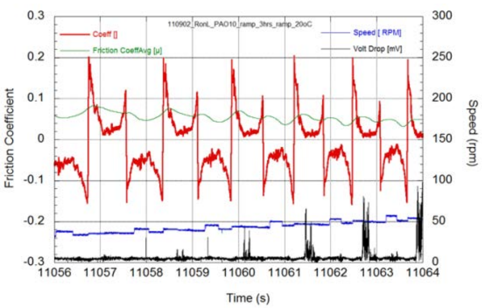
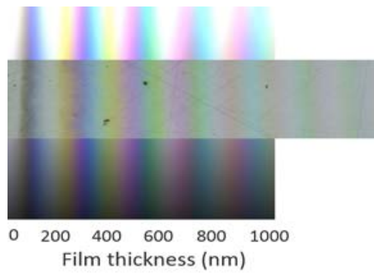
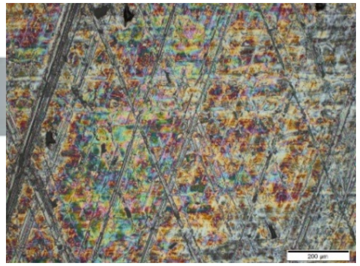
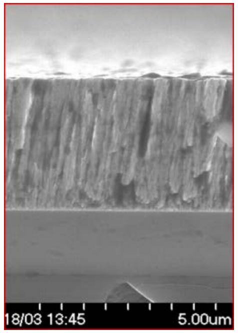
Engine Friction Reduction Technologies









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Argonne National Laboratory

June 11th, 2015

Project ID # FT012

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Overview

Timeline

Project start date	FY 13
Project end date	FY 19
Percent complete	40%

Budget

FY 14 Project Funding	$1838K
DOE Share	$1588K
Contractor Share*	$250K
FY 15	$970K

* CRADA in-kind and funds-in contributions

Barriers

- Fuel economy improvement via lubricants and tribology
- Reduction of greenhouse gas (GHG) emissions
- Reliability/durability
  - Impact of lubes on after-treatment devices
  - Lube compatibility with alternative fuels
  - Lubricating alternative (non-traditional) materials
  - Alternative lube stocks (bio-based)

Partners

- MIT – Lube Consortium
- Vehicle and Engine OEMS
- Component OEMs
- Lubricant Suppliers
- Additive Suppliers
- Small Businesses, Academia

Relevance: Overall Project Take-Home Message on Lubricants: Parasitic friction losses in engines and transmissions consume up to 10-15% of fuel used in transportation

- Researchers worldwide are developing advanced transportation concepts to improve energy sustainability and reduce GHG emissions, including
  - Alternative fuels (bio/renewables, compressed natural gas, etc.)
  - Alternative materials - high power density components (lightweight materials, compact designs), higher temperatures
  - New fuel-saving concepts – such as turbocharging and cylinder deactivation
  - Advanced combustion strategies
  - After-treatment
  - Fuel efficient lubricants

250 million on-road vehicles
10-12 MBBL/day
5 MMT/day CO_2
1.5 to 1.8 MBBL/day friction

- Researchers worldwide are developing advanced lubrication concepts that:
  - Are compatible with current and future vehicle concepts
  - Improve mechanical efficiency (reduce parasitic friction losses)
  - Reduce GHG emissions

- Tasks developed for this project address critical barriers to the development of advanced fuel efficient lubrication concepts:
  - Improvement of lab-engine correlations
  - Understanding of how additives interact to form low-friction protective tribofilms
  - Development of specific technologies (additives, basefluids, and other materials)

Goals/Objectives of Engine Friction Reduction Technologies Project

- **Goals of Lubrication Activities:** The goals of the ANL lubrication project are to develop the science and understanding needed to develop advanced lubrication technologies that:
  - **Reduce parasitic friction losses / reduce consumption of petroleum**
  - **Reduce emission of GHGs**
  - **Ensure reliability and durability of critical systems impacted by lubricants**

	Parasitic Losses	Fuel Consumption	GHG Reduction
Legacy Vehicles	Near-Term: 10% Long-Term: 20%	1.5% - 150K BBL/day 3% - 300K BBL/day	75K tonnes/day 150K tonnes/day
New Vehicles	Near-Term: 25% Long-Term: 50%	3-4% - 400K BBL/day 7-8% - 800K BBL/day	175K tonnes/day 375K tonnes/day

