air energy storage
  - Isothermal compression/expansion
  - Combined hydraulics & pneumatics
- 20x energy density increase over conventional accumulator
- Targeting storage of roughly 10 hours of full load power

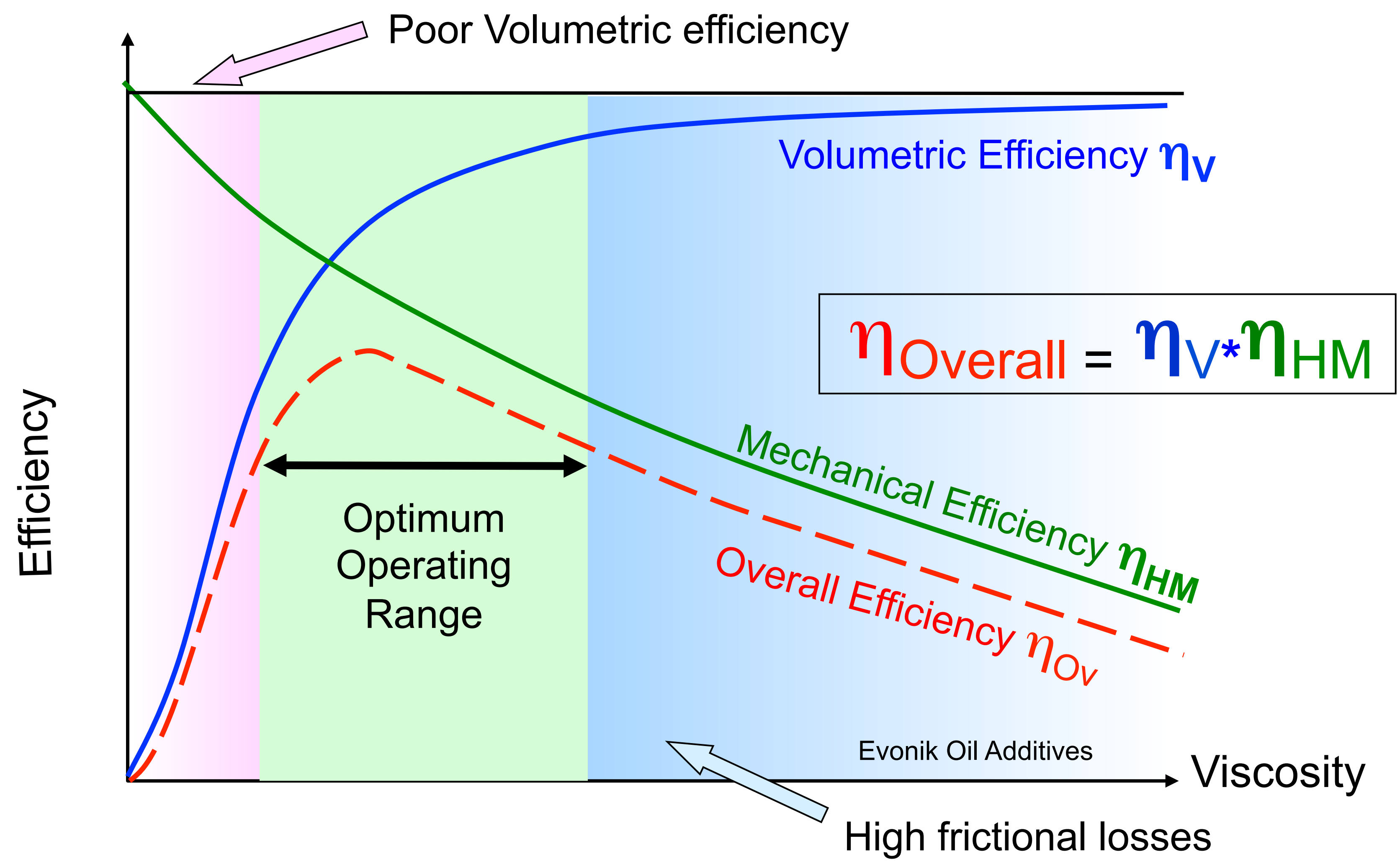
- Started as Center for Compact and Efficient Fluid Power project
- Research continuing as an NSF project with a $2 million grant
- Technology has been licensed by two companies

The Need for Proper HF Viscosity Selection

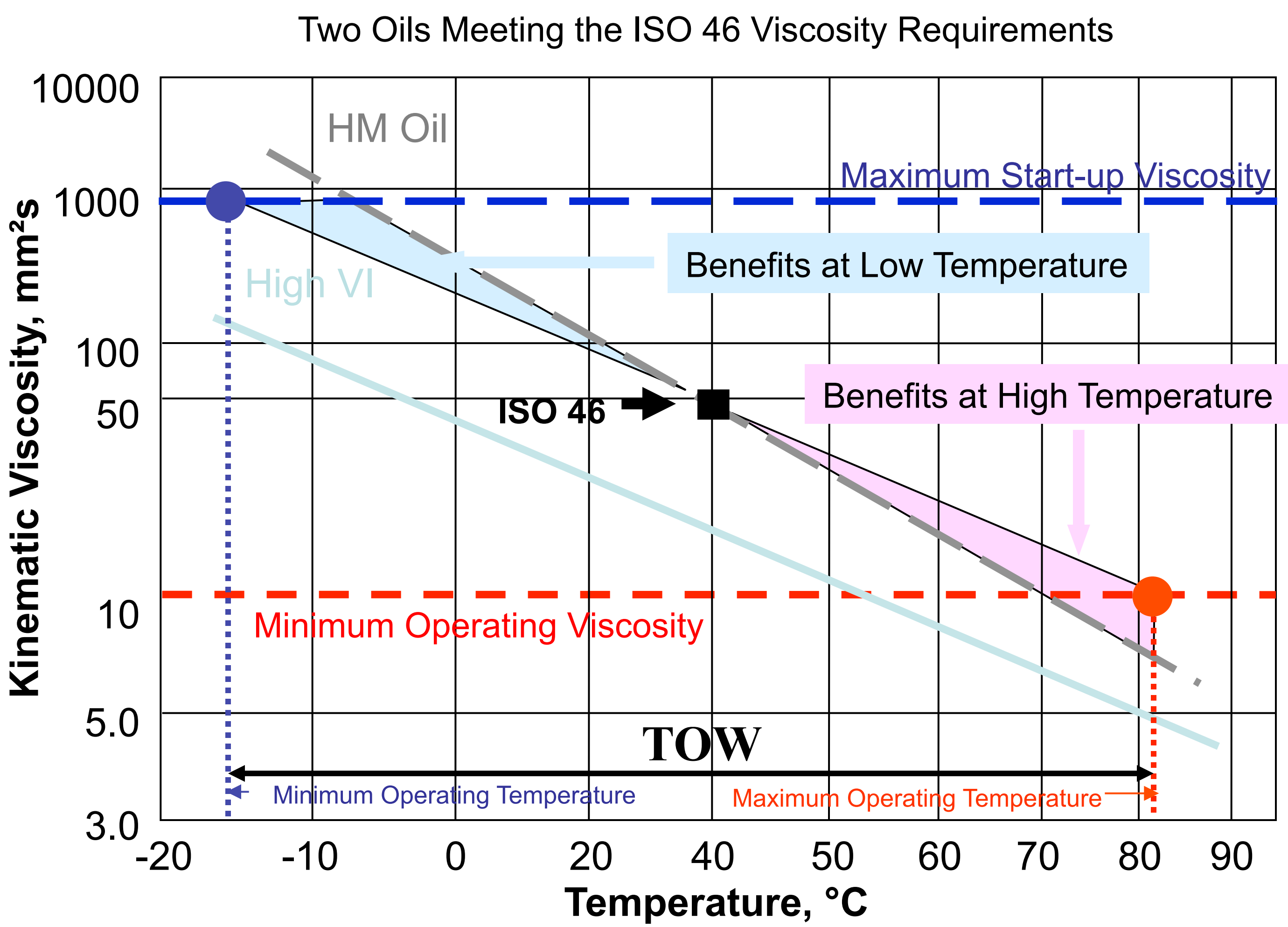


Courtesy of Steven Herzog, Evonik Oil Additives

Effects of Viscosity on Overall Efficiency

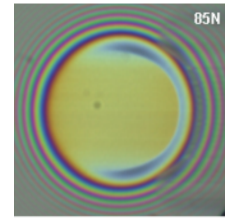


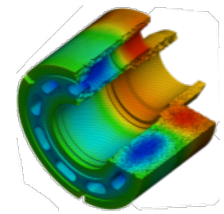
Benefits of High VI Oils Are a Consequence of their Improved Viscosity Temperature Relationship

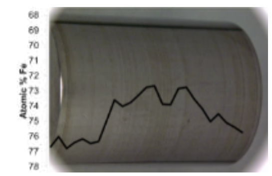


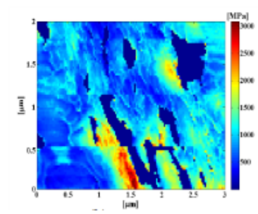
CCEFP Fundamental Tribology and Lubrication Research

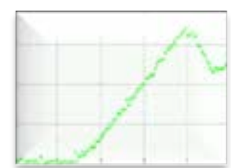
- High pressure behavior of hydraulic fluids
- Thermo-elastic bushing behavior in piston pumps
- Tribofilm structure and chemistry in hydraulic motors
- Leakage reduction in fluid power systems
- Surface effects on start up friction
- Surface patterning for improved efficiency

