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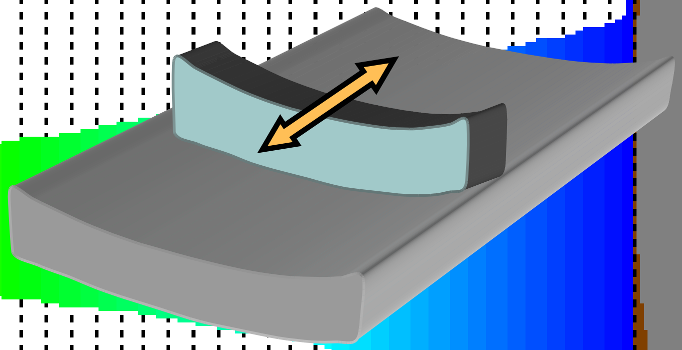
Friction/Wear – Parasitic Energy Losses



George Fenske
Argonne National Laboratory

Sponsored by Lee Slezak
Vehicle Systems Simulation and Testing

DOE VEHICLE TECHNOLOGIES PROGRAM ANNUAL MERIT REVIEW
February 25th, 2008

“This presentation does not contain any proprietary or confidential information”

U.S. Department of Energy

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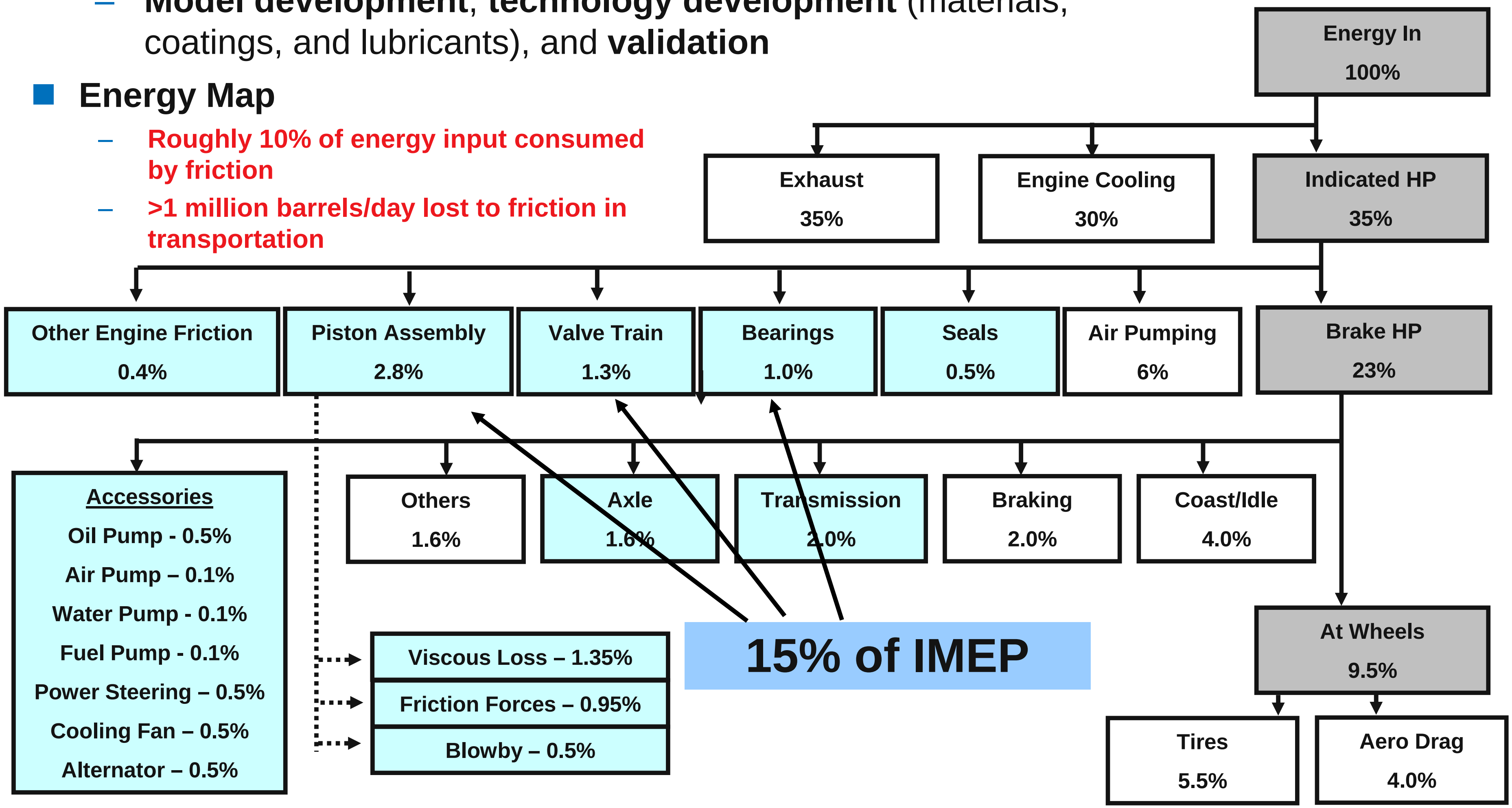
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Outline

- **Purpose / Objectives of work**
- **Approach**
- **Accomplishments / Progress**
- **Plans for Next Fiscal Year**
- **Summary**
- Address Previous Review Comments (time permitting)
- Barriers (time permitting)
- Technology Transfer (time permitting)
- Publications/Patents (time permitting)

Purpose/Objective of Work

- **Reduce PARASITIC FRICTION to Increase FUEL EFFICIENCY and Reduce Use of Petroleum**
  - **Model development**, **technology development** (materials, coatings, and lubricants), and **validation**
- **Energy Map**
  - **Roughly 10% of energy input consumed by friction**
  - **>1 million barrels/day lost to friction in transportation**



Significant Reduction in Petroleum Consumption by Reducing Parasitic Friction Losses

	Petroleum Used (MBPD)	Engine Efficiency Potential (%)	Engine Petroleum Savings (kBPD)	Driveline Efficiency Potential (%)	Driveline Petroleum Savings (kBPD)	Total Savings (kBPD)
HVs	2.5	3/(10)	75/(250)	2/(4.2)	50/(105)	125/(355)
LTs	4.3	3/(10)	129/(430)	1.5/(2.7)	65/(116)	194/(546)
Cars	4.7	3/(10)	141/(470)	1.4/(2.5)	66/(118)	207/(588)
Total	**12**		**345/(1150)**		**181/(339)**	**526/(1504)**

- Consumption of petroleum can be reduced by **0.5 to 1.5 MBPD**
  - 0.1 to 0.4 MBPD in HVs
  - 0.2 to 0.5 MBPD in LTs
  - 0.2 to 0.6 MBPD in Cars

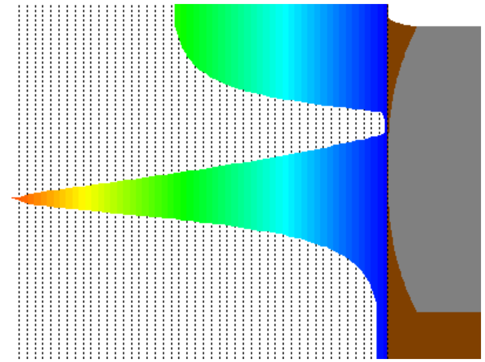
- **Parasitic Friction Technologies Applicable to ALL Vehicle Platforms**

Barriers

- **Vehicle Technologies Barriers *(MultiYear Program Plan):***
  - Vehicle Systems: "…. Reduce heavy truck parasitic losses (friction, aero, rolling, etc.) …. from 39 percent of engine output … to 24 percent…"
  - Combustion and Fuels: "…Improve the efficiency of ICEs from 30 percent … to 45 percent for light-duty passenger and from 40 percent … to 55 percent for commercial heavy-duty vehicle applications while utilizing an advanced fuel formulations…"
- **Tribological systems historically are highly refined, are primarily based on ferrous chemistry, and require a coordinated effort between engine OEMs and lubricant/additive suppliers.**
- **Introduction of new technologies (alternative fuels, low-sulfur fuel, aftertreatment, EGR …) present significant challenges to current tribological systems. Future tribological systems will differ significantly from today's system and must be considered in engineering high-efficiency vehicles**