- **Goals are consistent with DOE/VTO efficiency and emission goals:**
  - By 2015, develop technologies and a set of options to enable up to 50% reduction in petroleum-based consumption for light-duty vehicles.
  - By 2030, develop technologies and deployment strategies, to enable up to 80% of the energy for light-duty vehicles to be from non-carbon or carbon-neutral energy sources.
  - Demonstrate a 50% improvement in freight hauling efficiency for trucks (ton-miles per gallon).
  - Develop and demonstrate parasitic friction reduction technologies that decrease driveline losses by 50%, thereby improving Class 8 fuel efficiencies by 3%.
  - Achieve 35/55 mpg CAFÉ Standards – Multiple technologies will be required to achieve current and future CAFÉ standards.

Project Identified Pathways and Approaches to Achieve Goals and Technological Barriers

- **Multiple pathways** to reduce parasitic friction losses and improve reliability and durability
  - Lubricants – additives and basefluids
  - Materials and coatings
  - Engineered surfaces – design and texture

LEGACY vehicles will benefit from advanced lubricants;
NEW vehicles will benefit from all three approaches

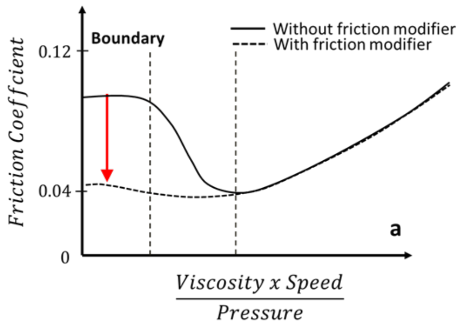
- **Barriers** to achieving goals and targets identified:
  - **Inadequate data and predictive tools**: Ability to predict impact of advanced technologies on fuel economy, impact of alternative fuels on lubricant performance, interaction of additives and chemistry with ferrous and non-ferrous materials, and information on mechanical efficiency of accessories.
  - **Limited basestocks and additive formulations (one size may not fit all):** Competition of friction modifiers with antiwear additives; introduction of advanced concepts (e.g., turbocharging, cylinder deactivation, bifuels, etc.) with different performance requirements; compatibility with advanced materials, coatings, and engineered surfaces; compatibility with emission systems; backward compatibility; engine vs. driveline systems; alternative fuels.
  - **Limited validation of technologies – (costly, and time consuming)**

Project Organized into 3 Tasks with 5 Research Topics

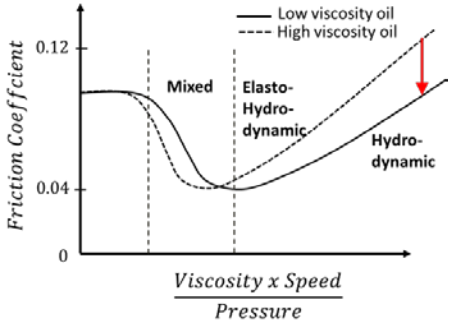
- **Phenomenological Investigation of Tribofilm Formation:** Develop and apply advanced surface analytical techniques to investigate structural and chemical behavior of tribofilms, and develop mechanistic models of tribofilm formation and behavior.
- **Lab-Engine Correlation (Intelligent Testing):** Develop intelligent lab-scale test protocols to evaluate tribological properties and to improve the value of such information to predict performance under prototypical engine and vehicle conditions.

Additives

Coatings



Basefluids



- **Technology Development:**
  - **a) Additives*:** Development and evaluation of advanced lubricant additives that lower asperity friction and improve wear and reliability performance.
  - **b) Basefluids*:** Development of advanced hybrid basefluids that reduce viscous losses over a wide range of temperatures and shear rates.
  - **c) Coatings:** Development of non-ferrous based coatings that lower boundary friction and improve wear resistance.

* Covered in separate AMR presentation by Ajayi - ANL: Additive and Basefluid Development

Phenomenological Studies of Tribofilm Formation – What is a tribofilm? What is its structure? What is its chemistry? How does it react to temperature and stress? What is the link to friction, wear, and durability?

