Engine Friction Reduction Technologies

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Overview

Timeline

▪ Project start date	FY 13
▪ Project end date	FY 18
▪ Percent complete	20%

Budget

▪ FY 13 Project Funding	$1250K
▪ DOE Share	$1140K
▪ Contractor Share*	$110K
▪ FY 12	$500K

* CRADA in-kind & funds-in contributions

* Incremental support for start of new projects

Barriers - see slides 4 & 9

- Improve the mechanical efficiency of internal combustion engines by 10% without causing increased wear, emissions, or damage to the emission after-treatment system.
- Improve researchers' understanding of the relationship between the results of benchtop and engine tests.
- Develop additives to lubricants that enable the use of higher levels of biofuels.

Partners

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

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

- With nearly 250 million vehicles on the road, the U.S. consumes 12-13 MBBL/day. Of this approximately 10% is lost to overcome engine friction, and another 5 % is lost to friction in the driveline (transmission, axles, bearings) – i.e., 1.5 to 2 MBBL/day is lost to friction.
- Reducing engine and driveline friction by 10% would reduce petroleum consumption by 150,000 to 200,000 BBL/day if applied to NEW and LEGACY vehicles.
- DOE is establishing lubrication goals:
  - Reduce parasitic friction in legacy vehicles by 10%, resulting in fuel efficiency improvements of 1-2 %.
  - Reduce parasitic friction in new vehicles by 50%, resulting in fuel efficiency improvements of 5-7 %.
- The tasks developed for this project address critical barriers to the development of advanced fuel efficient lubrication concepts:
  - Improved lab-engine correlations
  - Understanding of how additives interact to form low-friction protective tribofilms
  - Development of specific technologies (additives, basefluids, and other materials)

Listed below are specific references that link the relevance of advanced lubrication to DOE/VTO efficiency goals.

- **Lubricants Program Goals and Missions (VTO Website):**
  - Developing better base oils and oil additives that may have the potential to improve the mechanical efficiency of internal combustion engines by 10%.
  - Work to improve researchers' understanding of the relationship between the results of benchtop and engine tests when studying friction and wear performance data. This work will help improve standards and the accuracy of future research.
  - Investigating lubricants that can improve the mechanical efficiency of internal combustion engines by 10% without causing increased wear, emissions, or damage to the emission after-treatment system. This includes the potential of using ionic liquids (salts in a liquid state) as lubricants or lubricant additives, which research has shown may have 30% less friction than comparable lubricants.
  - Developing and optimizing tribochemical films (the protective layer that forms on metal surfaces when using oil additives) to reduce friction, reduce wear, and improve fuel economy.
  - Developing additives to lubricants that enable the use of higher levels of biofuels (such as intermediate blends of ethanol) in non-flexible fuel vehicles currently on the road.
- **Vehicles**
  - 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, enabling up to 80% of the energy for light-duty vehicles to be from non-carbon or carbon-neutral energy sources.
- **Heavy-Duty Vehicles**
  - By 2015, demonstrate a 50% improvement in freight hauling efficiency (ton-miles per gallon).
- **21st-Century Truck**
  - Develop and demonstrate parasitic friction reduction technologies that decrease driveline losses by 50%, thereby improving Class 8 fuel efficiencies by 3% (Roadmap and Technical Papers – 21st Century Partnership, Feb 2013).
- **Advanced Vehicle Power Technology Alliance** - Department of Energy**/** Department of Army Technical Workshop and Operations Report (Oct. 2011)
  - Alternative fuels and lubricants - increase fuel economy 1-3 % (engine), 2% (driveline).
- **35/55 mpg CAFÉ Standards – Multiple technologies will be required to achieve current and future CAFÉ standards.**

Goals/Objectives of Lubrication Project

- **Goals of Lubrication Activities:** DOE initiated a Lubricant Program to develop lubrication science and technologies that reduce parasitic friction losses in vehicles (e.g., engines and drivelines) and improve fuel economy. The tasks associated with the ANL Lubrication Project have two major goals:
  - **Next Generation Lubricants:** Develop advanced lubricant system (lubricant and engineered surfaces) to reduce parasitic friction losses by 50% and increase fuel economy by 5-7% in **NEW** vehicles.
  - **Legacy Vehicle Lubricants:** Develop advanced lubricants (base fluids and additives) to reduce parasitic friction losses by 10% and increase vehicle economy by 1-2% for **EXISTING** vehicles.
  - The technologies should maintain or exceed requirements for other performance metrics (reliability, durability, compatibility with alternative fuels, etc.) and be compatible with advanced engine concepts/technologies and materials.