Approach

- **Develop and Apply Mechanistic Models** of Friction (Boundary and Viscous) Losses to Predict Parasitic Losses as a Function of **Engine Conditions** (Load & Speed), and **Tribological Conditions** (Boundary Friction and Oil Viscosity)
  - Scale fuel consumption as a function of FMEP and IMEP for a prototypical HD diesel engine
  - Predict the impact of low-friction (boundary-layer friction) and low-viscosity lubricants on fuel economy
- **Evaluate/Screen the Potential of Candidate Surface Treatments and Additives** to Reduce Boundary Friction Under Lab Conditions Prototypical of Engine Environments
  - Benchtop friction tests using prototypical engine components
  - Impact of materials, coatings, surface texture, and lubricant additives and viscosity
- **Validate Codes/Models and High-Potential Solutions** in Fired Engines Using In-Situ Friction Measurement Techniques
- **Demonstrate efficiency improvements** in multi-cylinder engines



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RINGPAK
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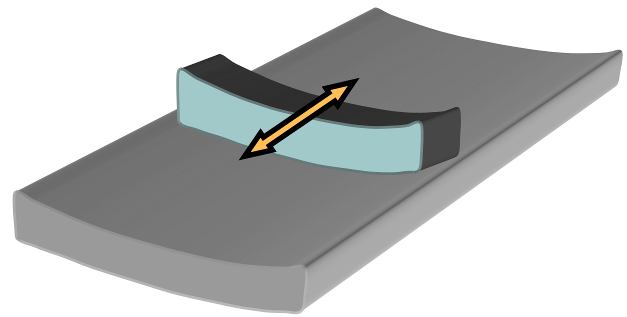
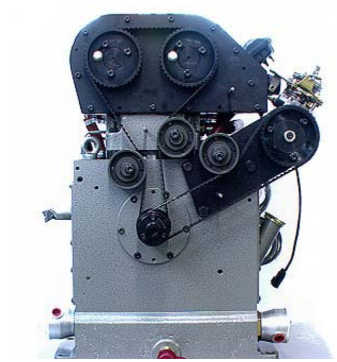
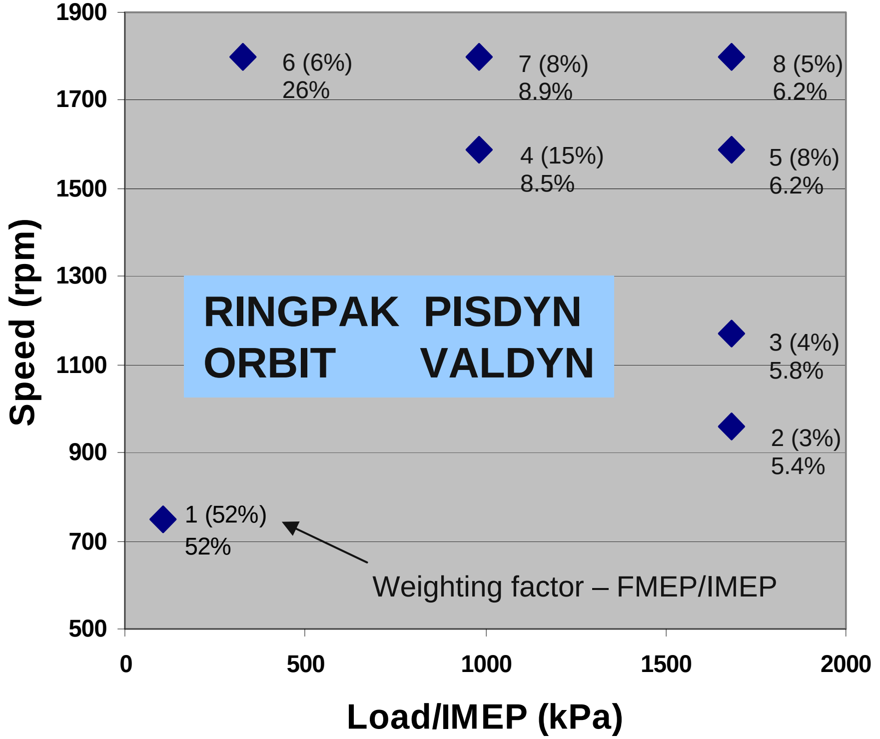


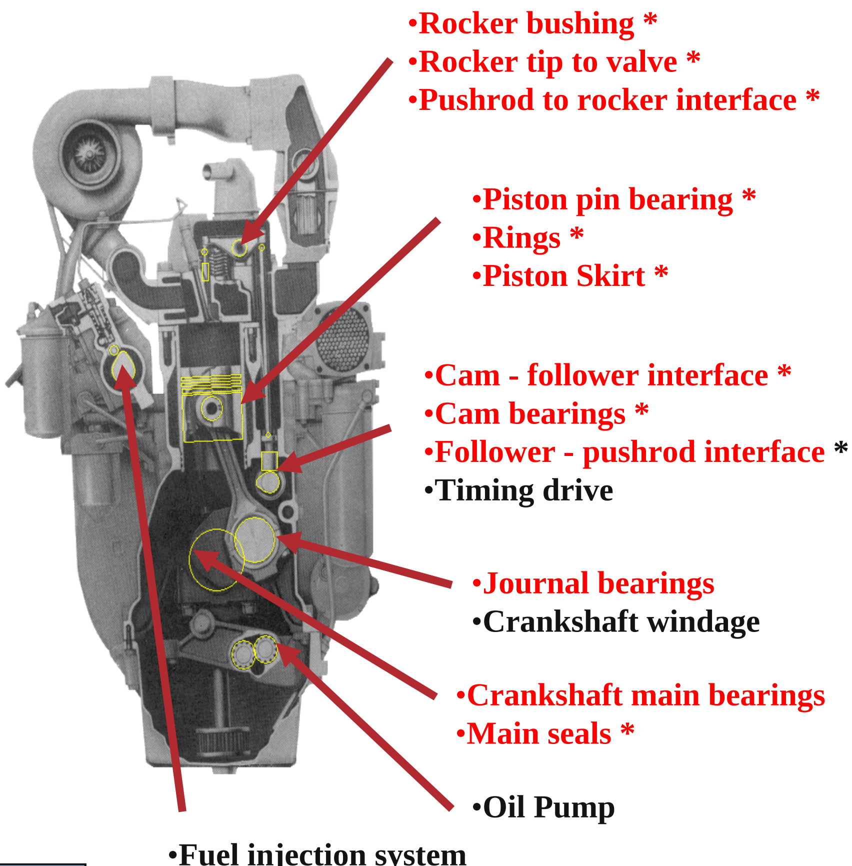


W.E. Lay
Automotive Laboratory

Integrated Mechanistic Models to Predict Impact of Low-Friction Surfaces and Low-Viscosity Lubricants on Parasitic Energy Losses (FMEP) and Fuel Economy

- FMEP calculated at 8 different modes and weighted to predict effect on fuel consumption for a HD driving cycle





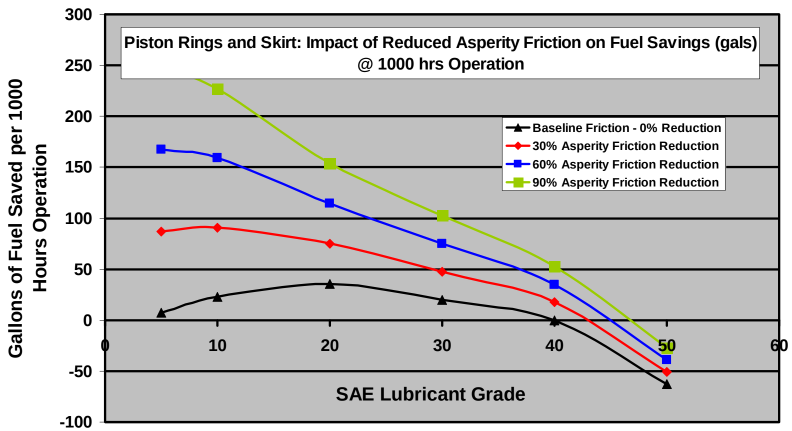
$$\text{FCSF} = \frac{\text{IMEP} + \Delta\text{FMEP}}{\text{IMEP}}$$