- **Issues/Background:**
  - The properties of thin tribofilms (<100 nm thick) that form on mechanical surfaces during rubbing will determine whether a component fails immediately, after 1-2 hours, or after more than 10,000 hours
  - The knowledge of how additives interact to form low-friction, protective films on engine components is limited. Development is largely by trial and error. Information on underlying film formation mechanisms is needed to guide development of new lubricants.
  - Sustainable friction reduction via the formation of tribochemical films will improve vehicle fuel efficiency. A connection established between the structure of tribofilms and friction will enable predictable and sustainable friction reduction.

- **Approach:**
  - Argonne is utilizing advanced surface analytical tools (e.g. x-ray and electron microscopy) to investigate the structure and chemistry of tribofilms formed under different tribological conditions and to formulate mechanistic models that link friction and wear performance to the structure and chemistry of the film.

- **Milestones/Deliverables:**

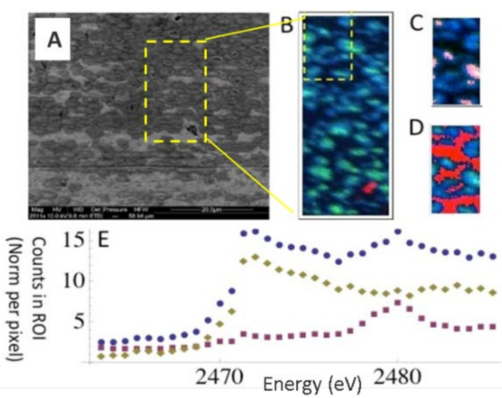
Milestone/Deliverable	Status
Develop/demonstrate focused ion beam (FIB) based electron microscopy technique to probe structure of tribofilms	Completed; Technique now in use
Validate use of x-ray absorption near edge structure (XANES) technique to probe tribofilm chemistry	In progress
Evaluate nanomechanical properties of tribofilms	In progress

PIs: Ajayi, Lorenzo-Martin

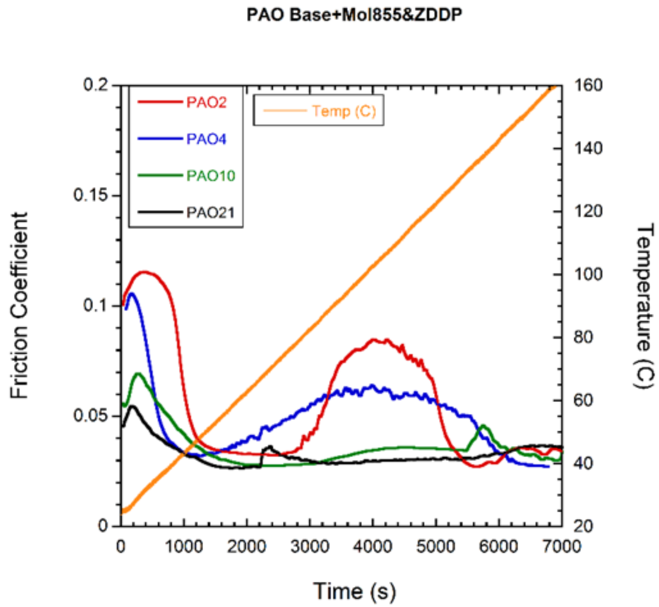
Investigations of Tribofilm Formation - Progress

1. Correlated structure (determined by GIXRD and TEM) with friction and load carrying capability.
   - **Amorphous (A)**: low friction, low load capacity
   - **Nanocrystalline (NC)**: high friction, high load carrying capacity
   - **Mixed (A/NC):** low friction, moderate load-carrying capacity
   - US patent 2015/0087566
2. Demonstrated use of micro XANES and micro x-ray fluorescence to map chemical make-up of thin tribofilms.

MicroXANES map of S and P in tribofilm of a commercial lubricant



3. Peculiar observation on effect of basefluid viscosity on frictional behavior of tribofilms at some temperature range – implications on failure mechanisms



Future Directions

- FIB, XANES, XRF of commercial and advanced lubes
- Friction-viscosity-temperature studies of base and formulated lubricants
- Scuffing mechanisms of power cylinder components
- Nanomechanical properties of tribofilms

Intelligent-Testing, Lab-Engine Correlation - Can lab-scale tests provide meaningful data that correlate with engine/vehicle performance? What are the limitations? Can we establish consistent protocols?