- **In FY 13/14, DOE Lubrication Projects at Argonne were re-structured into 3 main tasks consistent with EERE AOP guidelines:**
  - Improved lab-engine correlation
  - Phenomenological studies of tribofilm formation
  - Lubricant technology development (lubricant basefluids with enhanced viscometric properties, lubricant additives with enhanced boundary friction and wear properties, CRADAs, and non-ferrous coatings with enhanced tribological properties)

Long-term (project) and near-term milestones for the ANL Lubrication Project

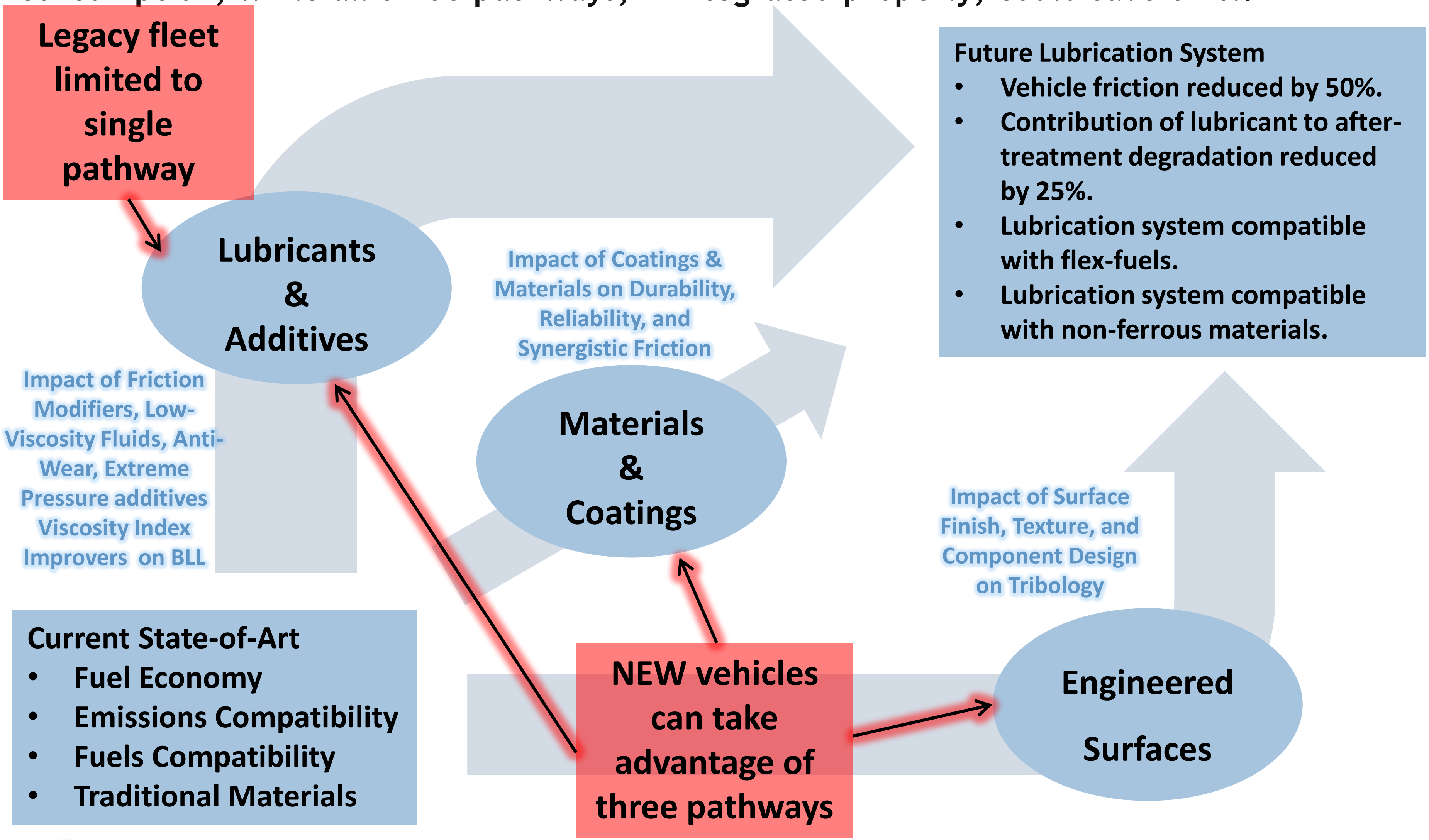
- **Long-Term Project Goals**
  - Develop improved lab-scale test protocols and data analysis procedures that: 1) better replicate engine and driveline tribological environments and 2) provide data that can more accurately predict friction and wear performance in vehicles.
  - Understand the physics and chemistry associated with the formation of thin low-friction, wear-resistant tribofilms to enable design of lubricants from a mechanistic framework rather than traditional Edisonian trial-and-error methodologies.
  - Develop advanced lubrication concepts that reduce parasitic friction losses while maintaining or improving reliability and durability of components. Develop advanced tribological concepts that enable use of alternative fuels and engine design concepts.
- **Near-Term (AOP Specific) Milestones (FY13/14)**
  - Make go/No-go decision on continued development of polyoxometalate supermolecules for friction reduction (Dec. 2013 – **Completed**).
  - Develop protocol to simulate oil control ring conditions using lab-scale reciprocating rig (March 2014 – **Completed**).
  - Complete focused ion beam (FIB) analysis of nano-oxide additives in unformulated oil (June 2014).
  - Complete Phase I CRADA activities on XG-Science graphene additive (Sept. 2014).

An approach and strategy was developed in concert with DOE, industry, and academia to identify targets on efficiency, pathways, solutions, and barriers to achieving targets

- Working with industry (site visits) and DOE, we identified potential pathways/solutions to develop advanced lubrication concepts for improving fuel economy (35/55 mpg). Identified barriers to the advanced solutions and initiated projects to address barriers.

