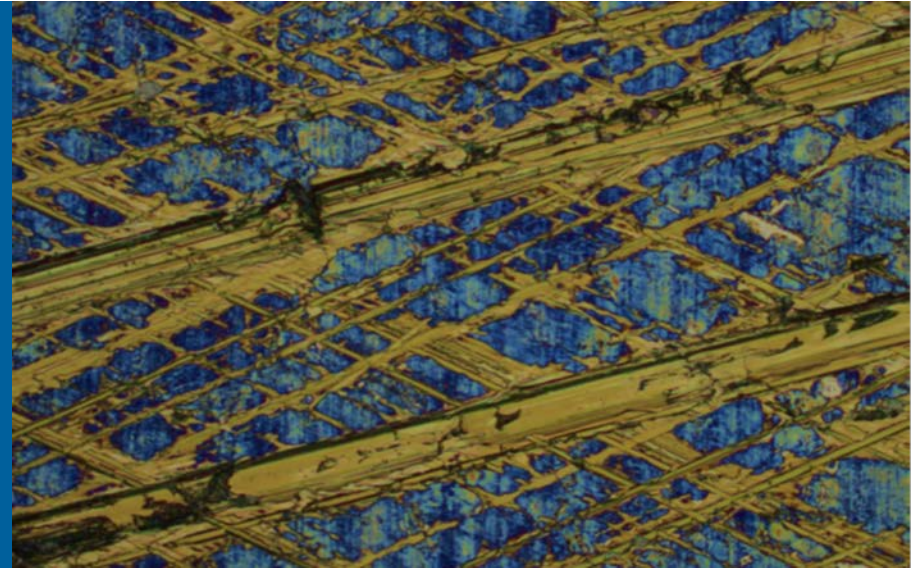


## **ENGINE FRICTION REDUCTION TECHNOLOGIES**



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Argonne National Laboratory  
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Project ID # FT012  
ft012\_fenske\_2016\_o

# OVERVIEW

## Timeline

**Project start date FY 13**

**Project end date FY 19**

**Percent complete 60%**

## Budget

<u>FY 15 Funding</u>	<u>\$1488K</u>
DOE	\$1228K
SPP	\$260K

<u>FY 16 Funding</u>	<u>\$1452K</u>
DOE	\$1202K
SPP	\$250K

## Barriers

- 10-15% energy consumed in transportation lost to parasitic friction in engines and drivelines.
- Low-viscosity lubricants improve fuel economy, but present challenges to reliability and durability.
- Introduction of transformational technologies present new challenges to lubricant performance.

## Partners

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

# RELEVANCE & GOALS

**10-15% energy consumed in transportation is lost to parasitic friction in engines and drivelines**

## Relevance

- Fuel economy/emissions
  - Café 2025 – 55 mpg
  - Supertruck – 55% BTE
  - GHG emissions
- Reliability/durability/new technologies
  - After treatment
  - Gasoline direct injection
  - Alternative fuels (*Co-Optima*)
  - Downsizing, downspeeding, power boosting



## Goals

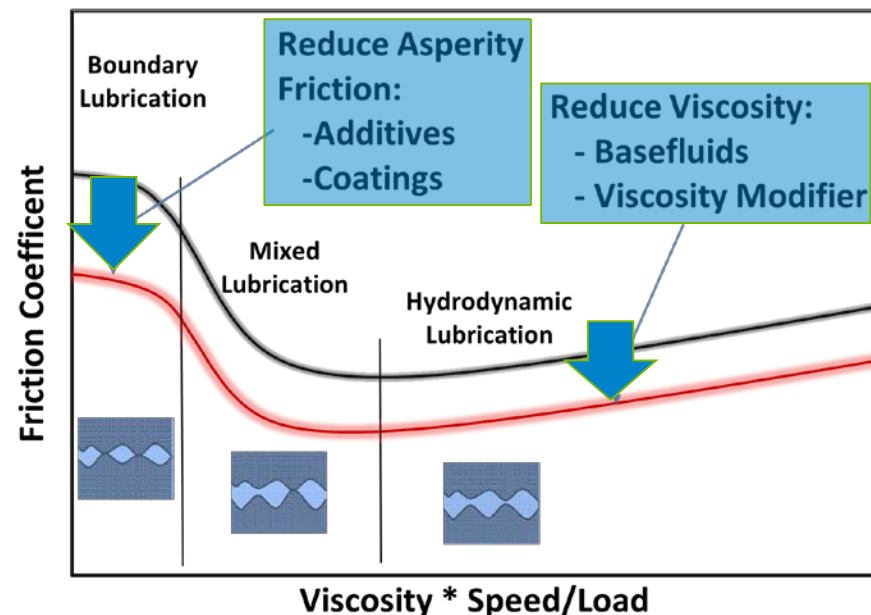
- Understand how lubricants, additives and materials interact and respond to environmental parameters that affect degradation and performance (friction, wear and durability).
- Develop lubricants, additives and materials/coatings that reduce frictional losses to improve fuel economy and enable implementation of transformational fuel efficiency technologies.