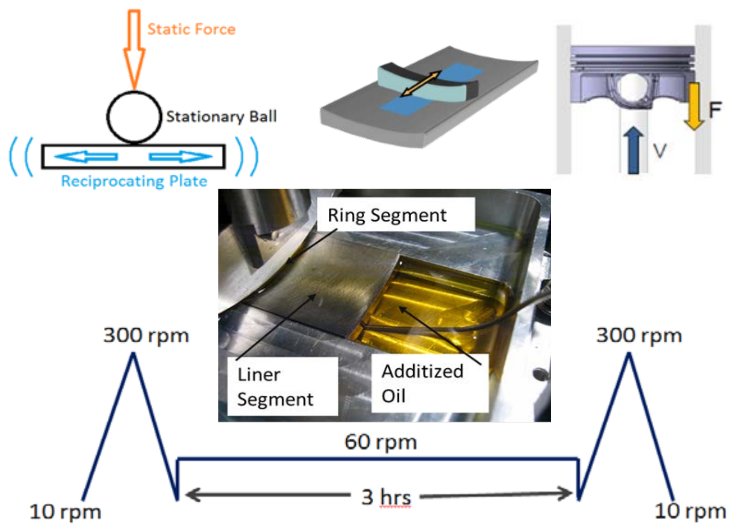
- **Issues/Background:**
  - For cost and time reasons, it is not practical to test every candidate technology in actual engines, on a dynamometer, or in the field.
  - Important tribological parameters such as load, speed, contact geometry, and temperature vary from one component to another as a function of crank-angle, engine speed, and engine load (IMEP) and complicate efforts to correlate the impact of lubricants on performance.
  - Researchers often rely on lab-scale rigs that simulate engine conditions as closely as possible during initial R&D of lubrication systems and then progress to system-level validation.
  - It is critical to understand how different lab-scale rigs vary from one to another, and how operating conditions for a given rig can affect the results to extract meaningful data that can reliably predict system performance.

- **Approach:**
  - Develop test protocols to replicate the wide range of tribological environments that exist in engines and drivelines.
  - Begin with simple geometries, then progress to more complicated engine geometries using actual components:
    - For example, ball-on-flat to cylinder-on-flat to ring-on-liner

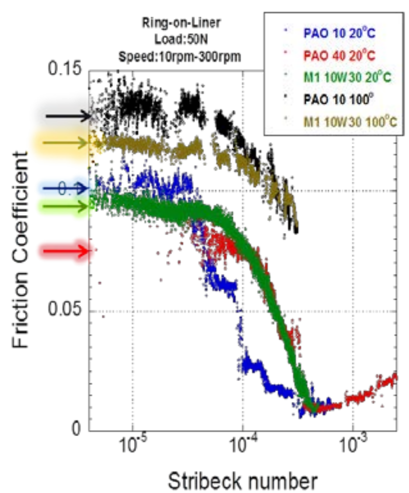
- **Milestones/Deliverables:**

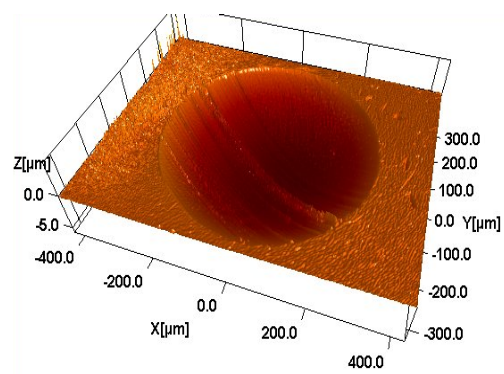
Milestone/Deliverable	Status
Develop ball-on-flat and cylinder-on-flat protocols – speed ramps	Completed and in use
Develop ring-on-liner and skirt-on-liner protocols	Completed and in use
Develop ring/liner scuffing protocols	In progress

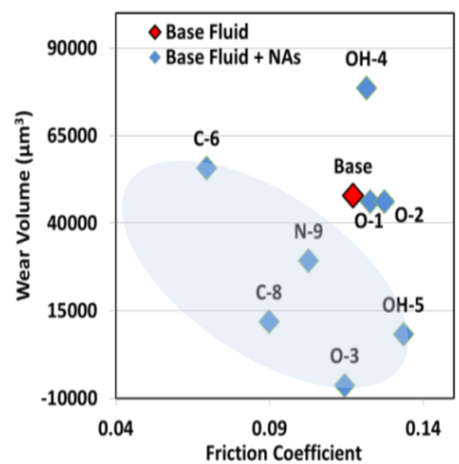
Intelligent Testing – Developing Consistent Test Protocols that Enable Reliable Comparison of Friction and Wear Properties of Different Technologies