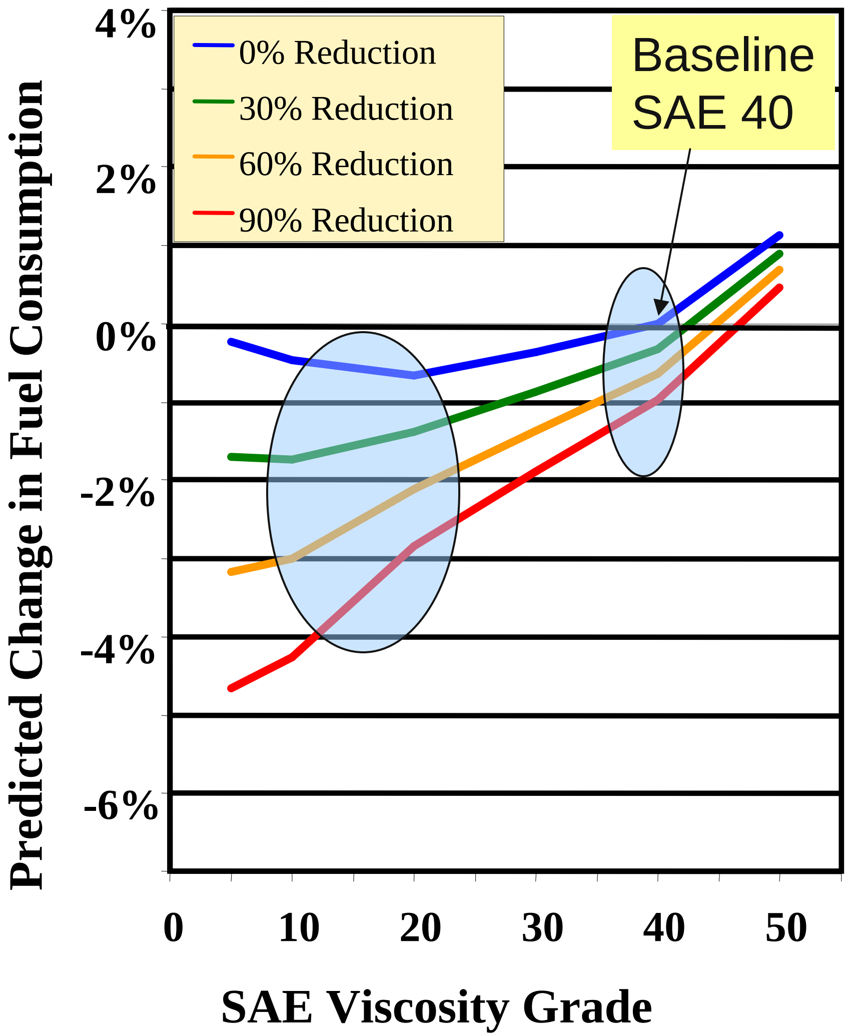
(Fuel Consumption Scaling Factor)

* interface considered in current study

Modeling the Impact of Friction on Fuel Efficiency and Identifying Critical Components

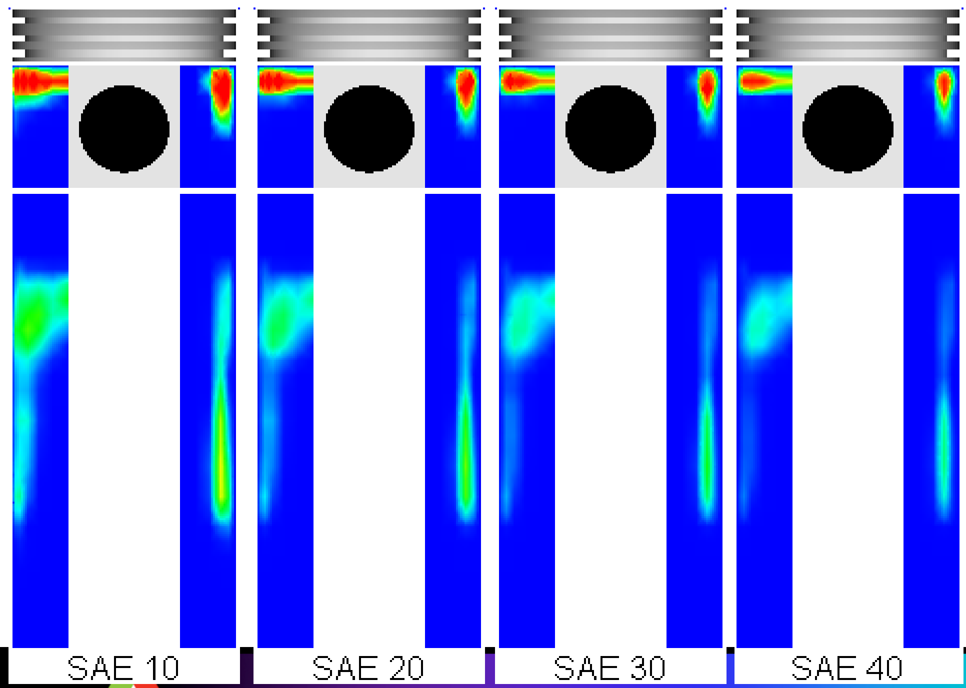
- **Prediction/Modeling of Fuel Savings**
  - Systematic studies on the effect of boundary friction and oil viscosity on fuel efficiency
  - Up to 1.3 % fuel economy improvement by low friction additives and/or coatings
  - 3-4% fuel economy improvement by reducing boundary friction and reducing oil viscosity
  - Additional 2-4% fuel economy gains in transmission and differential/axle

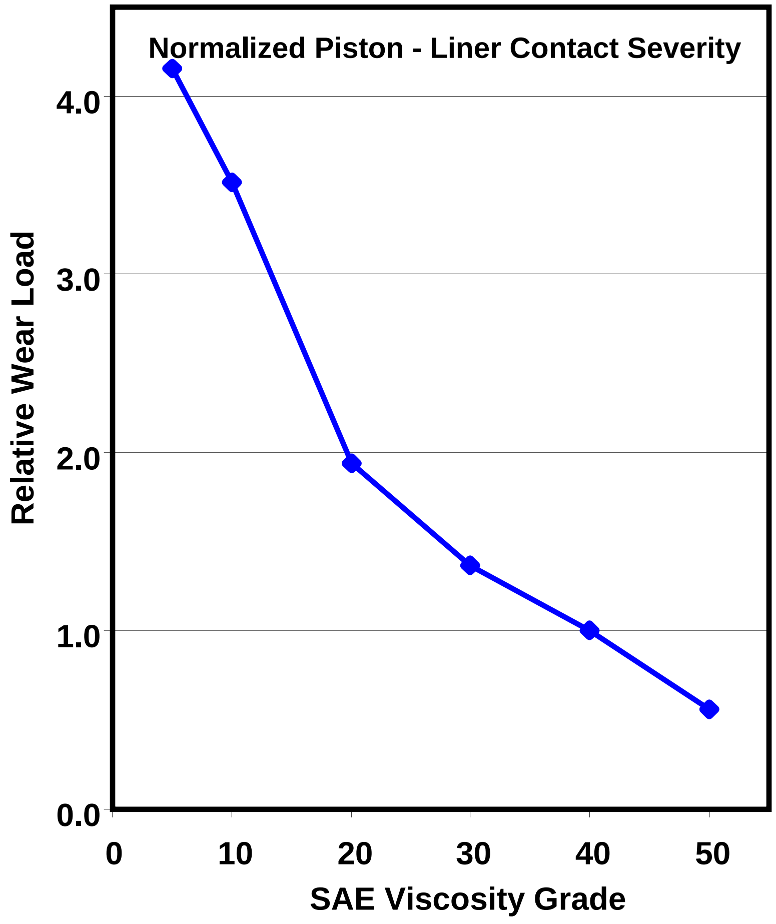




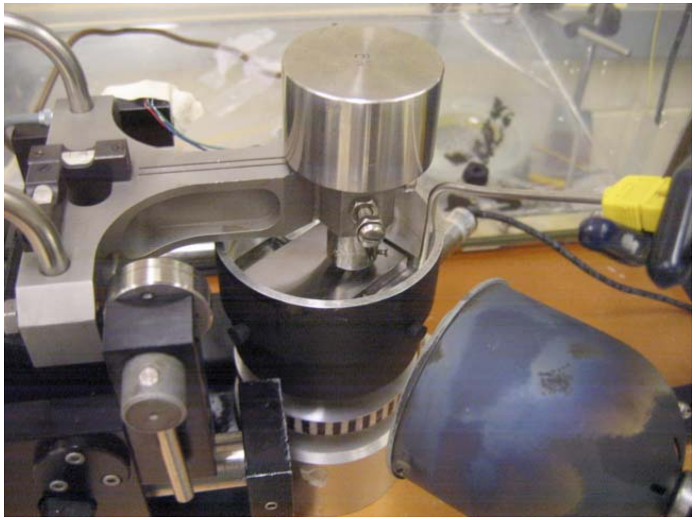
Modeled Contact Severity/Loads – Impact of Low-Viscosity Lubricants on Engine Components