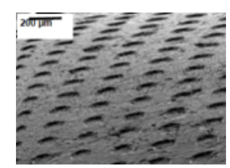








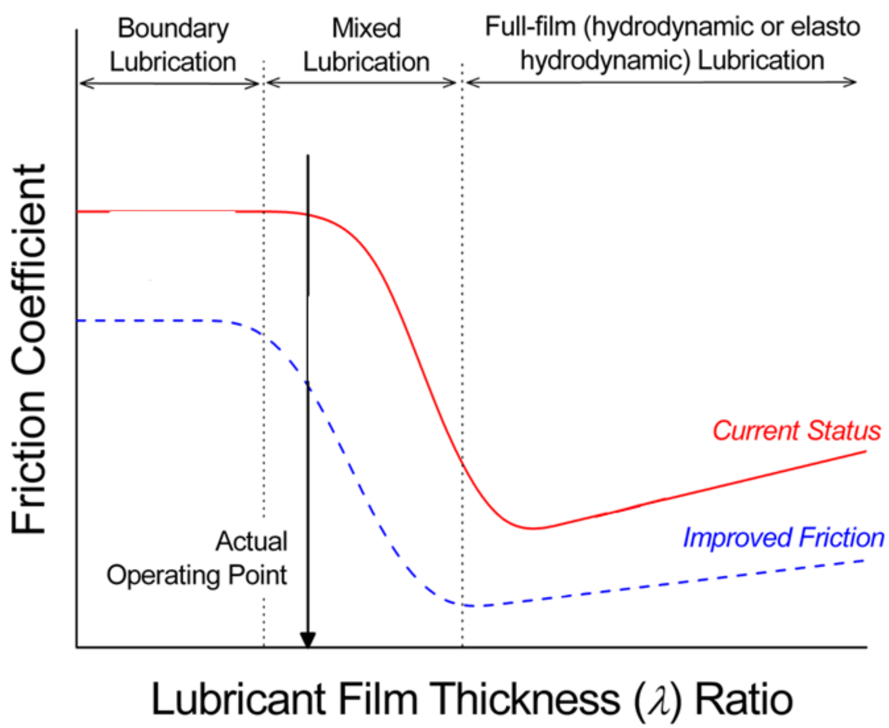




Stribeck Curve

- CCEFP tribology projects complement each other to improve efficiency through friction reduction across the lubrication regimes

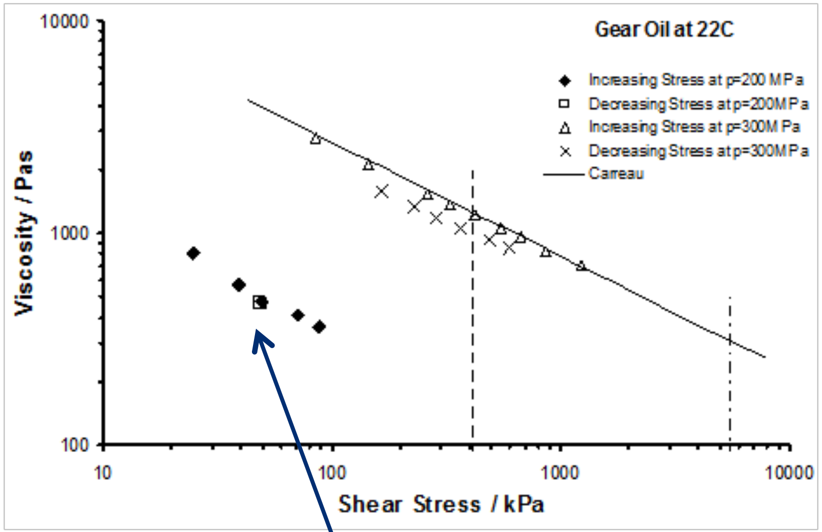
1. Improve boundary film performance
2. Reduce percent surface contact through surface design
3. Optimize full film fluid and interface behavior

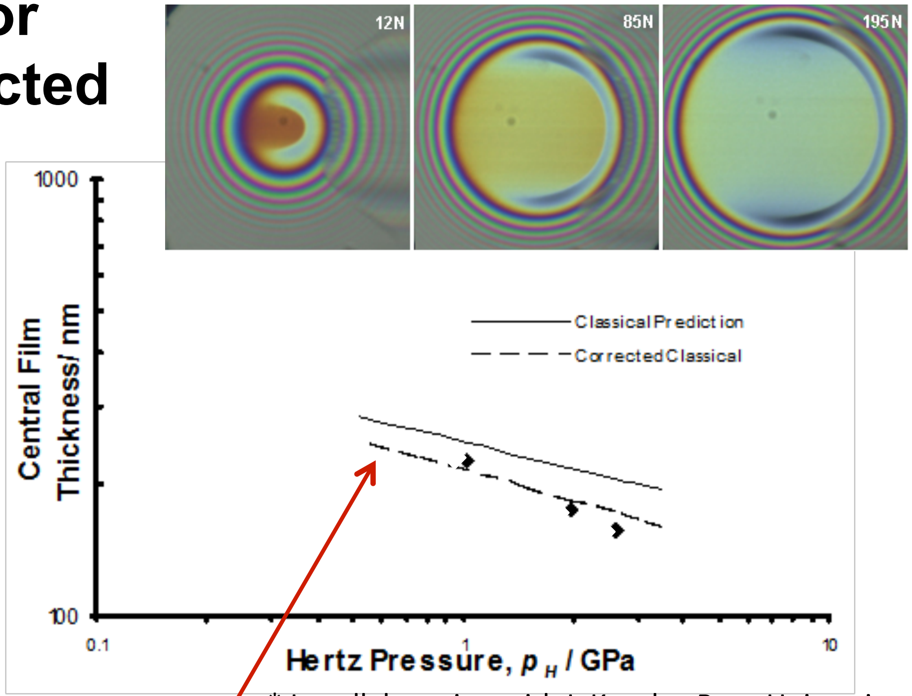


High pressure behavior of hydraulic fluids

Scott Bair, GeorgiaTech

- **High pressure viscosity and film thickness measurements indicate mechanical degradation may explain shear thinning behavior beyond what is typically predicted**





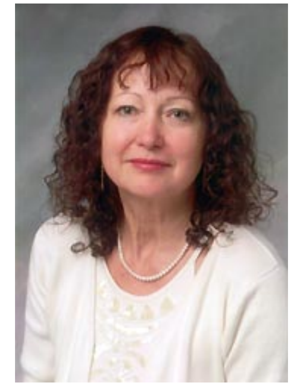
* In collaboration with I. Krupka, Brno University

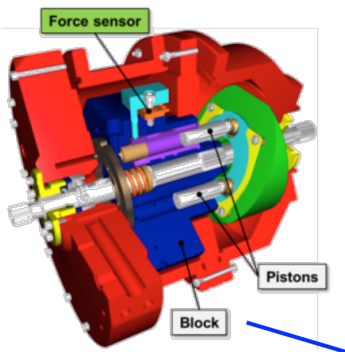
High pressure viscosity less than predicted by traditional models → Corresponding EHL model-predicted film thickness larger than observed

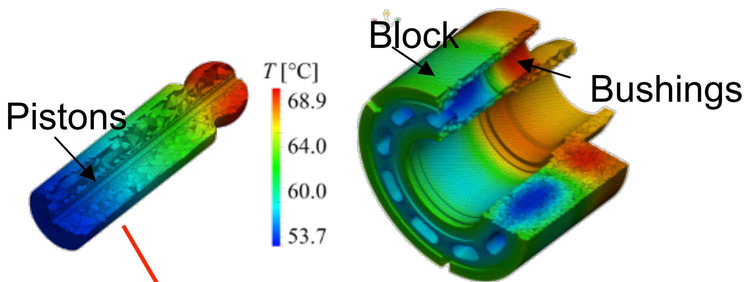
Thermo-elastic bushing behavior in piston pumps

- **Self-induced thermal waviness in brass bushings allows high pressure pumps to operate**