- Application of reciprocating ring-on-liner protocols to quantify impact of temperature, speed, and additives (friction modifiers) on friction and wear
- Use of Stribeck curve to extract asperity friction data – avoid conditions that induce mixed and hydrodynamic regimes

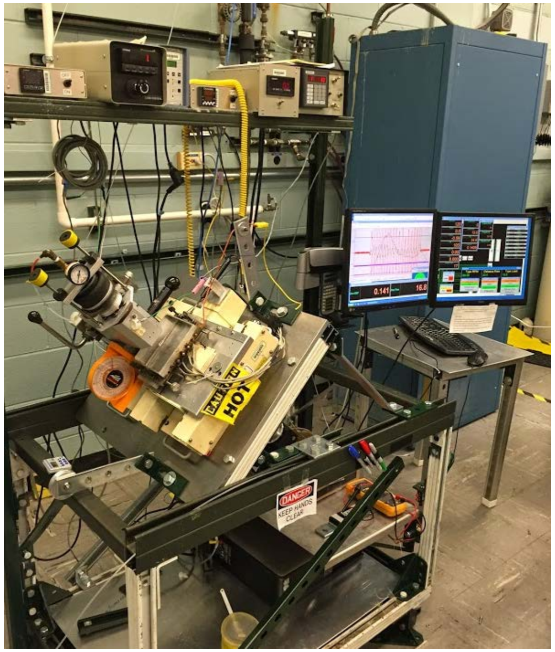






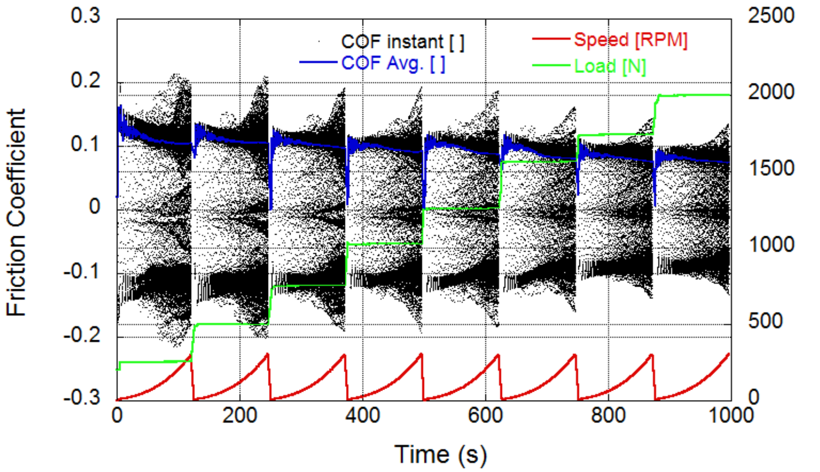
Intelligent Testing - Scuffing, Tilted-Liner Operation

- Develop an adjustable angle reciprocating tribometer (AART) to replicate oil drainage and oil starvation on cylinder liners:
  - Current reciprocating test configuration uses a horizontally mounted liner. The lubricant pools on the liner, which is unrealistic and leads to flooded lubrication.
  - Tilted liner configuration eliminates lubricant pooling, and flooded conditions.
  - Precise oil feed simulates conditions that lead to oil starvation and scuffing.
  - Modification performed in collaboration with a vehicle OEM to transfer in-house test protocols to suppliers.



AART Test Rig

Example of data collected during a short AART test – with load and speed ramps



Future Directions

- Examine impact of temperature, load, and oil supply on scuffing performance.
- Examine the effect of contact pressure, metallurgies, temperatures, speed, oil aging, and soot on friction.
- Develop journal-bearing protocols.
- Develop fuel-dilution test protocols.

Non-Ferrous Coatings - Can one design a coating with enhanced tribological properties? Is it possible to introduce catalytically active elements into a coating and still maintain coating integrity and performance?