- As lubricant viscosity is reduced, contact between the piston skirt and cylinder liner increases in both magnitude and extent
- Predicted total average contact severity per cycle, using SAE 5 oil, is more than 4 times as high as that using SAE 40 oil
- This model suggests that to allow the use of SAE 5 oil, a surface treatment would have to provide approximately four times the wear resistance of the baseline system, if the wear resistance remained constant over time



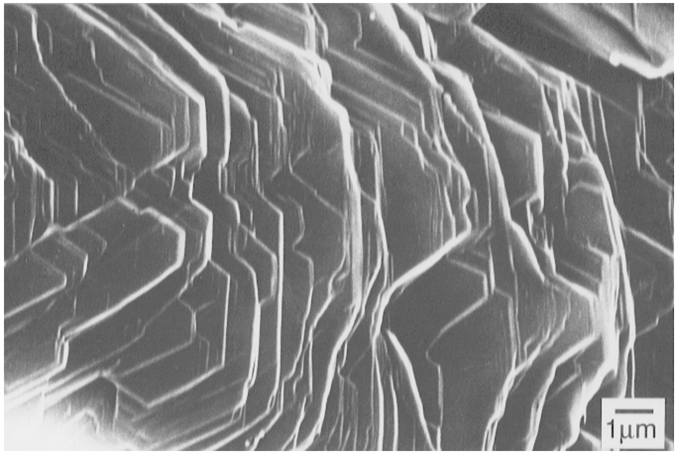


Identifying Low-Friction Technologies that Enable Low-Viscosity Lubricants and Maintain Durability/Reliability

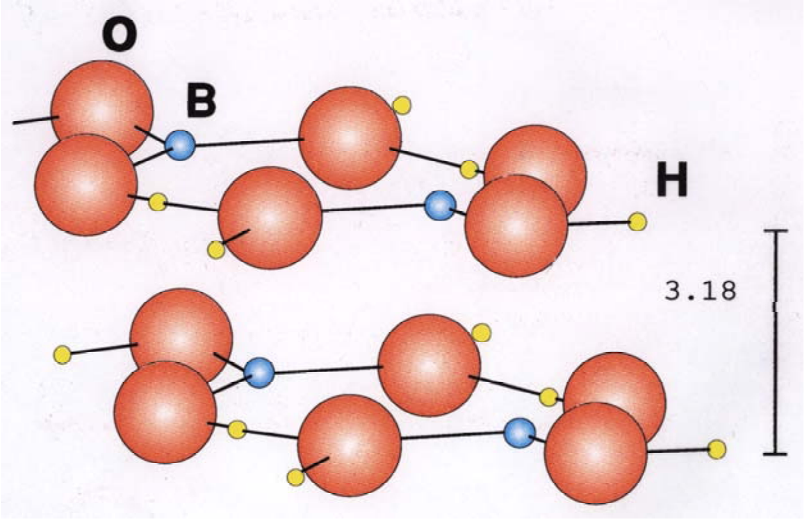


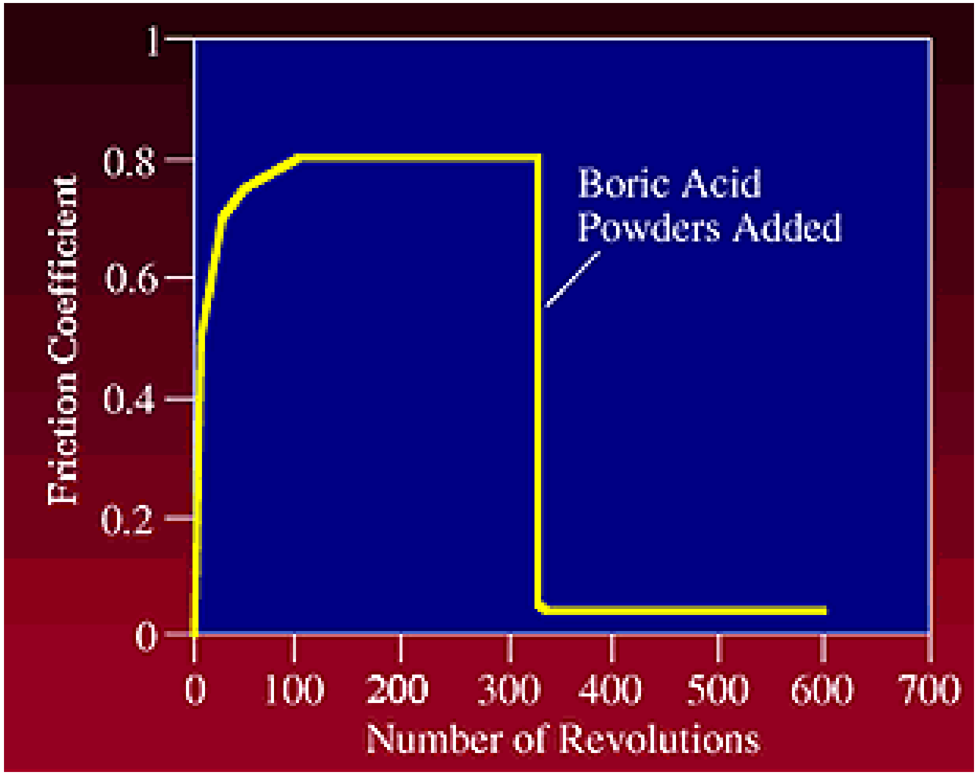
- **The mechanistic friction models answer the questions:**
  - ‘How much fuel can be saved if friction for a specific component is reduced by X% ?’
  - ‘What is the impact of a low-viscosity lubricant on engine durability/reliability ? … How much more wear-resistance must be built into a component for a low-viscosity lubricant ?’
- **But… the models don’t tell us how to lower friction, or, how to increase durability and reliability**
- **Therefore…the second objective of this project evaluates potential technologies to achieve the 30, 60, … 90% reductions in friction.**
  - Pin-on-disc configuration – simple to use and provides quick evaluation of friction (and wear) under well-defined geometry
  - Ring-on-liner configuration – more complicated, prototypic configuration, uses coupons obtained from standard components (rings)

Example: - Boric Acid Additives



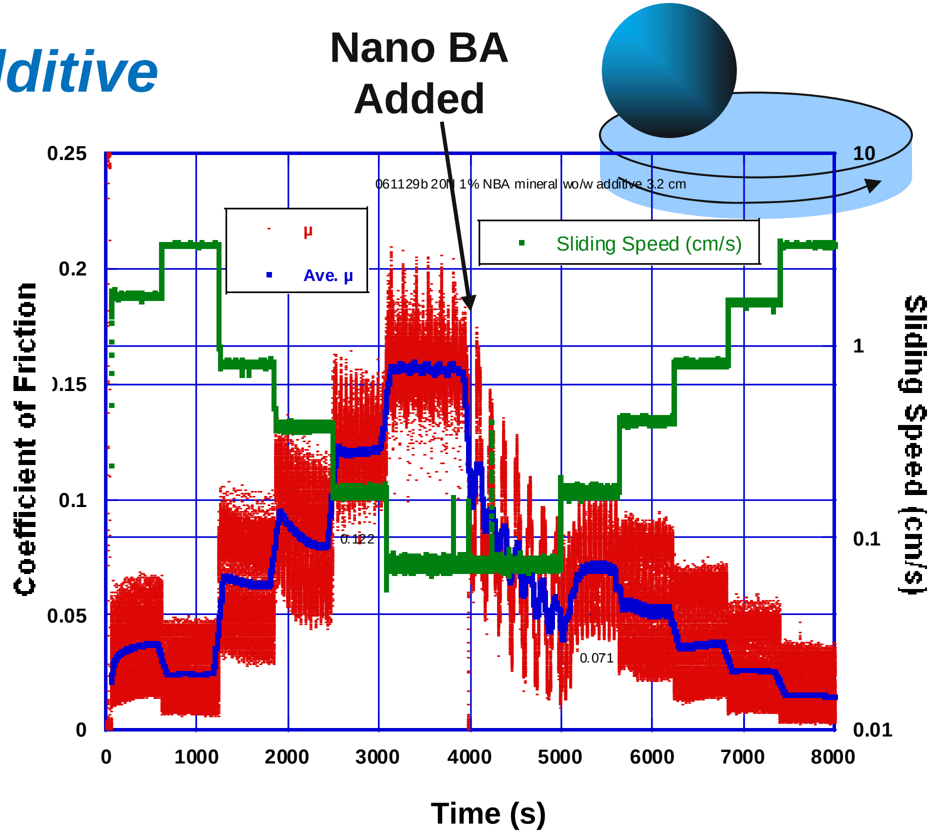
- Research at Argonne led to the discovery of the low-friction properties of boric-acid
- Extensive POD tests provided detailed information on friction under **dry sliding** conditions
- Extensive characterization provided details on low-friction mechanism
- Concepts developed to use BA as oil additive and commercialized
- Studies continue to explore nano-BA compounds as oil additives