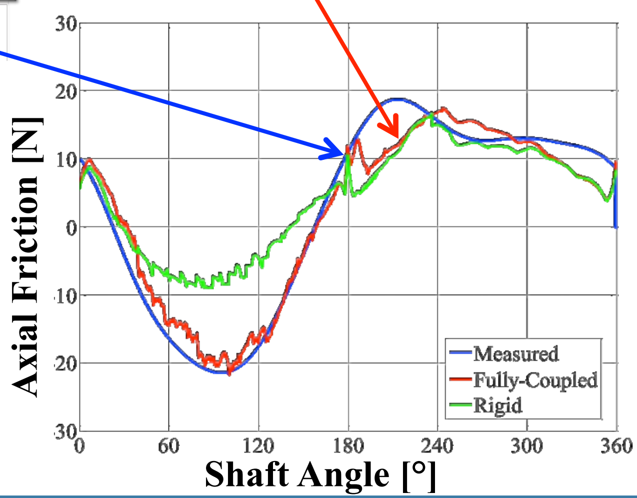
Monika Ivantysynova, Purdue



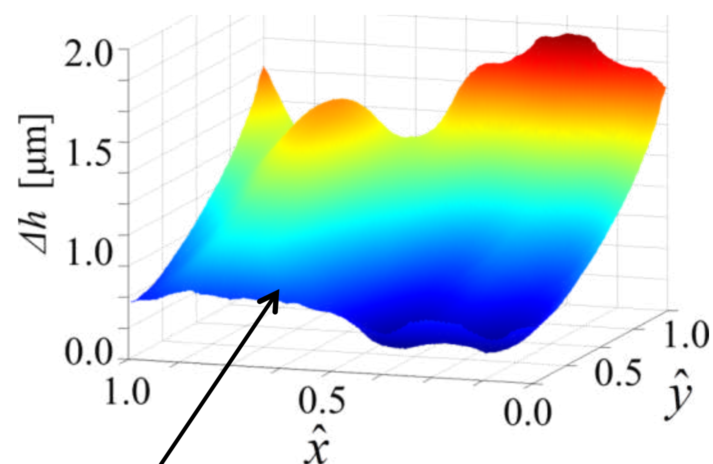




Model Validation



Recent Discovery



Thermal deformation difference between brass & steel bushings

Tribofilm Structure and Chemistry in Hydraulic Motors

Paul Michael, MSOE

Test Motors

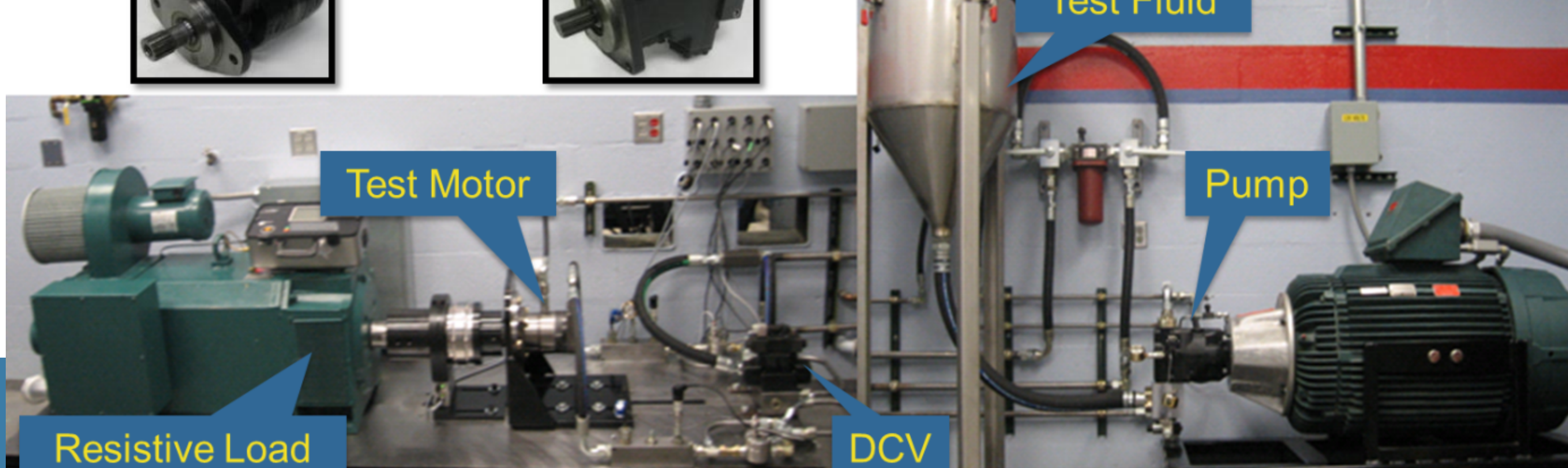
Geroler (Orbital)	**Bent-Axis**
Parker TG240	Sauer-Danfoss H1B
14.5 cu. in.	6.1 cu. In.
390 RPM	5350 RPM
3000 psi	6000 psi

Test Fluids

Viscosity Grade 46
Mineral Oil Base Group III
Ashless vs. ZDDP

Test Conditions

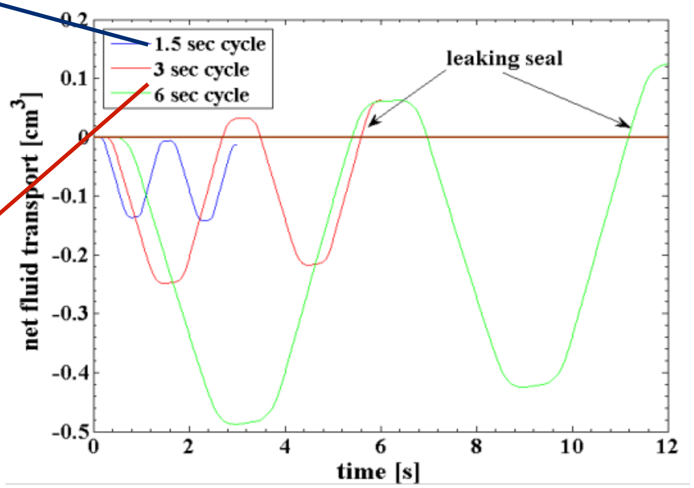
ISO 4392, 1 RPM, 50 & 80°C



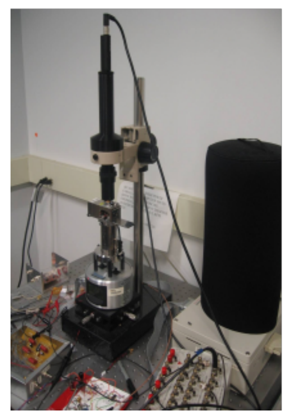
Leakage Reduction in Fluid Power Systems

Richard Salant, GeorgiaTech

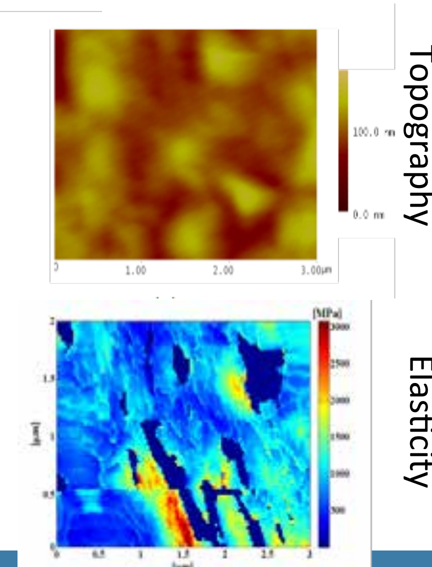
- **Models incorporating viscoelasticity capture dependence of leakage on cycle frequency**



- **Relaxation modulus on the *nano*scale is greater than on the *micro*scale affecting deformation characteristics and behavior of the seal**



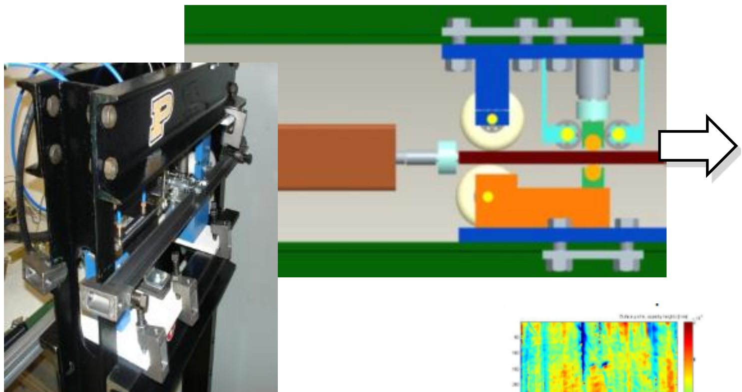
Tapping Mode AFM

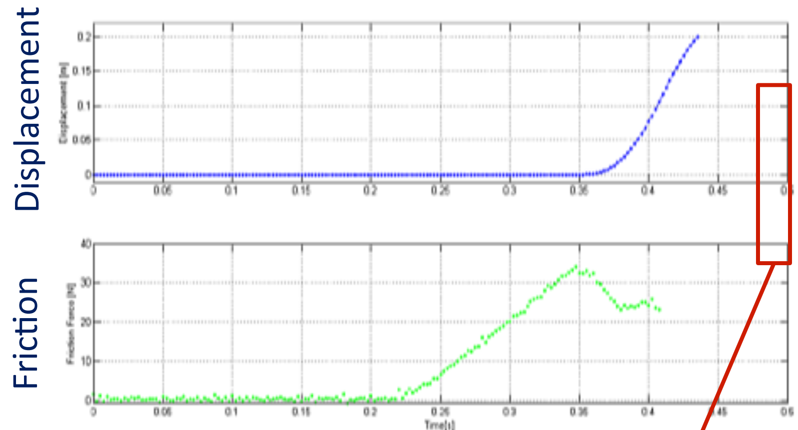


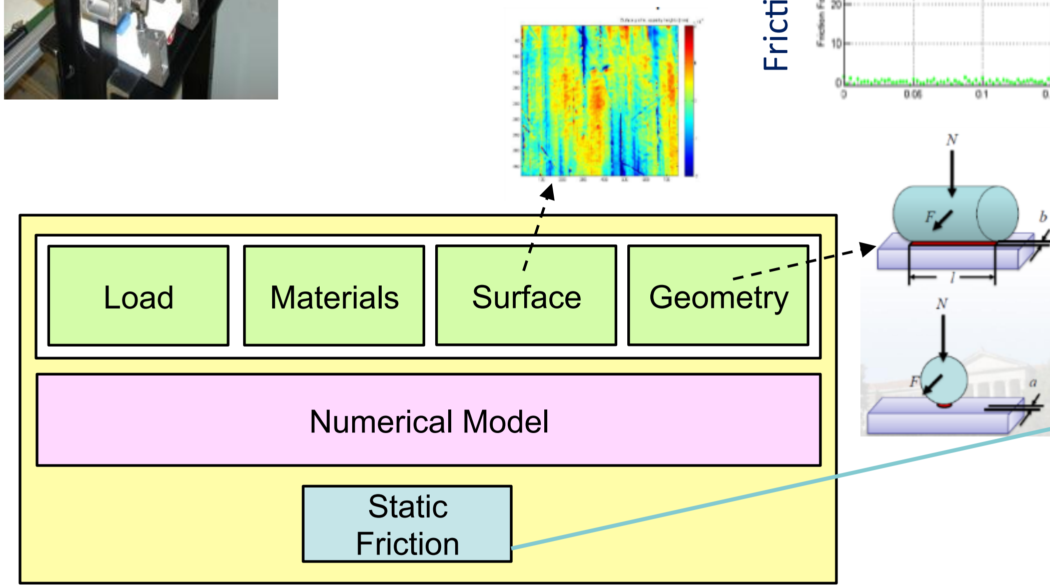
Surface effects on start up friction

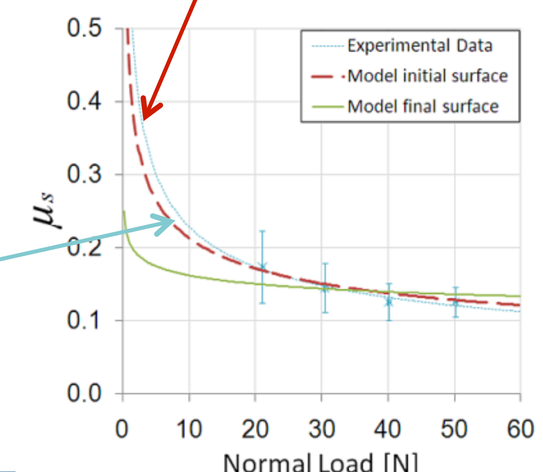
Ashlie Martini, Jose Garcia, Purdue

- **Accurate start-up friction measurements validate model and give insight into the effects of fluid properties and surface features**