- **Issues/Background:**
  - Current engine lubricants are formulated for use with iron-based engine alloys. The resulting additive chemistries are inherently linked to surface chemical reactions with ferrous alloys.
  - Introduction of a non-ferrous based coating would not only retain desired bulk properties of a ferrous-based alloy, but also provide benefits of a thin, chemically active, low-friction, wear-resistant coating.
  - Addition of catalytically active elements in the coating that promote in-situ formation of low-friction polymeric tribofilms offers a solution to reduce the use of SAPS (sulfated ash, phosphorus, sulfur) additives that degrade after-treatment performance.

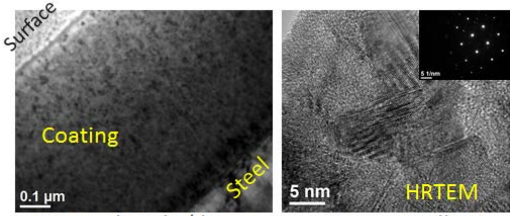
- **Approach:**
  - Argonne is using physical vapor deposition processing to deposit thin (<5 µm thick) nitride coatings that contain catalytically active elements.
  - Advanced lab-scale friction and wear tests coupled with advanced surface analytical techniques are used to optimize coating properties.

- **Milestones/Deliverables:**

Milestone/Deliverable	Status
Design/select candidate coatings (VN-Cu, VN-Ni, MoN-Ni) and characterize mechanical, structural, and chemical properties	Completed
Perform initial friction screening tests and confirm catalytic film formation	Completed
Test alternative nitrides (Ta, Nb) and long-term tribology tests	In progress

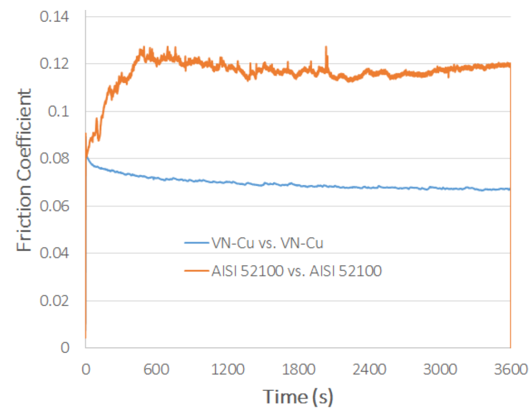
Non-Ferrous, Catalytically Active Coatings - Progress

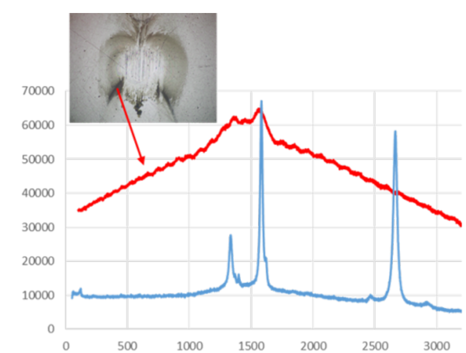
- Developed coating processes to deposit nitride coatings using commercial batch coating system.
  - VN-Cu, VN-Ni, NbN-Ni, NbN-Cu, WN-Ni, WN-Cu, MoN-Ni, etc.
- Completed surface and structural characterization of highly optimized MoN-Cu, VN-Cu, and VN-Ni nano-composite coatings using SEM, TEM and EDS.
- Conducted lab-scale tests confirming low-friction and wear.
- Completed testing of MoN-Cu and VN-Cu coatings in polyalphaolefin base oils and further confirmed the formation of a low-friction carbon-rich boundary film on rubbing surfaces.



Extremely tight/dense Structure

Nanocrystalline





Future Directions

- Analytical and structural characterization of catalytically-derived tribofilm
- Optimization of catalytic alloy composition – lower loading, Pt, Pd, Ag alloying
- Performance with bio-derived lubricants
- Long-term performance tests
- Transition to engine validation

PIs: Erdemir, Eryilmaz, Ramirez

Project Collaborations - Research activities include collaborations with leading industry and academic partners

- **Consortia Memberships**
  - Member of the MIT Lubrication Consortium
  - Member of the OSU Gear Consortium
- **Collaborations with Industry on Funding Opportunity Announcements (FOAs)**
  - FOA 239 (Cummins and Lubrizol)
  - FOA 793 (Ford, and NWU)
  - FOA 991 (Ricardo, Isuzu, ZYNP, Infineum)
- **CRADAs (which have led to focused follow-on projects)**
  - Ricardo
  - Pixelligent
  - XG-Sciences
- **Funded Research (business sensitive)**
  - Vehicle and Engine OEMs
  - Suppliers
  - Lubricant & Additive OEMs
  - Small Businesses (SBIR, STTR)