Example: Nano Boric Acid Additive

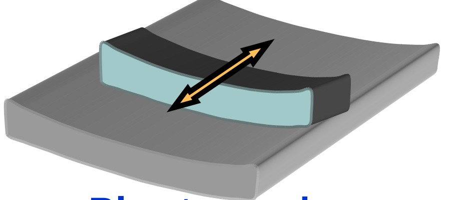
- Pin-on-Disc and Ring-on-Liner tests demonstrating low-friction properties of boron-based additives
- Early version of boron-based additive chemistry licensed and commercialized. Newer (nano BA) chemistry under evaluation for commercialization

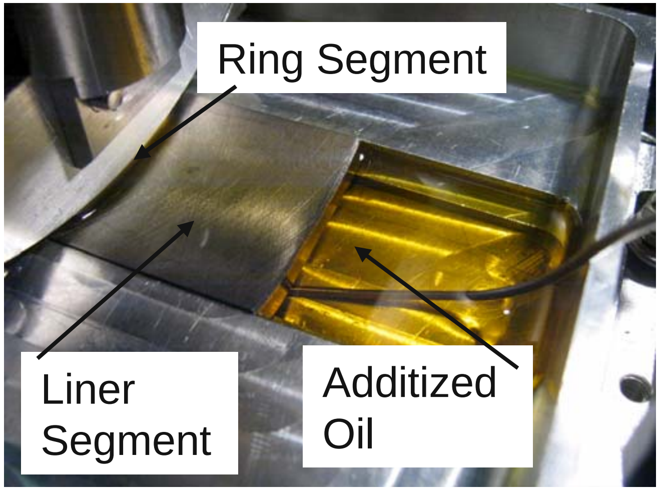


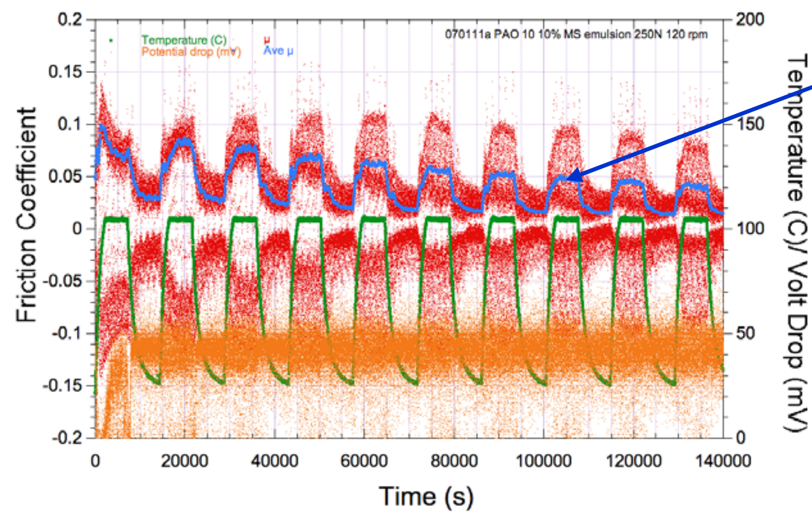
- Characterization continues to examine issues regarding the impact of particle size, loading, base fluid, and synergistic reactions with other additives and production method

1% NBA Mineral	**30-66% reduction**
1% NBA Ester	**30% reduction reproducible**
1% NBA 5W30 no sulfonate	**No change**
25% Commercial BA in PAO 10	**50% reduction, unsteady**
6.25% Commercial BA in PAO 10	**Slight reduction, unsteady**
1% NBA PAO 4	**77% reduction**

Example: Simulation of Ring-on-Liner Conditions

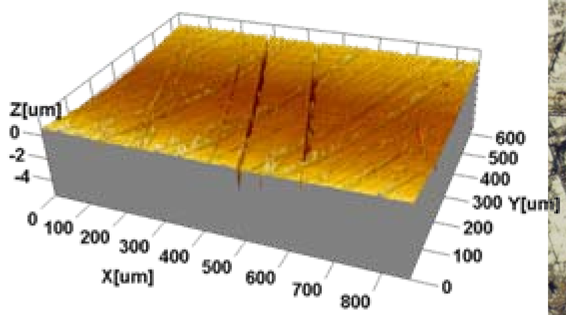


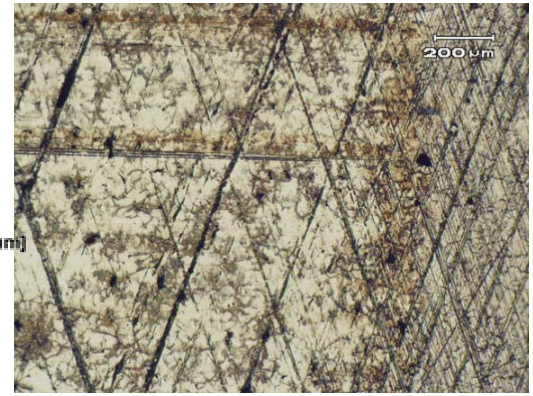




Blue trace shows friction coefficient during cyclic heating tests – Note how cyclic heating activates the action of the BA additive to produce low friction

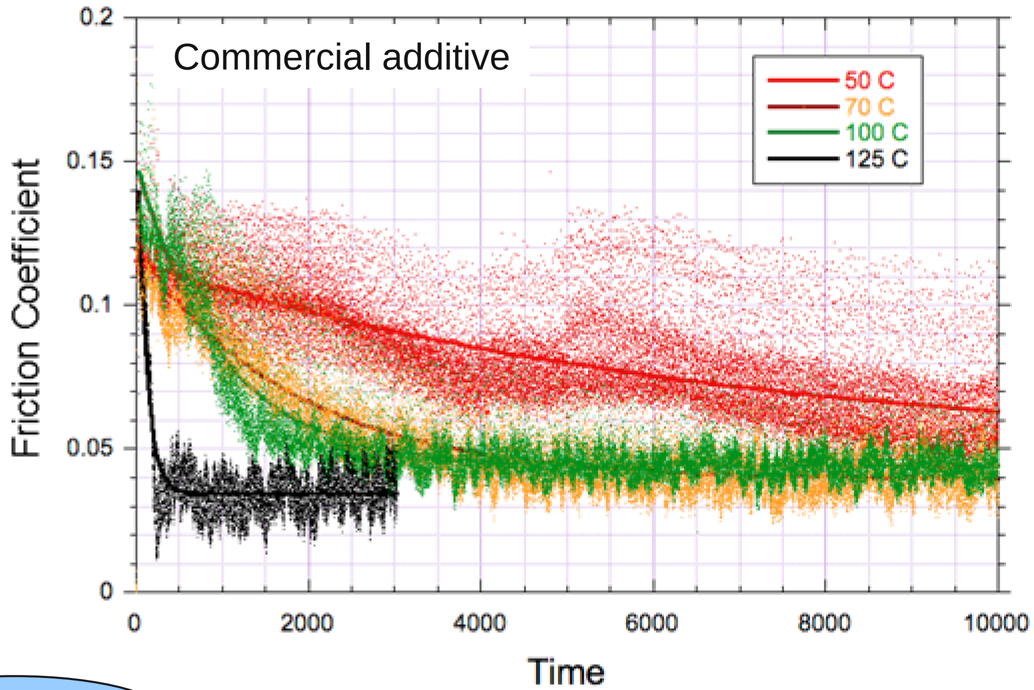
- Developed test rig to simulate ring-on-liner and piston-on-liner tribological environment
- Studied low-friction nature of boric-acid (BA) based additives – Friction reductions of 50% observed
- Post characterization of tribo-film formed during ROL tests
  - Smoother interhoned regions - accelerated polishing, or, tribofilm formation?