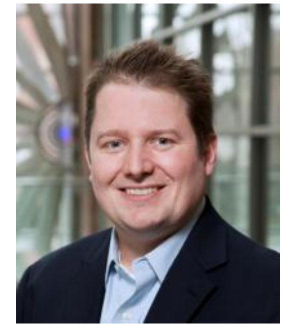






Surface patterning for improved efficiency

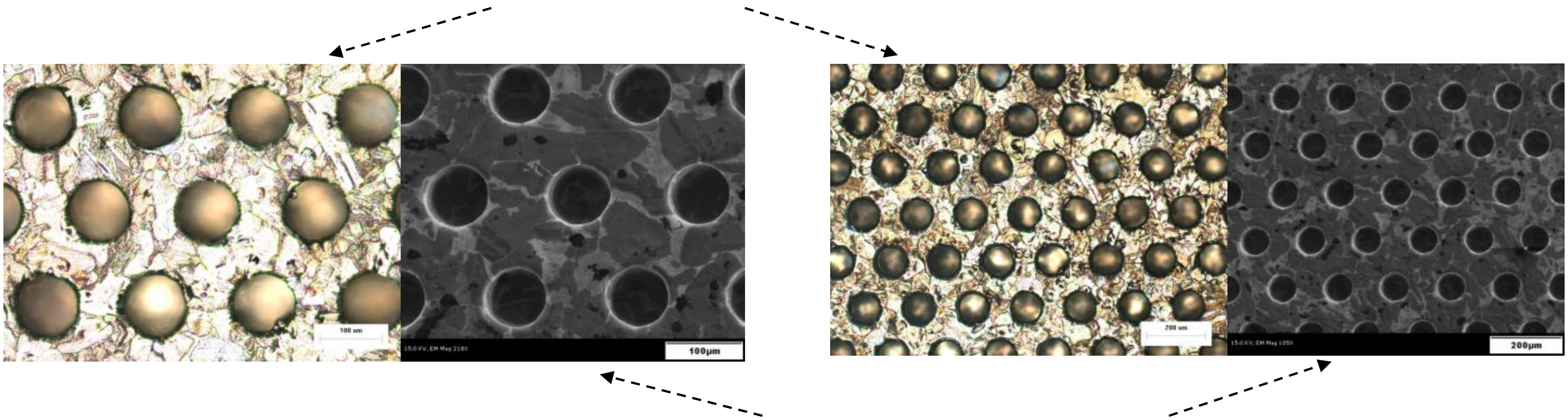
Bill King, UIUC



- **Accurate and industrially scalable patterning techniques enable surface designs with potential to reduce friction and wear**

Feature	Packing	Width (µm)	Depth (µm)	Pitch (µm)
Circle	Triangular	100	150	200

Optical Microscope



Scanning Electron Microscope

Test Bed 3: Hydraulic Hybrid Passenger Vehicle

Project Goals:

- Develop fluid power hybrid power trains for ***passenger vehicles***
- Drive / integrate CCEFP research projects
- Acceleration: 0-60mph in 8 seconds (0.37g) ***(High power density)***
- Fuel economy: 70 mpg under federal cycles ***(High efficiency)***
- Package size: compatible with vehicles such as Honda Civic, Ford Focus, etc. ***(Compact)***

Generation I: Polaris Ranger ATV

- Polaris Ranger all terrain vehicle
- Downsized diesel engine (~ 20kW)
- UMN-designed input coupled hydro-mechanical power-split architecture
- Modular transmission design
- Hybridized with composite accumulators
- Full engine management

Generation II: Ford F150

- Ford F150 full-size pickup truck
- Hydro-mechanical transmission from *Folsom Technology International (FTI)*
- Output coupled power-split
- Originally intended to be a continuous variable transmission (CVT)
- Will hybridize with composite accumulators

What is a Hydraulic Hybrid?

A hybrid powertrain includes 2 or more power sources, one which is reversible:

- ✓ Can recover, store and reuse power either **electrically** or **hydraulically**

A hybrid vehicle, in addition to its main engine, has a drivetrain that contains:

- ✓ A **reversible** energy storage system, and
- ✓ A special drive system to recover otherwise wasted braking energy, and then convert stored energy again to motive power.

Hydraulic Hybrid Vehicles (HHV)

- Store energy in hydraulic accumulators
- Use hydraulic pump-motors

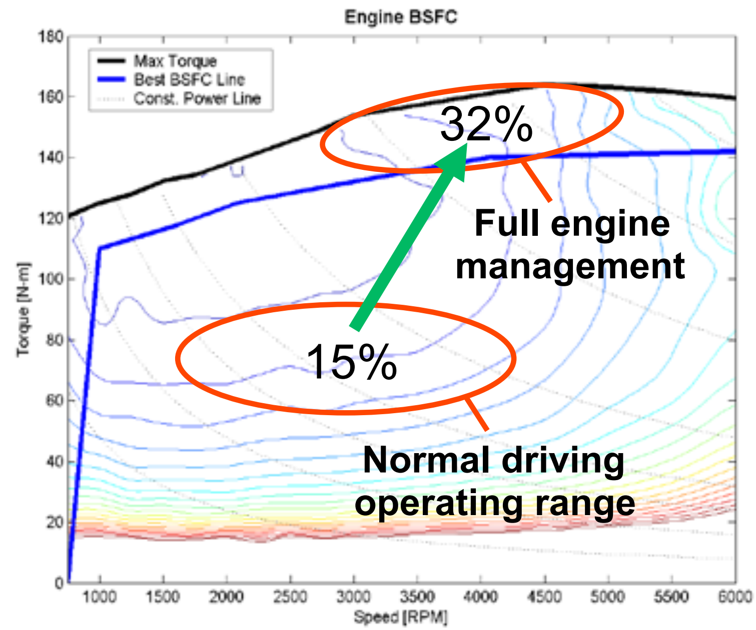
Hybrid Electric Vehicles (HEV)

- Store energy in batteries and/or ultra-capacitors
- Use electric generator-motors

How hybrid systems save energy

<u>The hybrid system allows</u>:

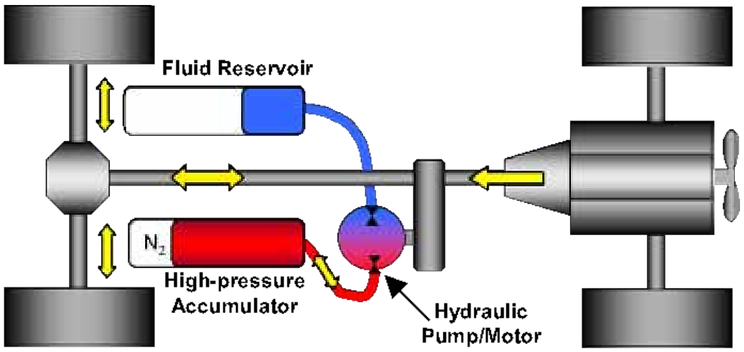
- Regenerative braking
- Engine management
- Engine off
- Engine sizing for continuous power



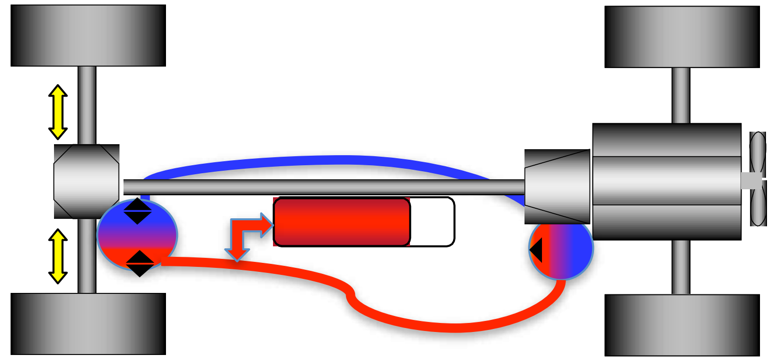
Example vehicle on EPA cycle:

- Baseline: 29 mpg
- With full engine management: 63 mpg
- Full engine management with regeneration: 87 mpg

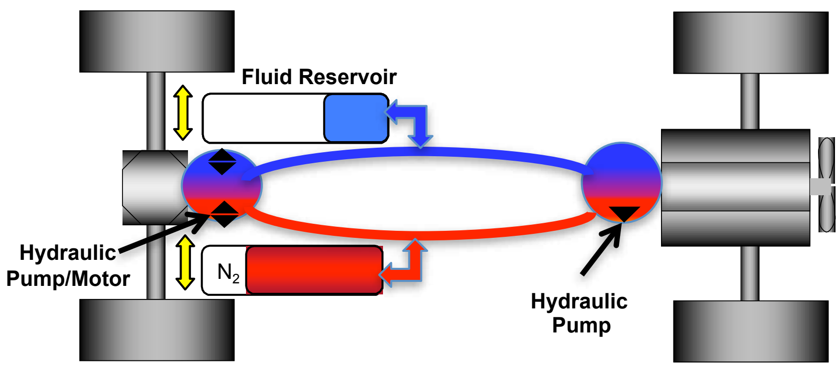
Major types of hydraulic hybrid architectures