- **Issues identified:**
  - Impact of basefluid viscometrics and additives on fuel economy (lubricant formulation – basestocks and additives)
  - Constraints associated with emission requirements and lubricant chemistry – lowering limits on beneficial additives that degrade after-treatment systems
  - Impact of alternative fuels (biofuels and compressed natural gas) – compatibility of lubricants with diluted fuel
  - Impact that lightweighting concepts (size reduction and nontraditional materials) have on friction reduction and reliability/durability
  - Identified role that bio-based basefluids may have on improving performance of bio-derived lubricant
  - Engineered surfaces – impact of advanced surface textures on lubrication regimes

Multiple pathways identified to improve fuel efficiency with advanced lubricant systems include: advanced lubricants (applicable to new and legacy vehicles), novel coatings and materials, and engineered surfaces. Advanced lubricants can save 2-3% in fuel consumption, while all three pathways, if integrated properly, could save 5-7%.



Identified <u>barriers</u> and program approach to develop advanced energy-conserving lubricants. After identifying barriers, major tasks were developed to address barriers.

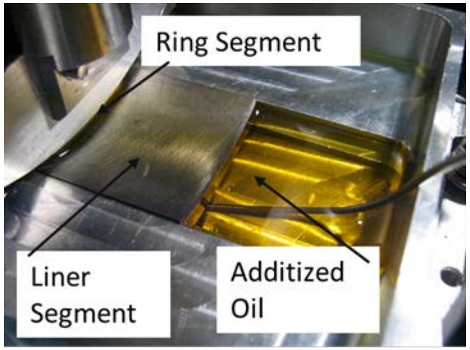
- **Barriers** to achieving goals and targets identified:
  - **Inadequate data and predictive tools**: ability to predict impact of advanced technologies on fuel economy, impact of alternative fuels on lubricant performance, interaction of additives and chemistry with ferrous and non-ferrous materials, information on mechanical efficiency of accessories – **Basis for Task 2 (Phenomenological Modeling of Tribofilm Formation)**
  - **Limited basestocks and additive formulations (one size may not fit all):** competition of friction modifiers with antiwear additives; introduction of advanced concepts (turbocharging, cylinder deactivation, biofuels, 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 – **Basis for Task 3 (Lubricant Technology Development)**
  - **Limited validation:** poor fidelity between benchtop tests with well-defined configuration and controlled environments to complex, integrated systems (engines, drivetrains) with widely varying operational cycles; poor extrapolation of science-based models to engineered continuum models/simulations – **Basis for Task 1 (Lab-Engine Correlation)**
  - **Cost to develop and certify advanced lubricants (time consuming and expensive):** changing certification requirements – cost to develop a new engine sequence protocol in excess of $5M, and lengthy (up to 6 years). Sequence tests are expensive ($100K/run).

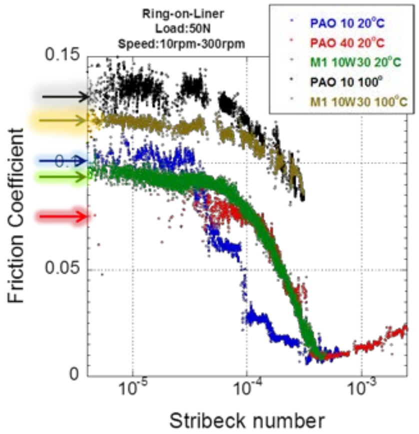
Project has three major tasks.

- **Improved Lab-Engine Correlation:** Objective is to develop test protocols and data analysis techniques to improve the fidelity of lab-scale tests to replicate the tribological environment present in engines and driveline components, and to improve the value of the lab-scale data to predict engine and driveline performance.
- **Phenomenological Studies of Tribofilm Formation:** Objective is to develop and apply advanced surface analytical techniques based on electron and x-ray microscopy to study the structure and chemistry of thin protective tribofilms and understand the physical mechanisms involved in their formation and performance.
- **Lubricant Technology Development:** Objective is to develop advanced tribological concepts and technologies to reduce friction and improve reliability and durability.
  - Lubricant basefluids with enhanced viscometric properties
  - Lubricant additives with enhanced boundary friction and wear properties
  - CRADAs with industry to evaluate innovative lubrication concepts
  - Non-ferrous coatings with enhanced tribological properties

Technical Accomplishment - Lab-Engine Correlation Task

- Issue: It's too expensive to use an engine or vehicle as a development tool for advanced lubricants and materials. High-fidelity lab-scale techniques are required to perform initial screening and development work followed by engine/vehicle validation.
- Argonne's approach uses widely accepted test techniques and carefully selects lab conditions (load, speed, temperature, and viscosity) that replicate lubrication regimes in engines:
  - Boundary or asperity lubrication
  - Mixed lubrication
  - Hydrodynamic lubrication
- Experimental friction and wear data are used to design new lubricants and to model impact of lubrication concepts on fuel economy.





Figures above illustrate the use of a reciprocating rig developed to simulate ring-on-liner conditions, and how the data are analyzed to extract boundary friction coefficients used in ring/liner simulation codes.