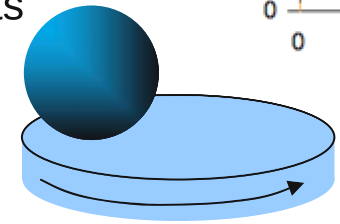


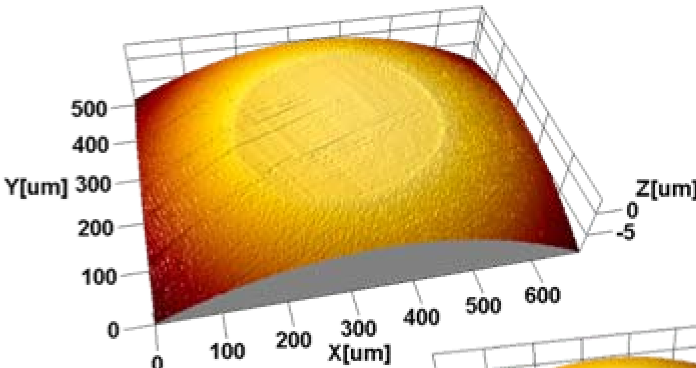


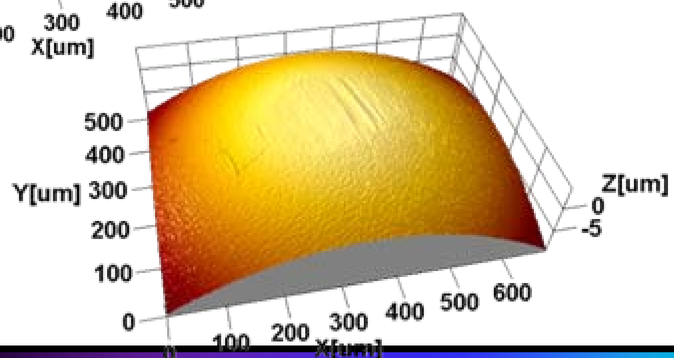
Example: Evaluation of Lubricant Additives Using Pin-on-Disc

- Systematic studies at relatively low speeds provide detailed data on the impact of additives (commercial and experimental) on **boundary film lubrication**
  - Develop test protocols to compare impact of lubricants





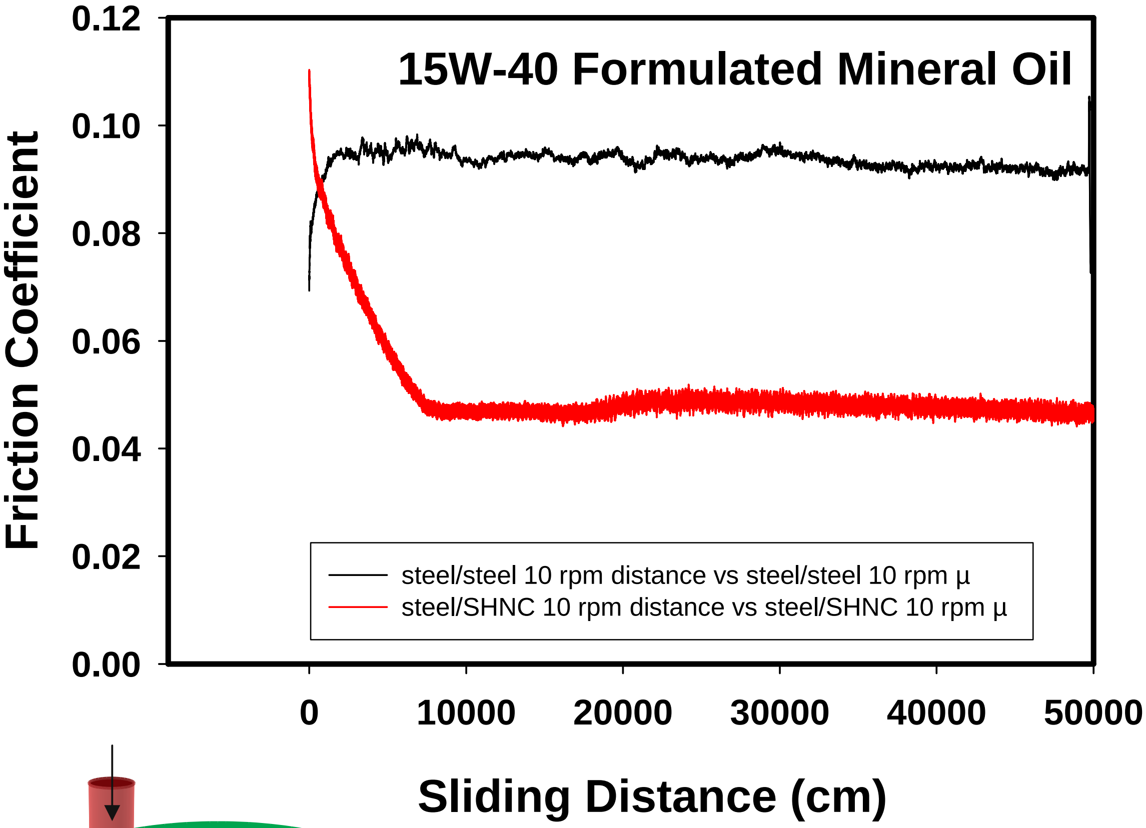


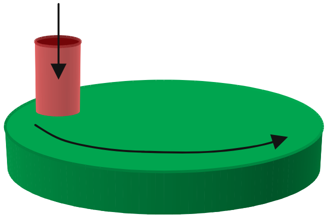


- Quantitative 3-D imaging of test coupons provide detailed information on the impact of lubricants on wear/durability

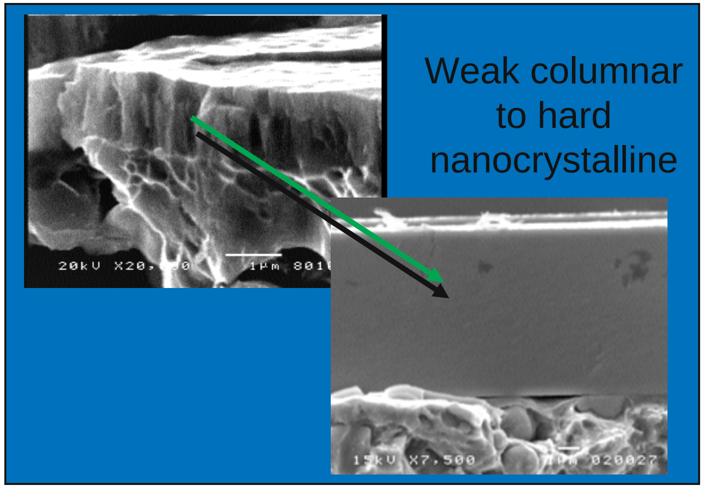
- **Tests scheduled for FY08 to evaluate commercial additive in HD basestock using ring-on-liner configuration**

Example: Pin-on-Disc Evaluation of Low-Friction Superhard Coatings – 50 % Reduction in Boundary Layer Friction





- Engineered coating microstructure and composition to provide superhardness and tribochemistry for enhanced low-friction properties



Ring-on-Liner Tests on Superhard NanoComposite Coated Rings

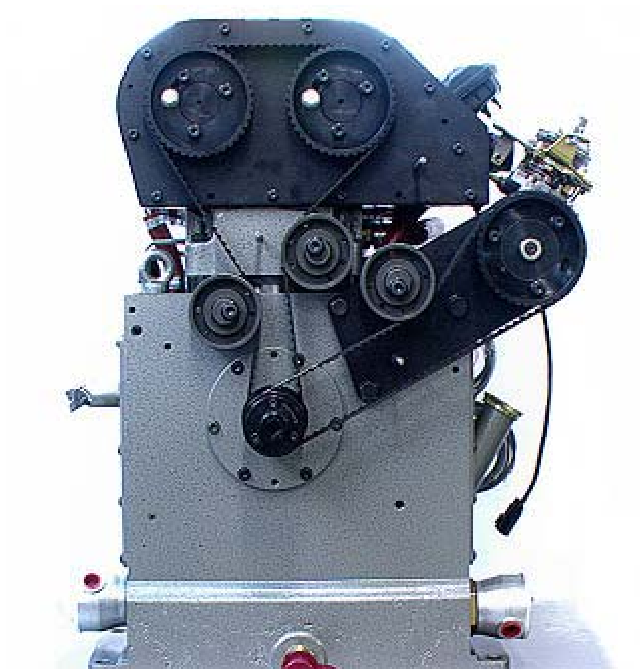
- Collaborating with ring/liner supplier to evaluate low-friction coatings
  - Gas-nitrided, PVD-CrN, 'ceramic-Cr', and nodular CI rings
- Developing SHNC coating processes for optimum adhesion and minimum ring distortion
  - Low-temperature (minimizes ring distortion)
  - Elevated temperature (enhances adhesion)