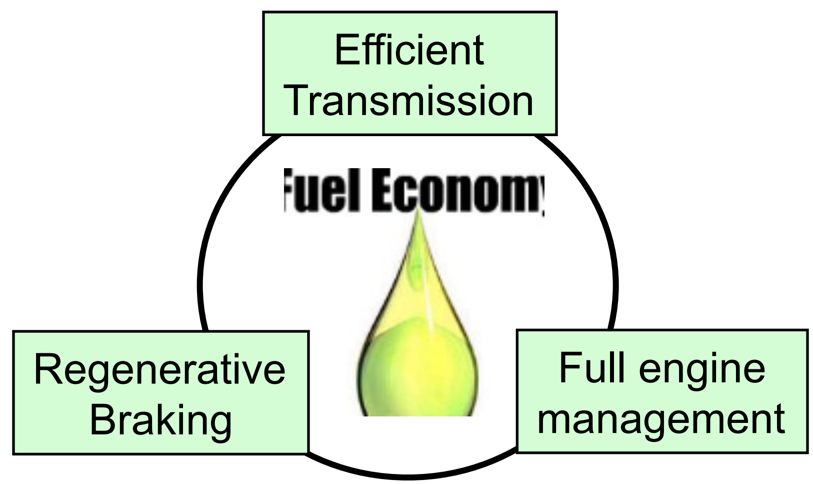
Parallel Hydraulic Hybrid



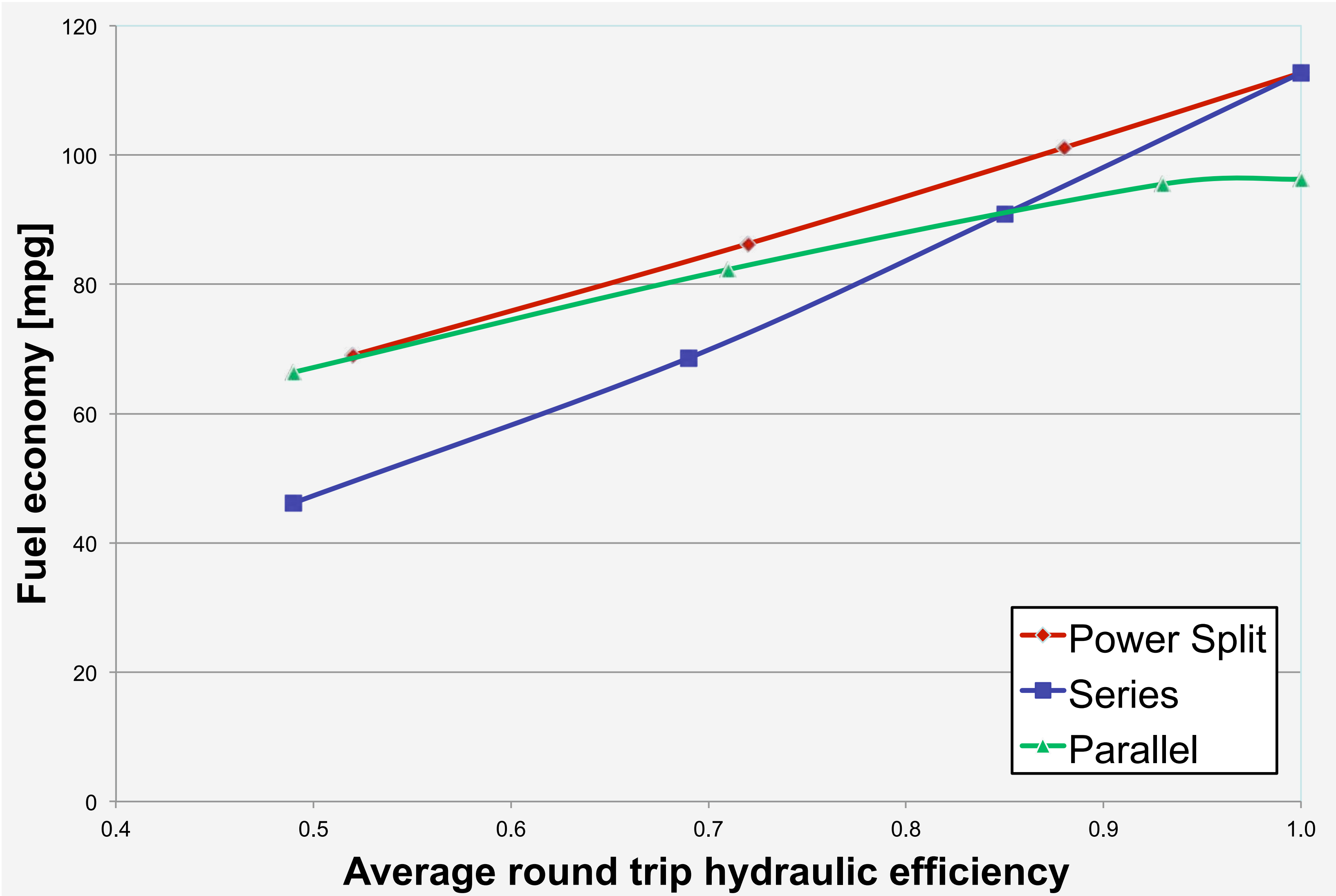
Power Split Hydraulic Hybrid (Hybrid HMT)



Series Hydraulic Hybrid



Hydraulic hybrid architecture comparisons



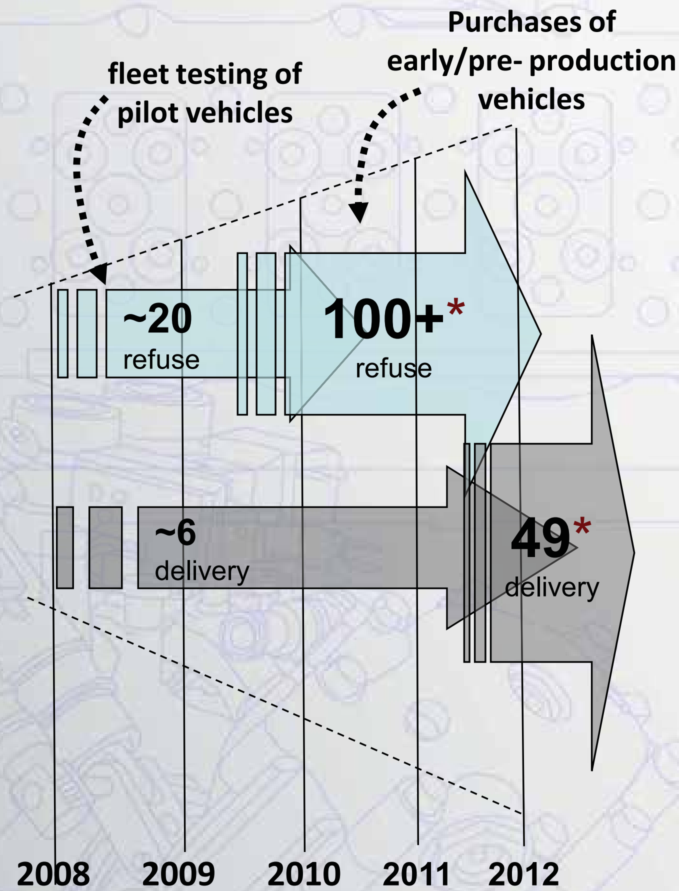
Commercially available hydraulic hybrid vehicles

Parallel: refuse trucks

HMT: package delivery vehicles

Industry is Active!

Moving to Full Production



Autocar refuse truck with Parker hydraulic drive

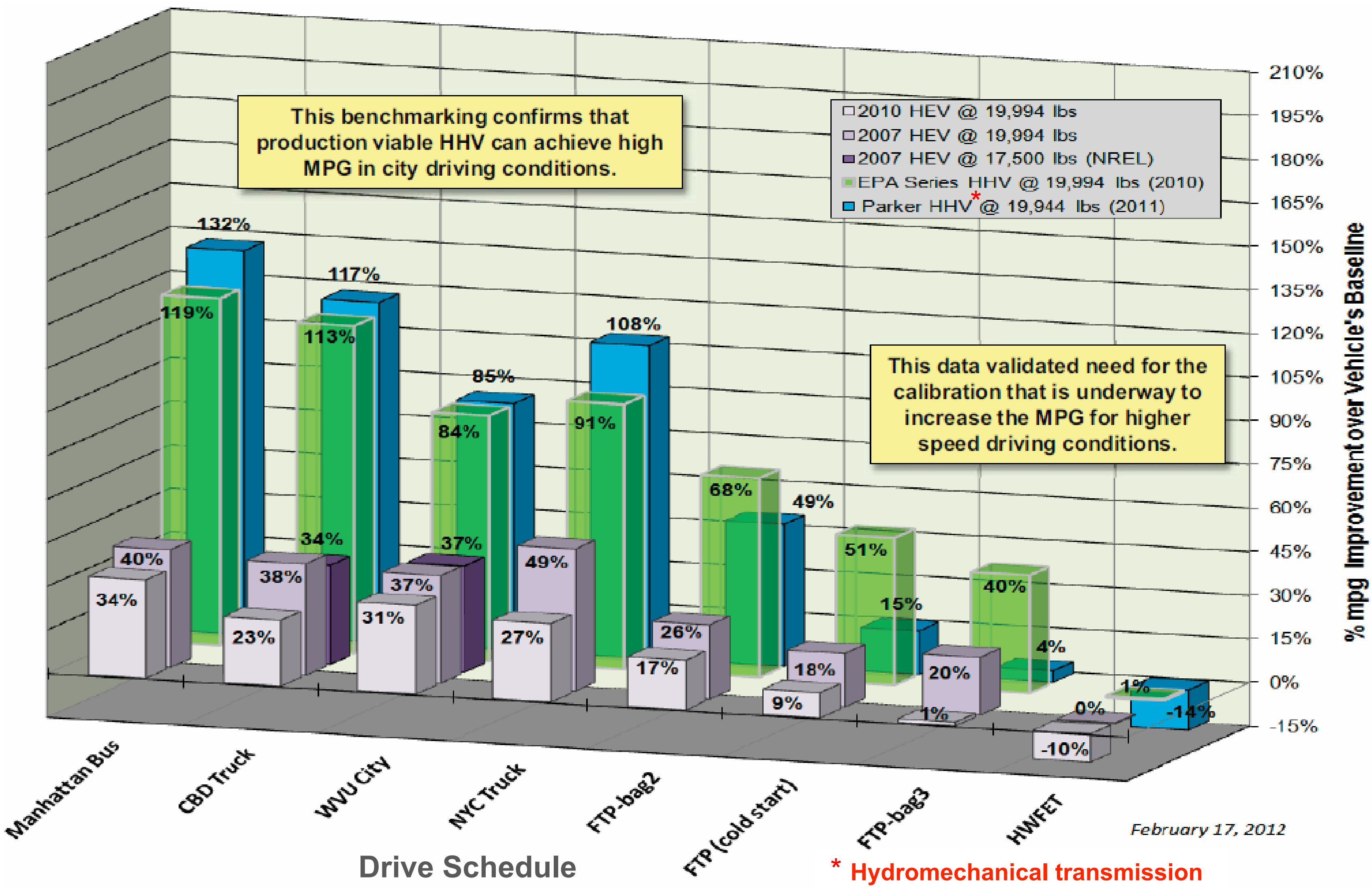
Peterbilt chassis, Heil body with Eaton hydraulic drive

Crain Carrier chassis with Bosch-Rexroth drive

**Purchases which have been announced (specific deployment dates are not known)*

Please note that there are also other companies that are developing original equipment and retrofit HHV systems for on-road, non-road, and military applications.