- **Topics (2-way interactions)**
  - Failure analysis
  - Tribological evaluation (friction and wear)
  - Surface characterization
  - Friction modeling
  - Oil formulation
  - Additive formulation
  - Coatings
    - DLCs, Fe-Boriding, Nitrides
  - Sample/Components for testing
    - Engine blocks
    - Liners, Rings, Pistons
    - Bearings

Response to Reviewers Comments

- Comment: "…authors created a very extensive list of barriers faced by crankcase oil industry. …select one specific area to pursue their interests, for example, HD diesel hardware, LD gasoline hardware, LD diesel hardware…"
  - Response - Many of the challenges in lubricants have common threads – two of the tasks, Study of Phenomenological Mechanisms and Lab-Engine Correlations, identify barriers and develop solutions that will benefit multiple applications (including CI and SI). Specific technology solutions are addressed in the Technology Development Tasks on additives, basefluids, and coatings. Issues addressing specific topics (CI or SI) are often addressed in proprietary work for others (WFO) projects with industry.
- Comment: "…protocols should be firmed up and published… it would be really great if others started using them…"
  - Response – We agree, and efforts are in progress to publish data of lab-scale protocols – both written and through technical meetings. Protocols are being developed in coordination with MIT Lubrication Consortium.
- Comment: \"…The reviewer offered that the most impressive progress was made on Task 1, aligning lab bench tests to engine tests. However, a better definition of the desired engine hardware needs to be put forward…."
  - Response – We agree that a better definition of desired engine hardware needs to be addressed, and that is a core issue when applying lab-scale protocols to engine applications. One of the FOAs mentioned in the collaborations specifically addresses this issue by mapping out the range of Stribeck numbers in different engine components (ring/liner, skirt liner, valvetrain, bearings, etc.) at different engine loads and speeds, and comparing the engine Stribeck numbers with those obtained in the lab-scale test protocols. We believe the lab-scale protocols replicate boundary and mixed lubrication regimes (where surface phenomena dominate) quite well, but are limited in replicating high Stribeck numbers.

Summary

- ANL lubrication projects were re-structured to focus on technology development, improved lab-engine correlations, and fundamental studies of friction and wear mechanisms.
- Lab-correlation protocols have been established that include speed, load, and temperature ramps coupled with intermediate steady-state operation to mimic break-in. The protocols can discriminate the effect of friction modifiers on asperity friction – care must be taken to interpret the friction data.
- The reciprocating test rig was modified for tilted-liner operation to better simulate oil supply in power cylinder components.
- Advanced analytical techniques based on FIBs and x-rays were developed and applied to characterize the structure and chemistry of thin tribofilms. Significant differences in structure were observed and correlated with frictional performance.
- An unanticipated trend on friction as a function of temperature at different viscosities was observed and is currently being examined using advanced surface analytical techniques to determine if changes in structure/composition can account for the friction trends.
- Lab-scale tests coupled with detailed surface analysis of the tribofilms formed on catalytically active coatings demonstrate that significant improvements in friction and wear are achievable.

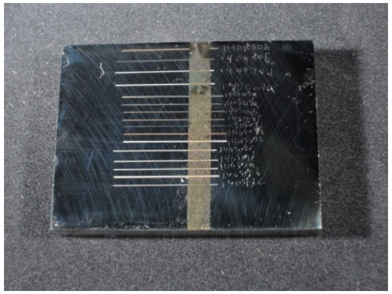
Thank-You

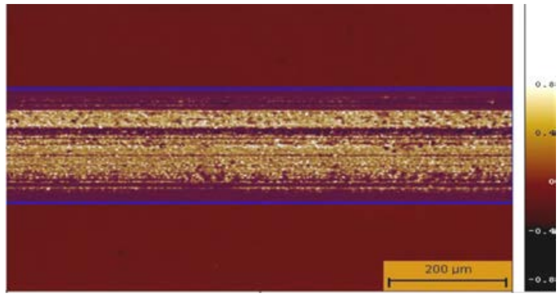
Questions?