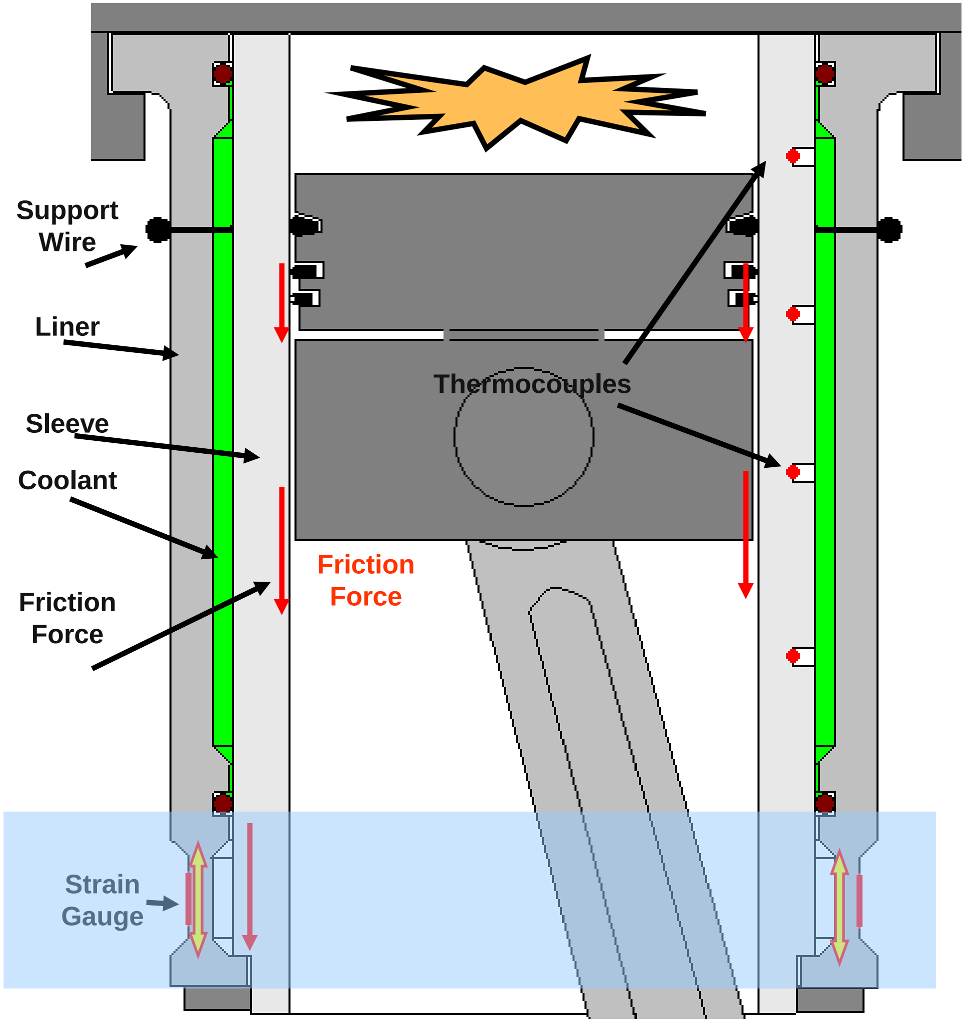
Process/Ring	Adhesion	Ring Distortion
Low-Temp / Gas Nitrided	Fail	Pass
Low-Temp / PVD CrN	Fail	Pass
Low-Temp Ceramic-Cr	Fail	Pass
High-Temp / Gas-Nitrided	**Pass**	**Pass**
High-Temp / PVD CrN	Fail	Pass
High-Temp / Ceramic-Cr	Pass	Marginal

- **Ring-on-Liner tests scheduled for 2nd half of FY08**

Ricardo/U-Mich – In-Cylinder Validation of Models and Low-Friction Technology

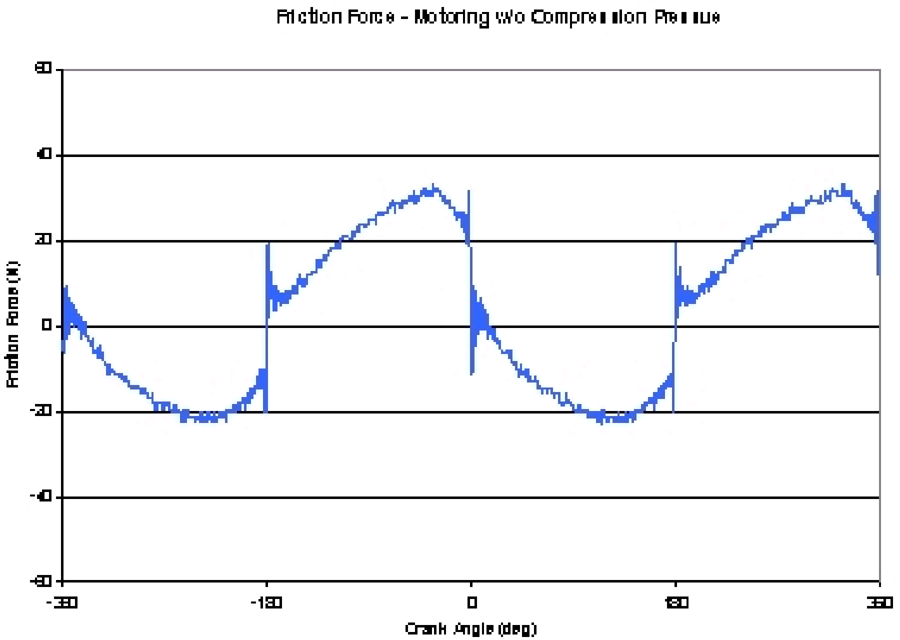
- **Single Cylinder, Fired Diesel Test Engine – Ricardo Hydra**
- **Engine Modified to Monitor Friction Force Between the Piston (Skirt & Rings) and Liner Continuously**

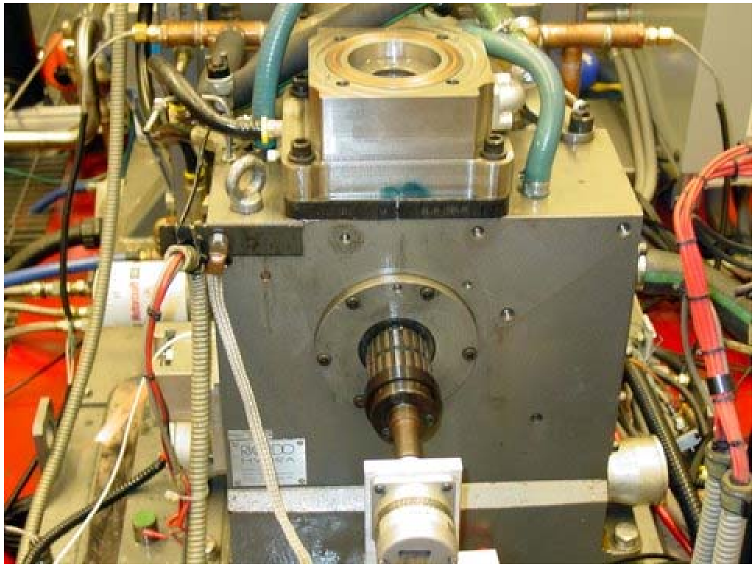




In-Situ Measurement of Ring/Piston – Liner Friction

- U-Michigan instrumented liner installed in single-cylinder Hydra engine
- Preliminary friction force trace as a function of crank angle under motored conditions
- 4-valve DI cylinder head to be installed for in-situ friction force measurements under fired conditions





Future Plans

- Evaluation of candidate technologies
  - Pin-on-Disc, Ring-on-Liner, **Skirt-on-Liner**
  - Additives, in-house coatings, commercial coatings
- In-situ measurement/validation of ring/piston/liner friction
  - Ricardo/UMich
- Multi-Cylinder Engine Tests
  - Model and technology validation
- Characterization of film formation mechanisms
  - Analysis of Ring-on-Liner coupons (boric-acid based additives)

Additives – boric-acid (micron & Nano-BA), commercial additive package

Coatings – SHNC, NFC, **CrN, EN-B**

Additive package selected and delivered to UMich

Identifying site/partner for multicylinder engine studies

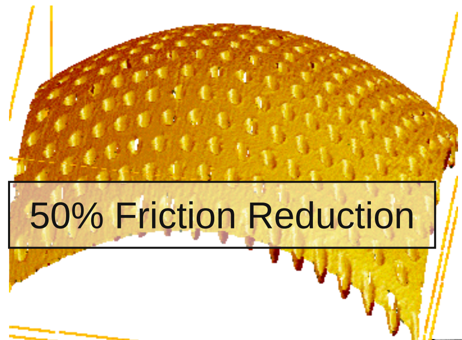
Continue coordination of studies with DOE Boundary Lube and Hard Coating projects – provide prototypic components for testing/characterization