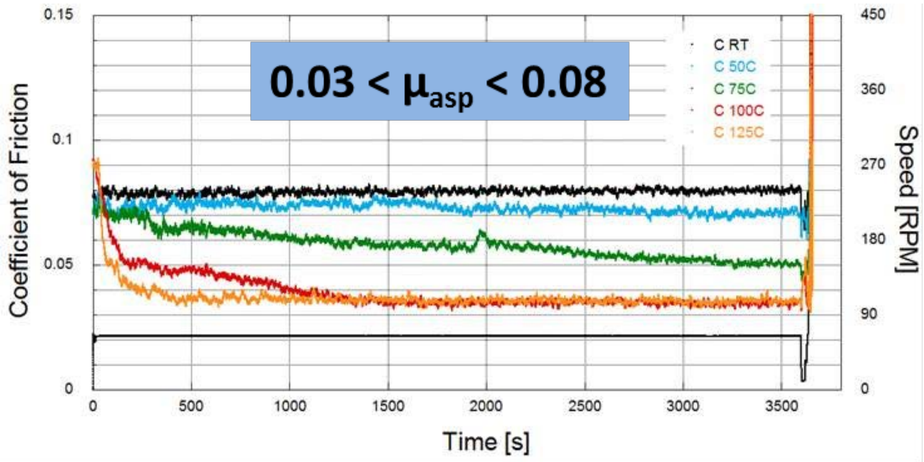
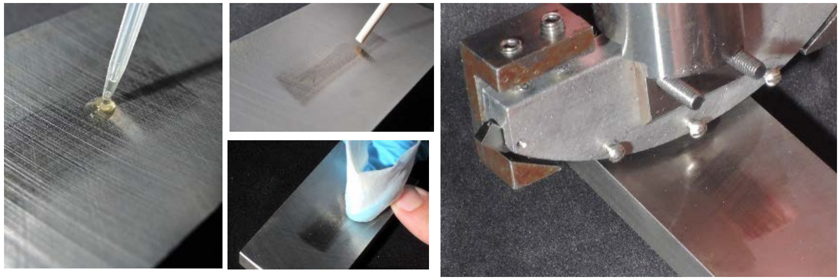


Figure above illustrates the impact of temperature on boundary friction of fully formulated lubricant.

Technical Accomplishment – Lab-Engine Correlation Task: Oil Control Ring (OCR) Investigation

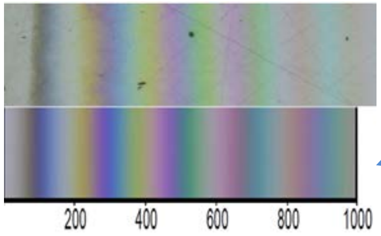
- Issue: The focus of this study was to determine how much oil is required to replicate conditions in the ringpack of an engine during lab-scale tests. Studies (Taylor & Morgan – Shell) show that when the inlet supply of oil is in the range of 5 to 10 µm, the ring can be considered "flooded," and further increases will not change the predicted oil film thickness in the contact zone. For oil supply thicknesses less than 5 to 10 µm, the predicted oil film thickness in the contact zone decreases, a condition called "starved" or "partial" lubrication, and the friction increases due to increased asperity contact.
- The results demonstrate that the inlet supply of oil can be accurately controlled during a lab test; however, the fact that the friction transitions from mixed to boundary quickly suggests it will be necessary to "re-supply" the contact zone during extended lab tests.
- The studies reported below also demonstrate that color interferometry can quantify oil film thicknesses up to several µm.



Apply 0.025 ml of oil

Smear out thin and remove 95%

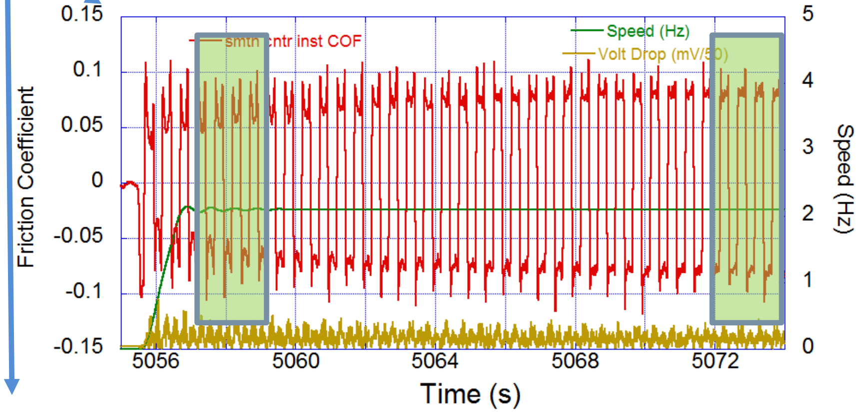
That leaves an oil thickness of about 4 µm



ANL-developed correlation chart for liquid films on surface

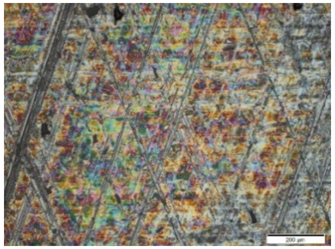
Industry-standard correlation chart for solid films on surface

When the colors disappear, the thickness should be about 2 µm.