Hybrid commercial vehicle testing by US EPA



* Hydromechanical transmission

Courtesy of John Kargul, US EPA

Example of the Importance of "Series" Architecture to Fuel Economy Improvement

Comparison of <u>Lab</u> Tests of EPA's 2006 Series Hydraulic Hybrid Vehicle (HHV) on EPA city driving cycle (FTP)	MPG	Series HHV Increase
Baseline Vehicle	10.4	---
HHV engine always running	14.4 15.0	39% 44%
HHV engine-off when truck not moving	15.8 16.5	52% 59%
HHV engine-off when truck decelerating and/or not moving	17.8 18.1	70% 74%

Hydraulic Hybrids

- Bosch Rexroth, Eaton, and Parker Hannifin are currently offering hydraulic hybrid systems for commercial vehicles.
- NYC bought ten Mack LE613 vehicles with the Bosch-Rexroth HRB system in 2011 and may deploy up to 300 hydraulic hybrid refuse trucks in their fleet of 2,000.
- UPS and FedEx are running hydraulic hybrid package delivery vehicles with the EPA series system and the Parker HMT.
- Chrysler and EPA is working on a hydraulic hybrid project for the Town & Country minivan.
- Several studies have shown that hydraulic hybrid passenger vehicles are as or more efficient than electric hybrids and potentially much more cost effective.
- Advancements in fluid power technology will further improve hydraulic hybrid vehicles.

	HHV	HEV
Efficiency	✓	
Cost	✓	
Performance	✓	

Near market hydraulic hybrid vehicles

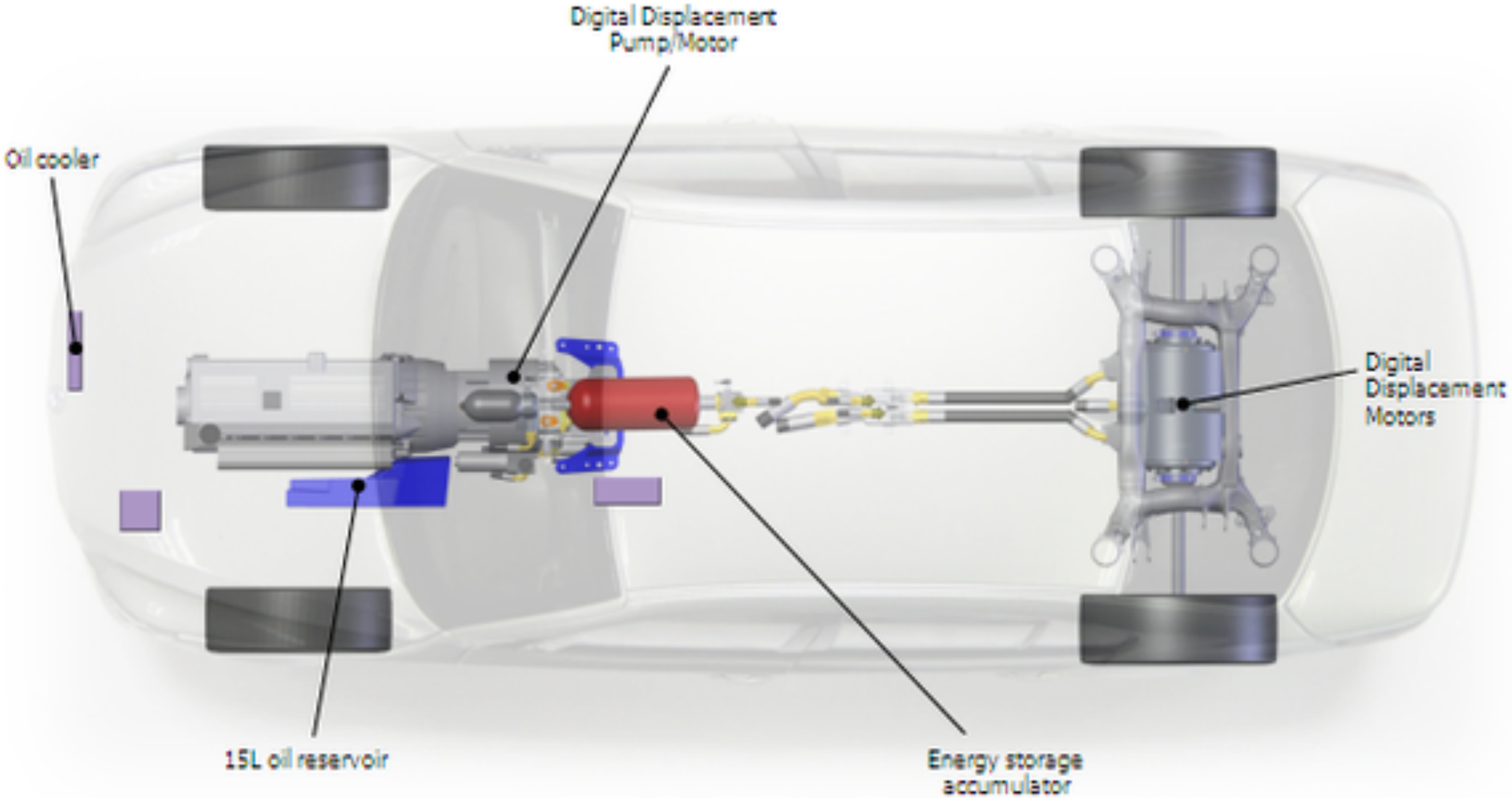
- Altair ProductDesign has designed a new 40 foot city transit bus using a series hydraulic hybrid transmission.
- The chassis is all new and constructed to be lighter weight than conventional buses.
- Test results using the Altoona 3 mode driving cycle:

Bus type	Fuel economy (miles/gallon)	Fuel consumption (liters/100 km)
Altair series hydraulic hybrid prototype	6.9	34
Conventional diesel city bus	3.3	71
Best diesel-electric hybrid bus today	5.3	44

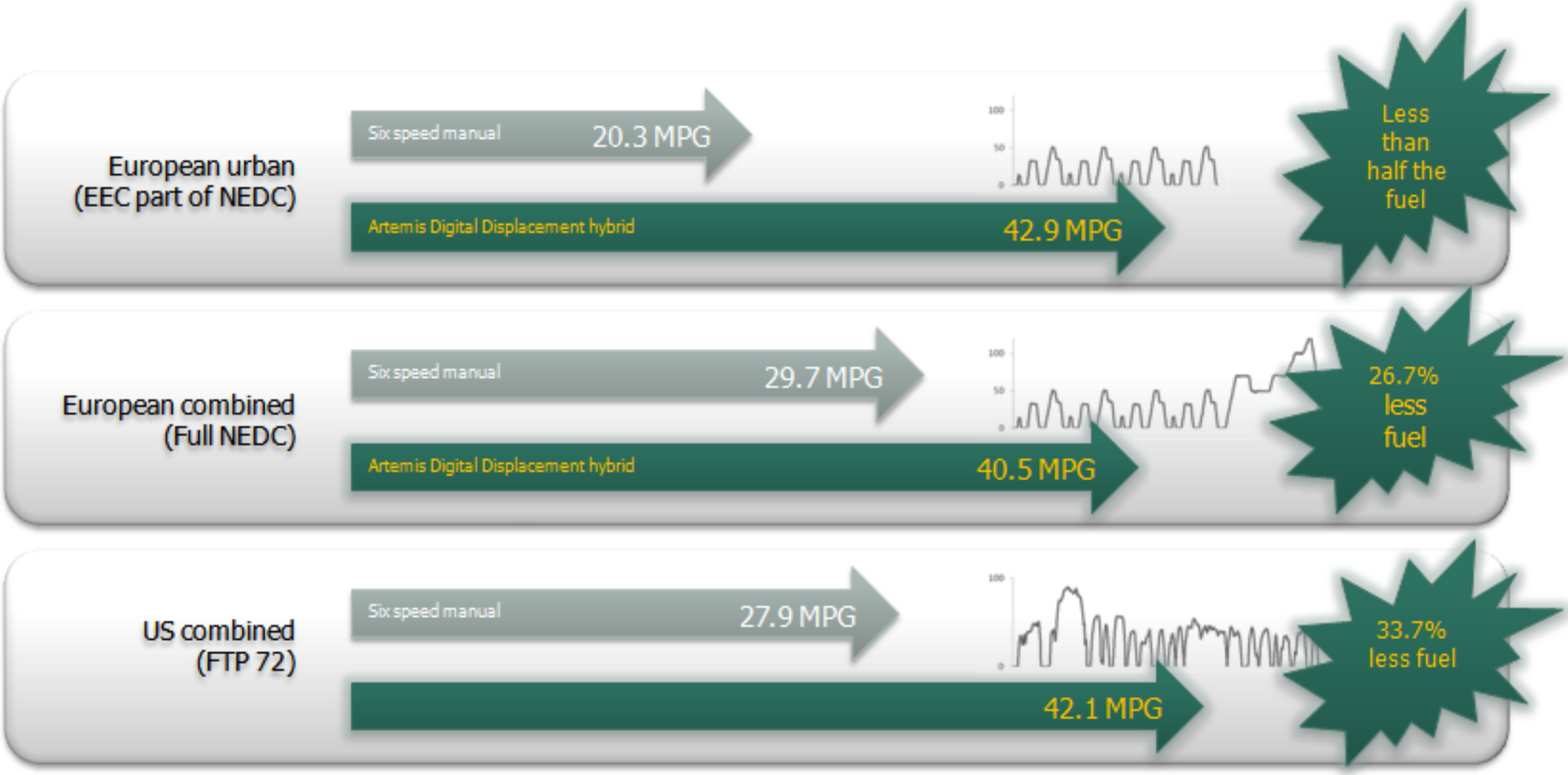
Source: Altair ProductDesign

Testing shows **110% better fuel economy** than conventional diesel city transit buses and 30% better fuel economy than the best diesel-electric hybrid buses.