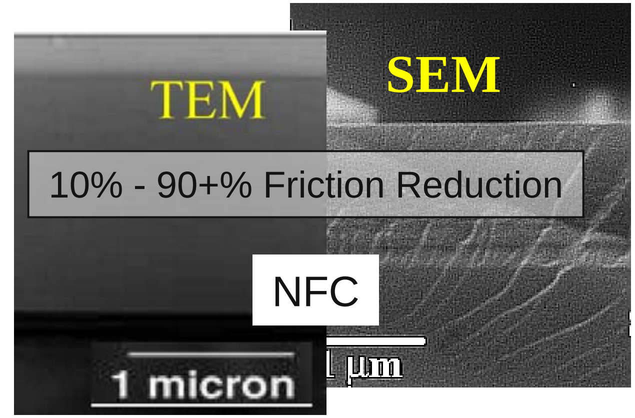
Summary

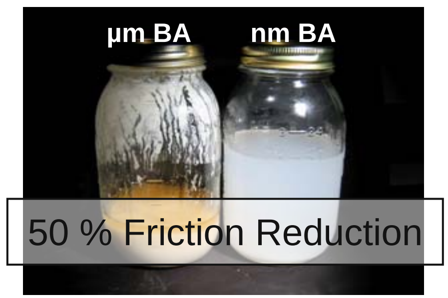
- Mechanistic models of parasitic friction losses were developed and integrated to predict the impact of low-friction technologies on fuel efficiency
  - **3-5 % fuel economy savings (0.5 to 1.5 MMBD)**
- Lab-scale test protocols were developed and applied to evaluate candidate technologies capable of providing low-friction under boundary layer conditions
  - Pin-on-disc tests identified 2 additive technologies capable reducing boundary friction by 50 to 80%
  - Pin-on disc tests also identified 3-4 coating technologies that exhibit low-friction (30 to 90 % reduction in boundary friction)
  - Ring-on-liner tests using prototypic ring and liner segments confirmed low-friction properties of a boric-acid additive
  - Further ROL tests scheduled to evaluate NBA and a commercial additive
  - ROL tests scheduled to evaluate low-friction, wear-resistant coating technologies (SHNC, CrN, EN-B)
- Ricardo/UMich designed and engineered a fired, single-cylinder diesel test rig capable of in-situ ring/piston/liner friction measurements
  - System undergoing motored, and fired shakedown tests
  - FY08 tests scheduled to provide baseline friction data as a function of lubricant viscosity
- Discussions in progress to select a site for multicylinder engine tests to validate models and technologies

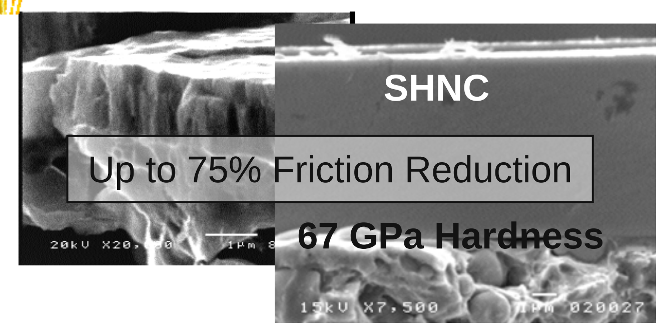
Low-Friction Technologies

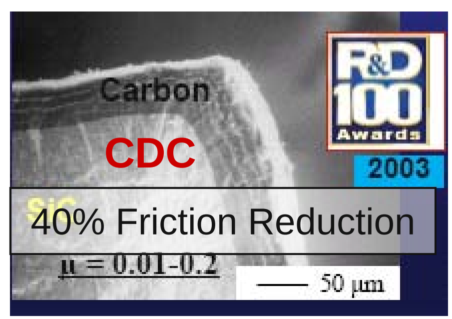
- **Development of engineered surfaces with low-friction and improved durability & reliability**
  - Low-friction carbon coatings (NFC- ultralow friction carbon, CDC- carbide derived carbon, nanocrystalline diamond, and carbon-carbon composites
  - Superhard nanocomposite coatings
  - Borided steels
  - Laser textured surfaces
  - Additives
- **Evaluation of Commercial Coatings & Materials**

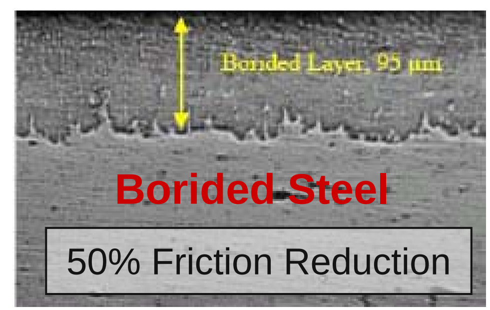






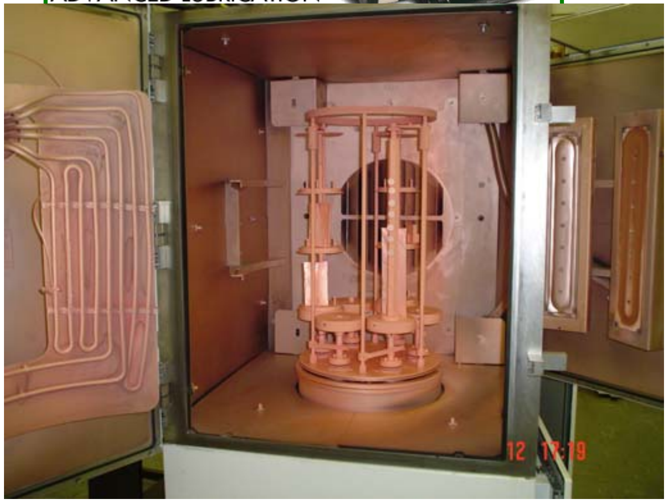






Technology Transfer

- Collaborations with additive suppliers and lubricant formulators
  - Boric acid additive – licensed to ALT
  - nBA license and development in progress
- Collaborations with engine OEMs and suppliers
  - Ring/liner supplier
  - CRADA
- Collaborations with coating OEMs
  - Coating technology licensed to 2 world-wide equipment OEMs



Publications & Patents/Inventions

- Publications
  - I. Fox, Numerical Evaluation of the Potential for Fuel Economy Improvement due to Boundary Friction Reduction within Heavy-Duty Diesel Engines, ECI International Conf. on Boundary Layer Lubrication, Copper Mountain, CO, Aug. 2003.
  - George Fenske, Parasitic Energy Loss Mechanisms: Impact on Vehicle System Efficiency, U.S. Department of Energy Heavy Vehicle Systems Review, April 18-20, 2006, Argonne National Laboratory, Argonne, Illinois.
  - George Fenske et. al., Parasitic Engine Loss, Annual Report of Laboratory-Directed Research and Development Program Activities for FY 2005
  - George Fenske et. al., Parasitic Engine Loss, Annual Report of Laboratory-Directed Research and Development Program Activities for FY 2006
  - George Fenske et. al., Parasitic Engine Loss, Annual Report of Laboratory-Directed Research and Development Program Activities for FY 2007
  - George Fenske et. al., Low-Friction Engineered Surfaces, DEER 2007
  - **Numerous publications on NFC, SHNC, and boric acid (see Erdemir, Eryilmaz, Ajayi, and Erck)**
- ANL Patents/Inventions (developed with DOE EERE support)
  - Boric-Acid Additive - **5,431,830** , Erdemir July 1995, **5,840,132** Erdemir et al (Nov 1998) – borided surfaces, **6,025,306** Erdemir (Feb 2000) – boric-acid/polymer composites (100 nm to 500 µm), **6,783,561** Erdemir (Aug 2004) – nm size boric acid particles for fuel and oil additives
  - NFC and SHNC inventions and patents
  - R&D `100 Award – 1991, 1998

Prior Review Comments/Comments

- Heavy Vehicle Systems Optimization Review (April 2006)

- Characterization work should be increased (referring to characterization of low-friction technology development)
  - *Coordinating efforts with boundary layer lubrication project and hard coating projects to include ion-beam and FIBS/SEM studies*

- ….. addition of some oil/additive industry participation
  - *Coordinating activities with oil and additive OEMs (DOE, NIST-ATP solicitations)*
  - *DOE support on additives and EGR-tolerant lubricants*

  - *Welcome collaboration with fleet operators*

Questions ???