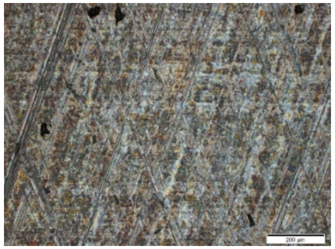


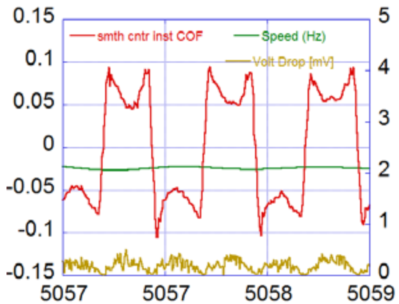
- Air blow-off should reduce the oil thickness to < 2 µm and produce starved conditions – **future activity.**

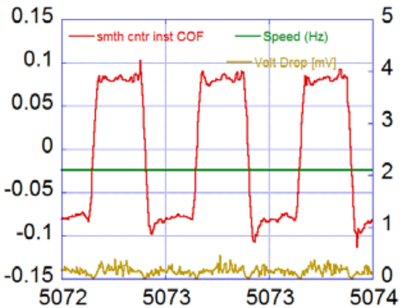
Before air blow-off oil is present



After air blow-off oil is removed

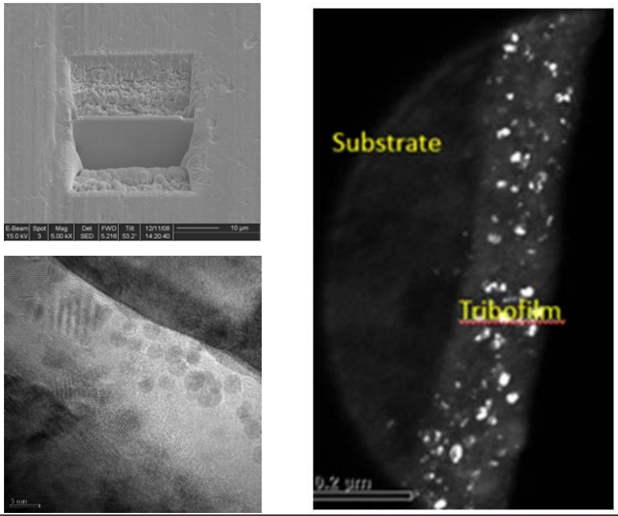


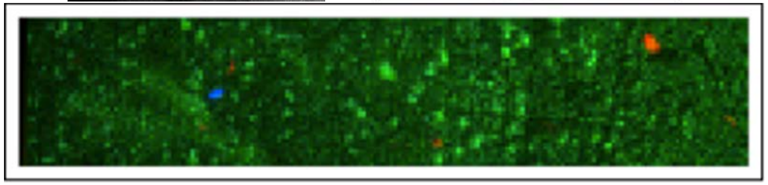




Technical Accomplishment on Phenomenological Studies Task

- Issue: How lubricant additives interact to form low-friction, protective films on engine components is unknown. Development is largely by trial-and-error, and information on underlying film formation mechanisms is needed to guide development of new lubricants.
- Argonne is applying advanced surface analytical techniques to investigate the structure and chemistry of tribofilms.
- Progress: FIB/TEM analysis was used to characterize thickness and structure of tribochemical films from variety of model and commercial additive systems:
  - Films are 50 to 120 nm in thickness.
  - Films are all amorphous, all crystalline, or a mixture.
  - Frictional behavior and durability of film depend on structure.
  - Transitions are often observed in film behavior, depending on temperature and contact load.



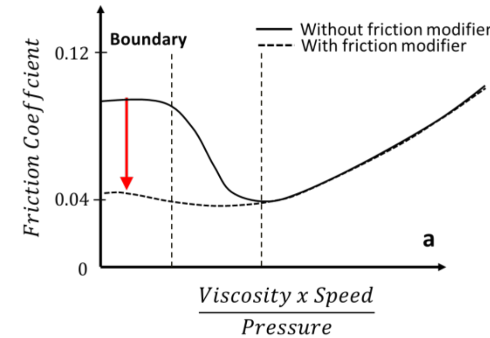


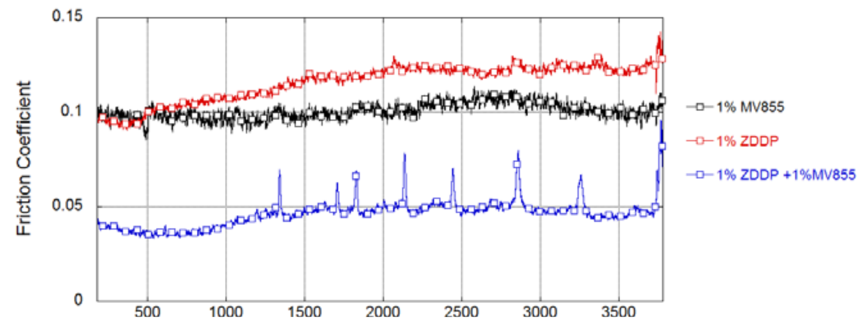
XANES map of P (green), S (blue), and Al (red)

- Future Activities:
  - Design and produce tribochemical film with optimized structure for friction and wear behavior.
  - Combine engineered tribochemical films with low viscosity base fluid for friction reduction in all lubrication regimes.
  - Correlate nanomechanical properties of tribofilm with structure and chemistry.