# PROJECT APPROACH

Multiple approaches identified; tasks structured to address barriers and technology development

## Approaches to reducing frictional loss

- Basefluids: composite basefluids with high viscosity index.
- Additives: colloidal compounds that lower asperity friction.
- Coatings: non-ferrous coatings that catalyze formation of low friction carbonaceous films.



**Barriers: Inadequate data and predictive tools, limited base stocks and additives, and limited cost-effective validation**

- Tribofilm Formation Mechanisms: determine how protective films form.
- Lab-Engine Correlation: determine how to best replicate engine conditions.

# INNOVATIVE 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

- Lab tests provide valuable performance information to optimize lubricant formulations prior to costly and time-consuming engine/fleet tests.
- A critical understanding is needed on how different lab-scale rigs vary from one to another, and how operating conditions for a given rig can affect the ability to extract meaningful data that can reliably predict system performance.

## Approach

- Develop and assess lab protocols to replicate the wide range of tribological environments that exist in engines and drivelines.
- Begin with simple geometries, then progress to more complicated geometries using actual components.

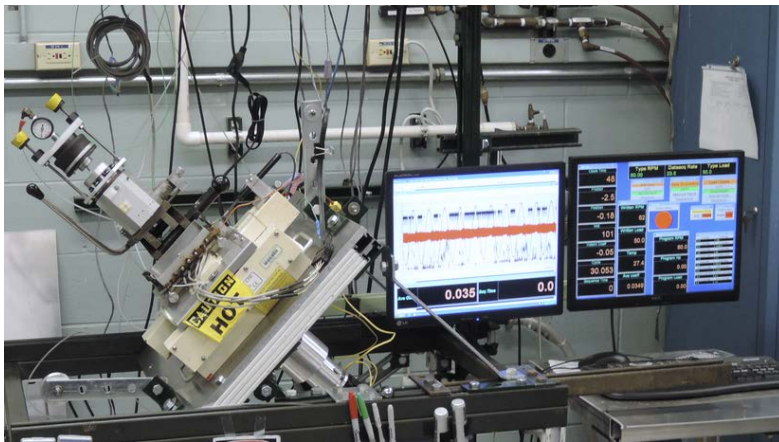
Milestone/Deliverable	Status
Developed ball-on-flat and ring/skirt-on-liner protocols	Completed & in use
Developing ring/liner protocols to simulate scuffing (load, temperature, oil supply)	In progress