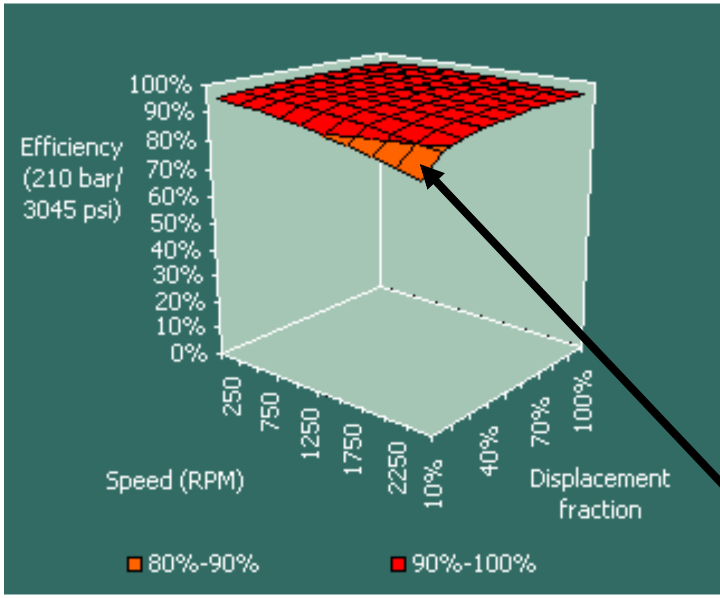
Concept car: BMW series hydraulic hybrid

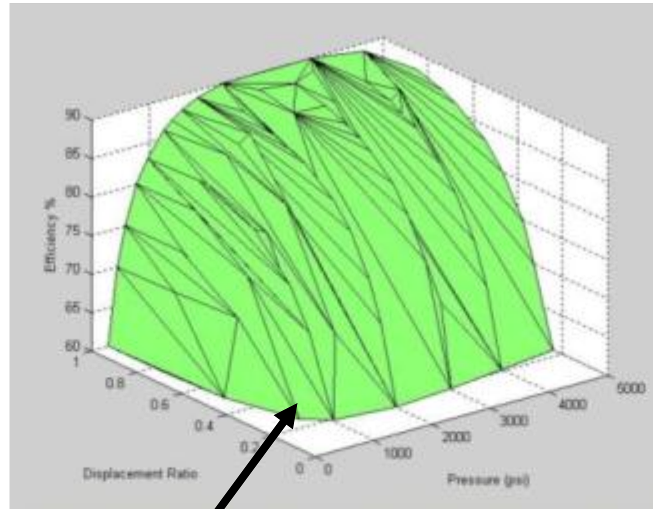


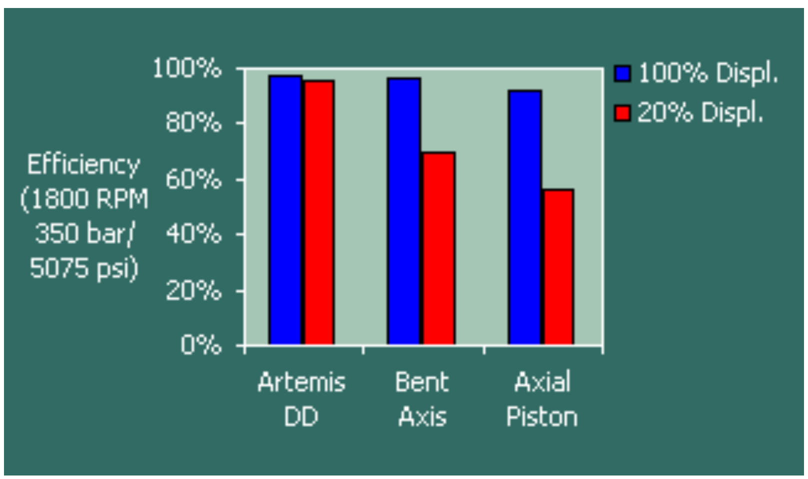
Concept car: BMW series hydraulic hybrid



Digital pump performance



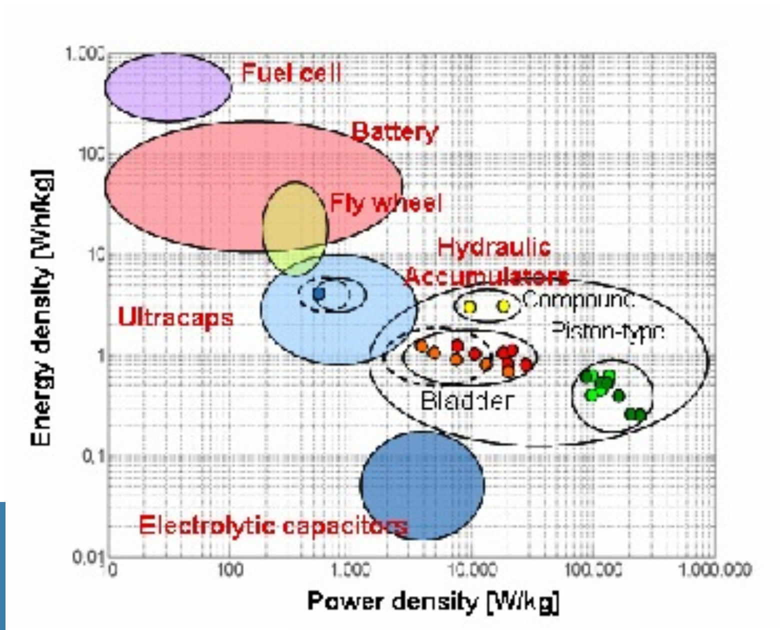




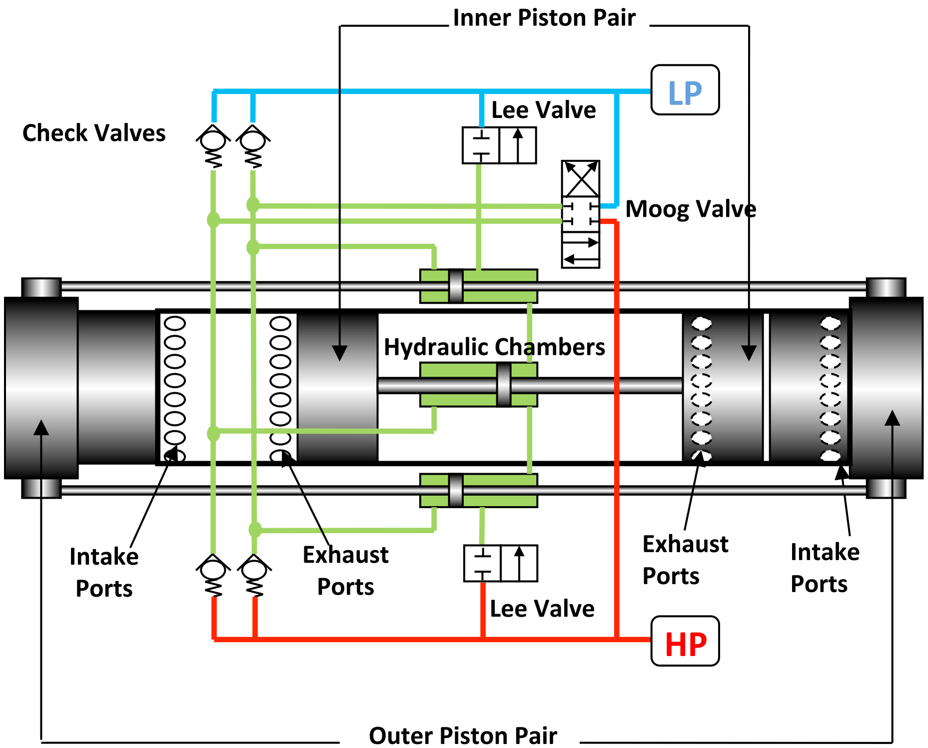
- Performance improvements at partial displacement are dramatic
- Smaller pumps/motors needed

Compact Energy Storage

- Elastomeric Accumulator
- Stores energy in strain of elastomer
- 4-5 times greater energy density
- Eliminates gas leakage
- Compact and inexpensive



Compact Power Supply: Free Piston Engine Pump



Potential to dramatically improve efficiency, emissions & power density

- Combines engine and pump in a single unit
- Opposed Piston Opposed Cylinder (OPOC) Design*
- Direct Injection
- Uniflow scavenging
- HCCI combustion

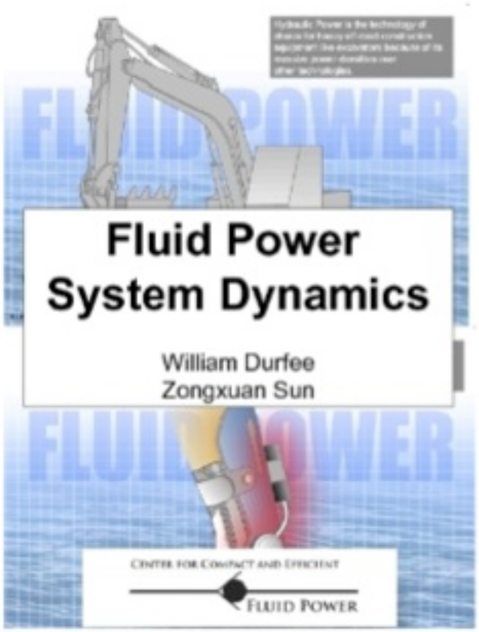
✓ Variable compression ratio
✓ Better fuel economy
✓ Multi-fuel operation
✓ Instant on-off
✓ Higher power density
✓ Modular
✓ Internally balanced

* Many of the advantages of this FPE can be retained for other FPE architectures. The proposed IP is independent of the specific FPE architecture.