Technical Accomplishment on <u>Advanced Additives Task</u>

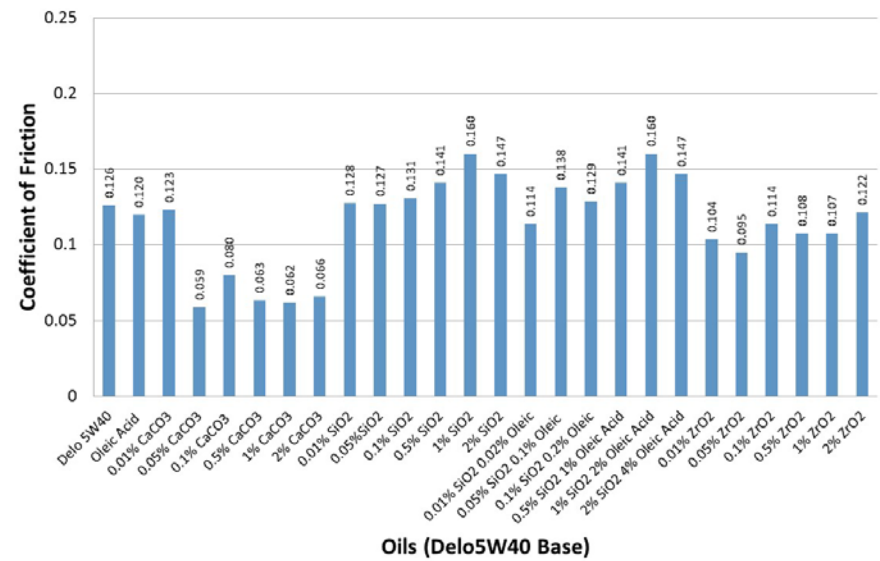
- Issue: Parasitic friction arises from metal-metal contact and viscous shear. Low-friction additives, either liquid or solid, can significantly reduce metal-metal friction.
- Argonne is evaluating the performance of advanced friction modifiers as a route to reduce asperity friction and improve fuel economy.
- <u>Progress</u>
  - Reactive additives combined with friction reduction under boundary regime.
  - Several encapsulated nano-particulate additive systems provided significant friction and wear reduction in comparison with current advanced lubricants.
  - Preliminary results on the effect of operating condition, concentration, and encapsulator indicate pathway to system optimization.
- <u>Future Activity</u>
  - Mechanistic study of good nano-additive systems
  - Assessment of nano-additive combinations
  - Evaluation of scuffing performance attributes of nano-additive system





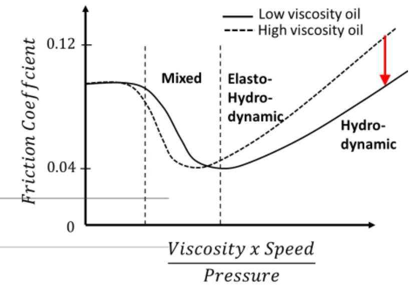
CSEM – Average Coefficient of Friction

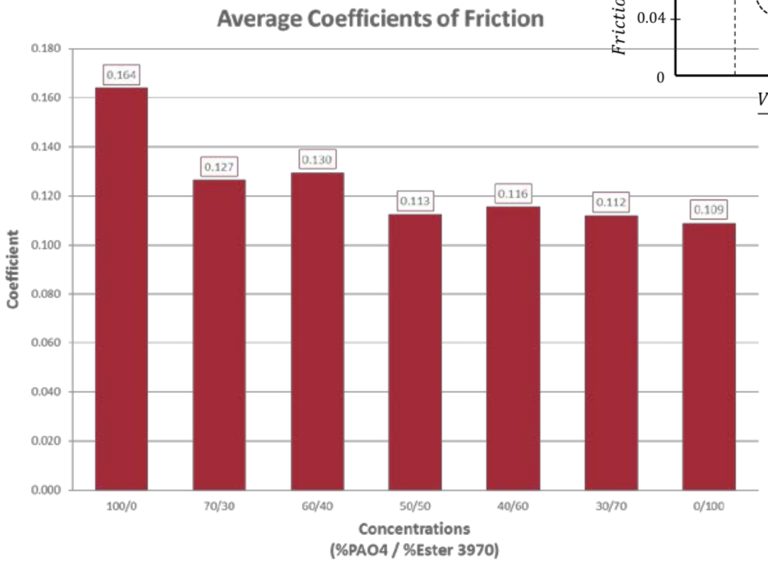
All tested with Delo5W40 Base at 100C



Technical Accomplishment on Hybrid Basefluids Task

- Issue: The viscous shear component of parasitic friction losses can also be reduced by utilizing low-viscosity basefluids.
- Argonne is evaluating the performance of advanced hybrid basefluids comprised of Grp IV (PAO) and Grp V (esters) to reduce viscous shear under mixed and hydrodynamic conditions.
- **Progress**: Demonstrated control of base fluid viscometric properties for sustainable friction reduction over a wide range of temperature (-30^{o}C to 150^{o}C) for Grp IV/V basefluids.
- **Future Activity**
  - Perform mechanistic modeling of molecular interactions in fluid mixture.
  - Evaluate the impact of different boundary additive systems on mixed fluid tribological performance.
  - Optimize fluid and additive systems for friction and wear reduction under different contact conditions.