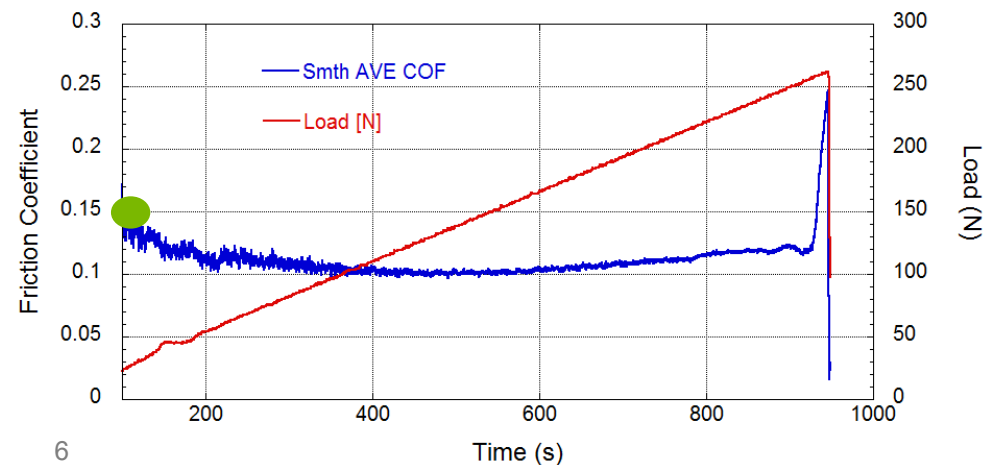
# LAB-ENGINE SIMULATION OF SCUFFING

**Accomplishment/Progress:** developed and validated scuffing protocols that replicate power cylinder scuffing working with industry and academia consortia

- Precise control of oil feed to ring/liner interface before and during loading.
- Tilted operation to replicate engine environment and to avoid pooling of oil at the ring/liner interface.



*Friction and load as functions of time during scuffing test*

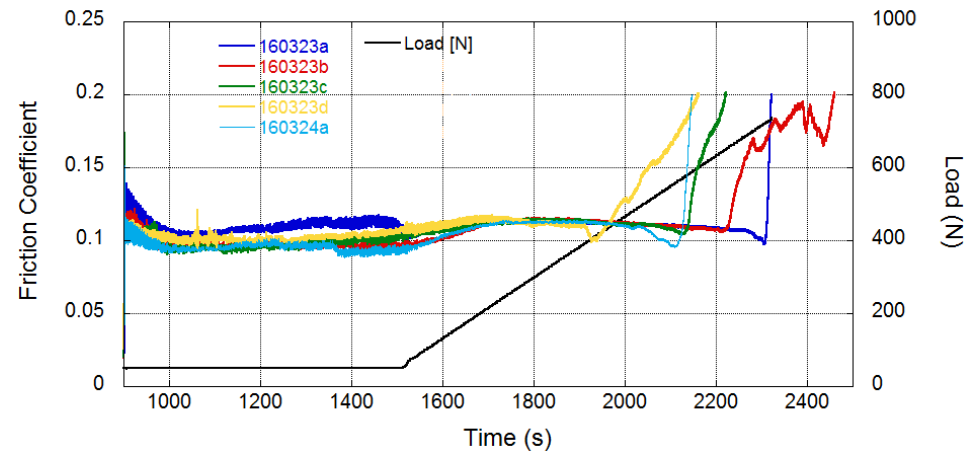


# LAB-ENGINE SIMULATION OF SCUFFING

## ***Accomplishments/Progress:***

- Identified factors that affect scuffing—temperature, speed, load, surface topography, oil supply and tilt angle.
- Stochastic nature of scuffing requires multiple tests to obtain reliable scuffing limits.
- Characterization of scuffed regions reveal nature and composition of scuffed material.

*Friction traces and load as functions of time during five repeat scuffing tests*



## **Future Directions - Lab-Engine Correlation**

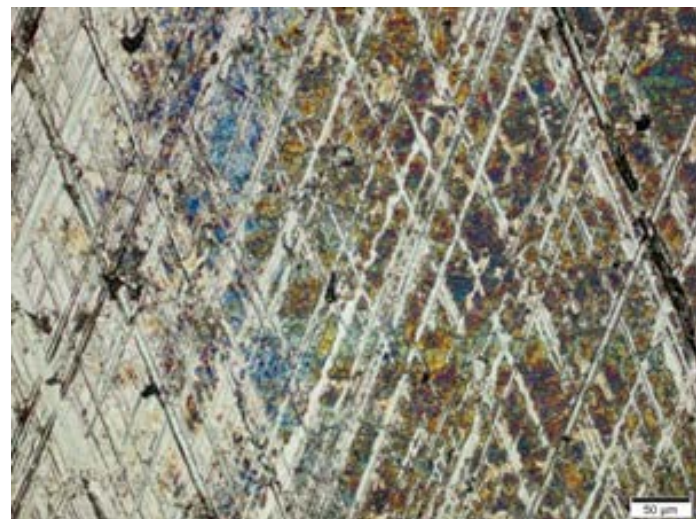
- Detailed mapping of scuffing as function of temperature, speed, load, surface topography, oil supply and tilt angle
- Impact of coatings and oil chemistry on scuffing
- Characterization of scuffed material (liner and ring)
- Impact of oil ageing on scuffing performance