Fluid Power: Undergraduate and Graduate Education

- Long-term: infuse fluid power into undergraduate curriculum of all mechanical engineering departments in US; create and maintain digital repository for collegiate level education of fluid power materials

- Approaches:
  - Develop additional mini-books: tribiology, sealing
  - Develop fluid power lab content
  - Support new course development by CCEFP faculty
  - Encourage advanced topic presentations by industry and faculty experts
  - Disseminate education materials to colleagues at CCEFP institutions and beyond
  - Evaluate effectiveness of fluid power modules
  - Encourage ME departments nationwide to include fluid power in ABET knowledge outcomes



Research Experiences for Undergraduates (REU) Program

- Goal is to create the next generation of fluid power engineers and academics
- All attend a Fluid Power Boot Camp at outset of the 10-week research
- Over 128 REU students since 2007, 23 in 2012
- Over 55% go into graduate school, 33% into PhD
- At least 50% of the REUs are under-represented in engineering

2010 Fluid Power Scholars

Henry Kohring (**Deere**)
Brett Nagel (**Enfield**)
Jean Pierre Zola (**Sun**)
Cami Horton (Horton Fluid Power*)
Jane Buckus (Timken Co*)
Troy Tempel (BP*)
Brad Guertin (Boston Sci)

Fluid Power Scholars hired into the Fluid Power Industry!

2011 Fluid Power Scholars

Philip Gaffney (**HUSCO**)
Jeffrey Jones (**Cat**)
Stephen Featherman (**Sun**)
Alex Allaby (**Cat**)
Matt Lynch (Entrepreneur)
Alex Mooney (Student)
Robert Margherio (Student)
Jeremy Couch (Grad Stu)

O = *Hired in CCEFP Member Companies*

**Not a CCEFP member*

CCEFP Members and Supporters

Afton Chemical Corporation
Air Logic
Bobcat
Bosch Rexroth Corporation
Caterpillar Inc
CNH America, LLC
Concentric AB (formerly Haldex)
Deere & Company
Delta Computer Systems
Deltrol Fluid Products
Eaton Corporation
Enfield Technologies
Evonik RohMax USA, Inc
ExxonMobil
Fluid Power Educational Foundation
Freudenberg NOK
G.W. Lisk Co., Inc
Gates Corporation
HECO Gear, Inc
Hedland Flow Meters (Racine Federated)
High Country Tek, Inc
Hoowaki, LLC
HUSCO International, Inc
Idemitsu Kosan
International Fluid Power Society
Linde Hydraulics Corporation
The Lubrizol Corporation
Main Manufacturing Products
Master Pneumatic-Detroit, Inc
MICO, Incorporated
Moog Inc
MTS Systems Corporation
National Fluid Power Association
National Tube Supply Company
Netshape Technologies, Inc
Nexen Group, Inc
Nitta Moore
Parker Hannifin Corporation
PIAB Vacuum Products
Poclain Hydraulics
Quality Control Corporation
Ralph Rivera
Ross Controls
Sauer-Danfoss
Shell Global Solutions
Simerics
StorWatts
Sun Hydraulics Corporation
Takako Industries
Tennant
The Toro Company
Trelleborg Sealing Solutions US, Inc
Walvoil
Woodward, Inc

54 industry members and supporters

Economic Assets: Intellectual Capital

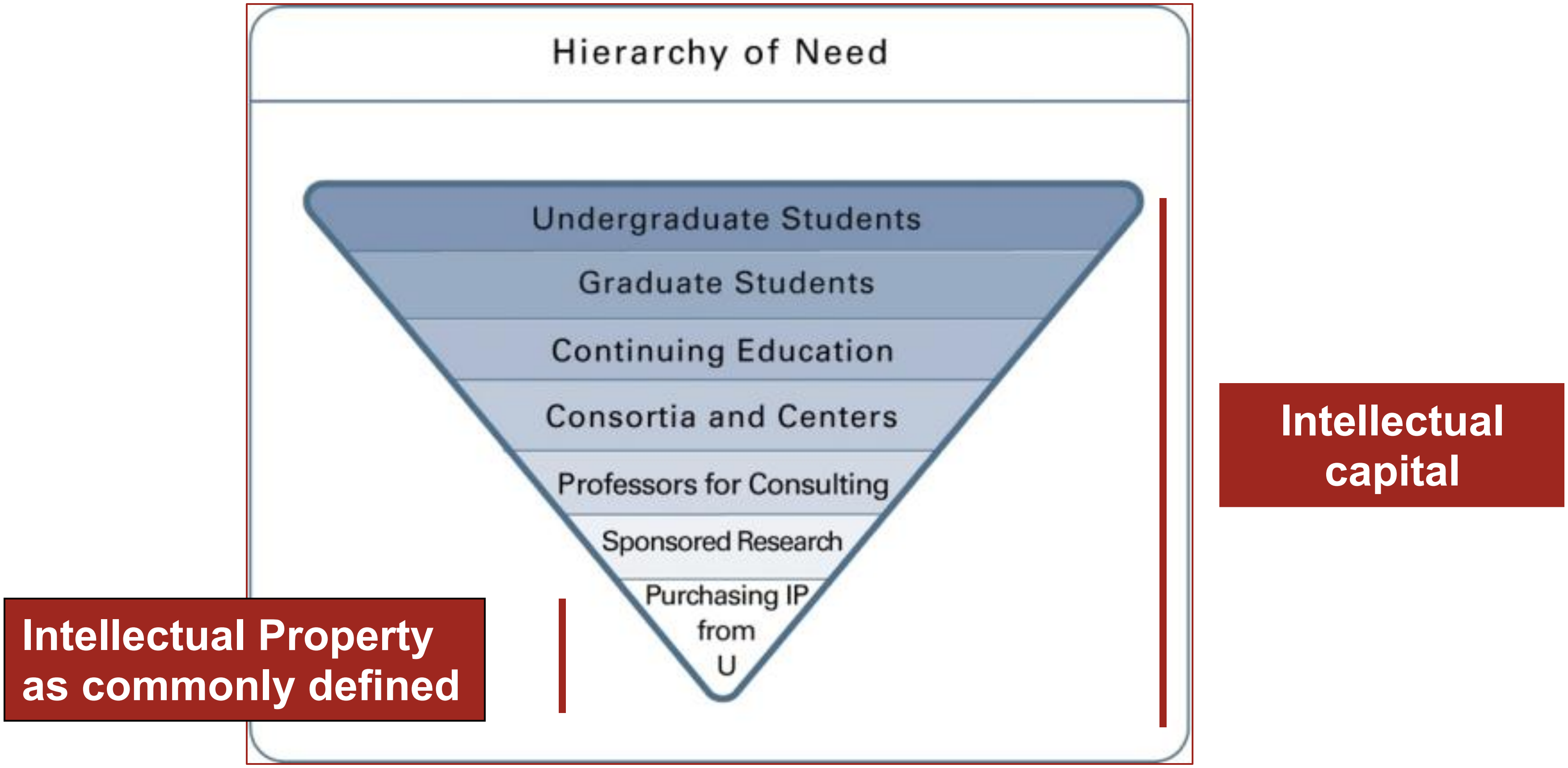
Many consider transfer of a university's intellectual property to be its major contribution to economic development.

But…

…a more accurate statement would be that a university's *intellectual capital* is its true economic impact.

Source: R. Timothy Mulcahy, Vice President for Research, University of Minnesota

What MN companies look for from UMN



Source: R. Timothy Mulcahy, Vice President for Research, University of Minnesota

Minnesota Innovation Partnership

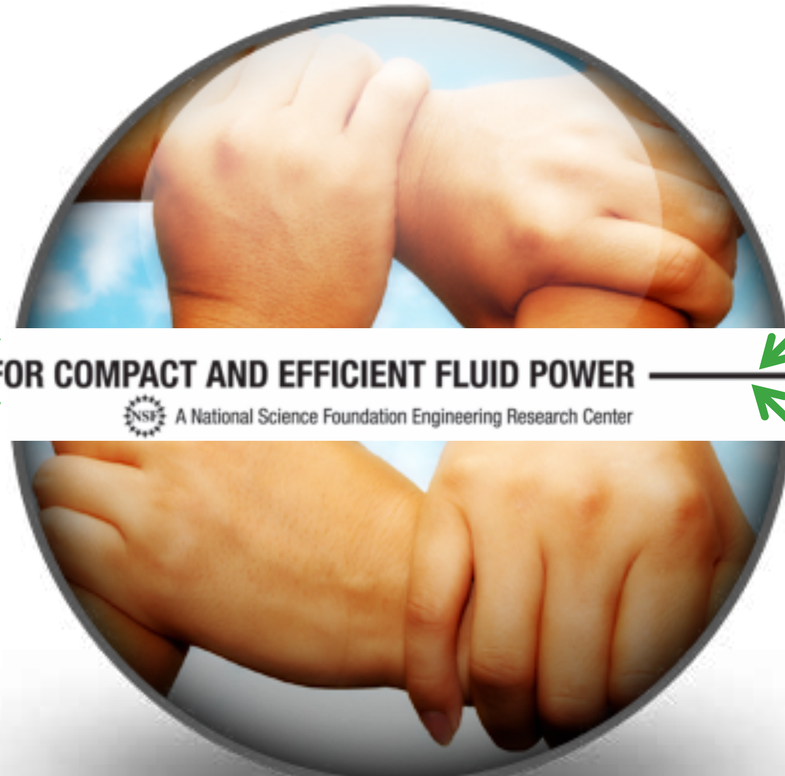
- Unique approach to intellectual property terms for industry sponsored research
- Pre-pay a fee and receive an exclusive worldwide license
  - 10% of research contract or $15,000, whichever is greater
  - no annual minimums or other fees
  - sublicense/cross-license rights
- If annual sales exceed $20 million, company pays 1% royalty
- Company pays patent costs and drives prosecution

IAB Site Visits

CCEFP Builds Collaborations for Innovation in Fluid Power

Industry

Universities



National Labs

Federal agencies