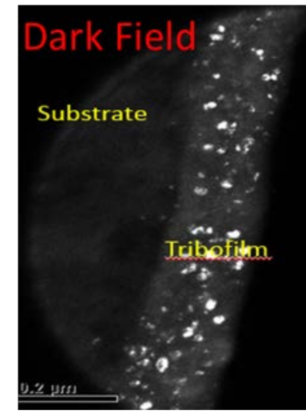
Fluid	40°C Viscosity (cSt)	100°C Viscosity (cSt)	Viscosity Index	-30°C Viscosity (mPa-s)
100% PAO4 base	18.2	4.02	120	1307
70% PAO4, 30% Ester	17.8	4.06	130	1067
60% PAO4, 40% Ester	17.9	3.95	117	999
50% PAO4, 50% Ester	17.9	4.01	123	941
40% PAO4, 60% Ester	18.3	4.16	133	900
30% PAO4, 70% Ester	18.4	4.34	150	859
100% Ester 3970	19.6	4.33	132	842

Take Home Message on CRADAs/WFOs: Argonne is working with businesses to evaluate innovative additives and materials. Our work focuses on quantifying friction and wear performance and understanding how industrial additives function.

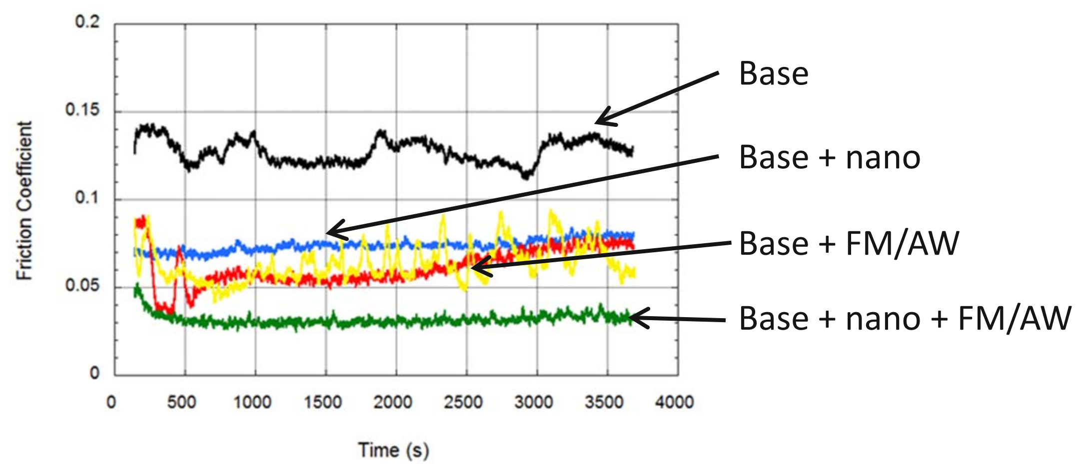
- Argonne is working with industry to evaluate friction and wear performance of proprietary additives, materials, and coatings.
- CRADAs include:
  - Pixelligent (nano-oxide) additive
  - Xg-Sciences (nano-graphene)
- Progress:
  - Experimental data developed on the impact of nano-oxide material on viscosity (negligible change), suspension (excellent), friction, wear, and structure.
  - Experimental data developed on the impact of GrP powders on friction, wear, and suspension properties.

Base + nano	FF no FM + nano	FF no FM + CA1	FF + CA#1	FF + nano	Base + CA1

Capping agent used to suspend nanoadditives can affect other additives in FF oils



Synergism between nanoadditives and FMs/AW additives

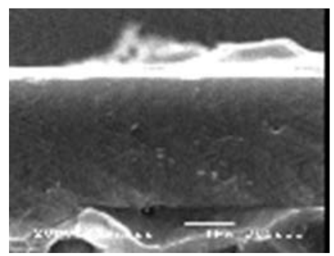


Take Home Message on Non-ferrous Coatings: Most lubricants are formulated for a ferrous-based chemistry. Coatings present a separate pathway to change the surface chemistry and lower boundary friction to reduce parasitic friction losses and achieve excellent wear resistance.

- Argonne has a long history in the development of advanced coatings for tribological applications:
  - Diamondlike carbon (DLC), superhard nano-composites, ultrafast boriding
- OEMs are all looking at coatings as a pathway to improve fuel economy.
- The ANL research is identifying novel coatings that can form low-friction films *in-situ*.