BACKUP SLIDE

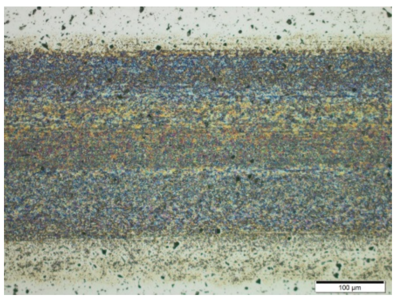
Different Ways to Image Tribofilms

Naked Eye

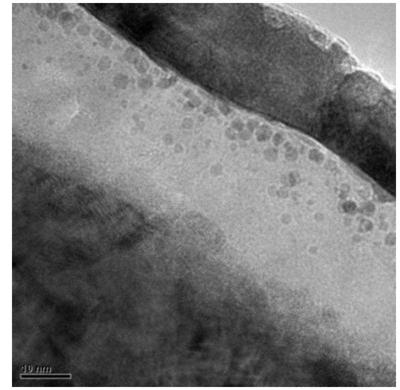




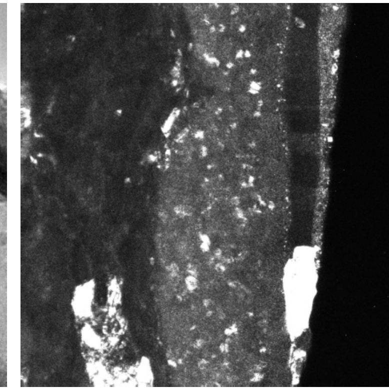
White Light Interferometry

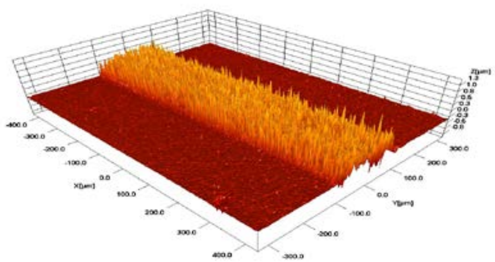


TEM Bright Field

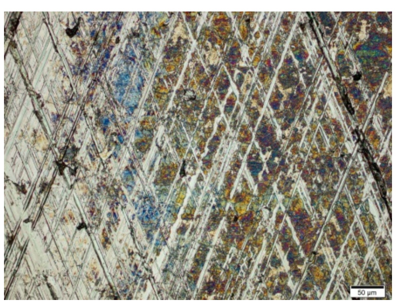


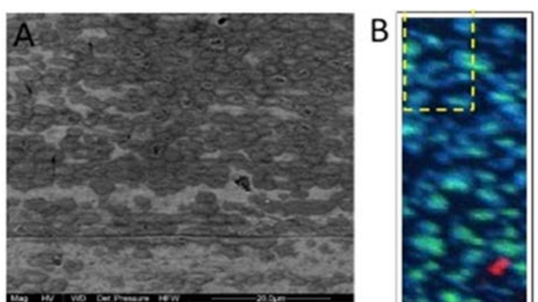
TEM Dark Field





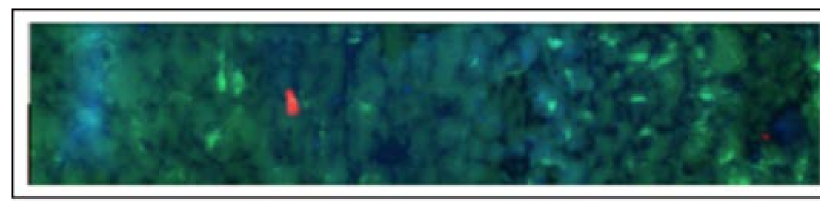
Optical

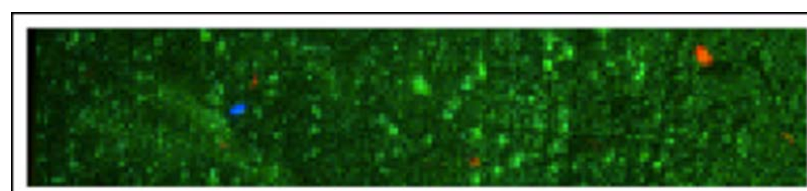




SEM

Micro Xray Fluorescence





Micro XANES