Identify

Design

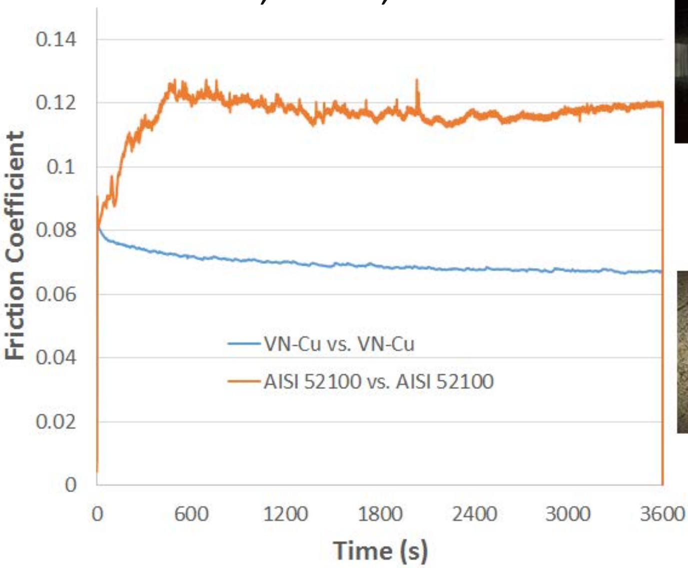


Synthesize/ Characterize & Test

Demonstrate/ Deploy

Technical Accomplishment on Non-ferrous Coatings: The non-ferrous coating activity on VNCu coatings was initiated in FY14. During this time, activities focused on procurement of deposition hardware (targets), optimization of deposition conditions to form adherent coatings, and preliminary tribological evaluation of coated test coupons.

100°C, 1 GPa, PAO 10



- Preliminary tribological performance of VNCu coating coupons is encouraging. Despite high contact loads, a significant reduction in friction is observed with negligible wear.

Future Activities

- Evaluation of tribological performance in formulated lubricants.
- Characterization and confirmation of DLC-like boundary film formation on non-ferrous coating.
- Evaluation of other non-ferrous nitride-based coatings.
- Demonstration/validation of concept on engine components (with industry collaboration).

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-engine correlation activity has developed reciprocating rig test protocols that more closely replicate power cylinder conditions. Previous activities focused on geometrical, load, speed, temperature, and time requirements to replicate engine conditions. Recent activities have addressed levels of oil supply needed to replicate engine component conditions – how much oil should be applied. We identified color interference methods to measure amount of oil present and demonstrated that starved-lubrication conditions need to be replenished during long-term tests. These capabilities are being applied in several WFO projects to evaluate proprietary engine lubricants and low-friction coating treatments.
- 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.
- Viscometric characterization of advanced Grp IV/V hybrid basefluids (PAO/ester) demonstrated one can optimize cold crank viscosity, kinematic viscosity, viscosity index, and high-temperature high-shear properties.
- Benchtop tests on functionalized nanoparticles demonstrated that significant reductions in boundary friction are feasible.
- Preliminary tribological studies of VNCu coatings exhibited excellent wear resistance and significant reductions in friction.
- CRADA activities on oxide and graphene nanoadditives demonstrated improved friction and wear properties.

Future Activities

- Lab-Engine Correlation
  - Develop test protocols to include both speed and load ramps to better replicate changing load and speed conditions in an engine.
  - Current protocols use either hardened steel ball/cylinders sliding against hardened steel flats or prototypic ring/skirt segments sliding against liner segments. Future activities will explore the use of ring and/or skirt segments sliding against cast iron flats (polished or "honed"). This combination will better replicate interfacial chemistry conditions that occur in an engine.
  - Continue refining the investigation of how much oil is required to simulate starved and flooded lubrication – quantify frictional response as function of oil supply thickness.
- Phenomenological Mechanistic Studies
  - Design and produce tribochemical film with optimized structure for friction and wear behavior.
  - Combine engineered tribochemical films with low viscosity basefluid for friction reduction in all lubrication regimes.
  - Correlate nanomechanical properties of tribofilm with structure and chemistry.
- Hybrid Basefluids
  - Perform mechanistic modeling of molecular interactions in fluid mixture.
  - Evaluate the impact of different boundary additive systems on mixed fluid tribological performance.
  - Optimize fluid and additive systems for friction and wear reduction under different contact conditions.
- Advanced Additives
  - Perform mechanistic study of good nano-additives systems.
  - Assess nano-additive combinations.
  - Evaluate scuffing performance attributes of nano-additive systems.
- Coatings
  - Evaluate tribological performance in formulated lubricants.
  - Characterize and confirm DLC-like boundary film formation on non-ferrous coating.
  - Evaluate other non-ferrous nitride-based coatings.
  - Demonstrate/validate concept on engine components (with industry collaboration).

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

- **Oil/Additive OEMs:** Work with multiple additive and oil OEMs who supply specialty blends of lubricants and additives for use and evaluation in all three tasks. Interactions are often collegial in nature; others are performed under NDAs; while others are performed under WFO arrangements.
  - BP, Shell, Chevron, Exxon-Mobil, Valvoline, Infineum, Lubrizol, Afton, Pixelligent, and Xg-Sciences are examples.
- **Vehicle, Engine, Supplier OEMs:** Work with multiple vehicle, engine, and component suppliers who supply materials/components for use in tests as well as advice and software for use in simulation activities (under a separate DOE/VTO project). Interactions can be collegial in nature or formal (e.g., CRADA, subcontract to DOE FOAs, or WFO).
  - Mahle, Ricardo, Ford, + multiple companies (NDA-sensitive)
- **Academia/Consortium:** Argonne is a member of an MIT Lubrication Consortium investigating the impact of lubricants and oil transport and friction in ringpack designs. It specializes in the simulation, validation, and *in-situ* visualization of oil flow in fired engines, and *in-situ* measurement of power cylinder friction. Our involvement focuses on lab-scale simulation of trends observed in their simulation and *in-situ* measurements of friction mean effective pressure. Consortium membership includes major oil companies, part suppliers, and vehicle OEMs.