# MECHANISTIC 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 determine frictional and wear behavior.
- The knowledge on how additives interact to form protective films is limited, and what is known is derived by trial and error.



## Approach

- Investigate the structure and chemistry of tribofilms and formulate mechanistic models linking structure/chemistry to performance.

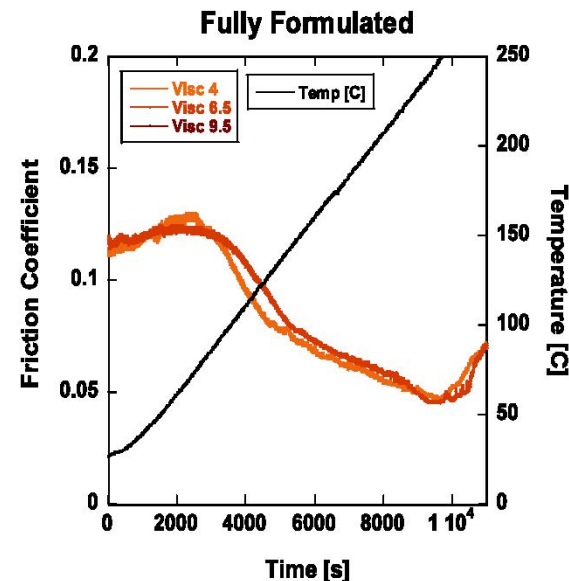
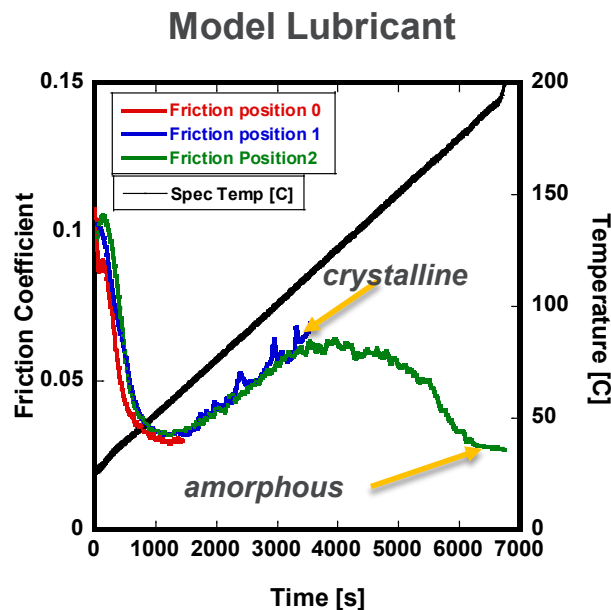
Milestone/Deliverable	Status
Investigate structure and chemistry of model basefluids that exhibit bimodal friction response and compare to formulated lubricants	Completed
Link tribofilms structure to mechanical property (hardness)	In progress



# INVESTIGATIONS OF TRIBOFILMS ON LOW-VISCOSITY FRICTION

***Accomplishment/Progress:*** Correlated temperature-dependent friction behavior of low-viscosity model lubricant with structure

- Previous work on low-viscosity model fluids demonstrated that friction exhibited a bimodal friction response.
- For fully-formulated low viscosity lubricants, gradual decrease in friction with increasing temperature, but NOT initial drop in friction.
  - Competition with other surface active additives



# INVESTIGATION OF MECHANICAL HARDNESS AND MODULUS OF TRIBOFILM

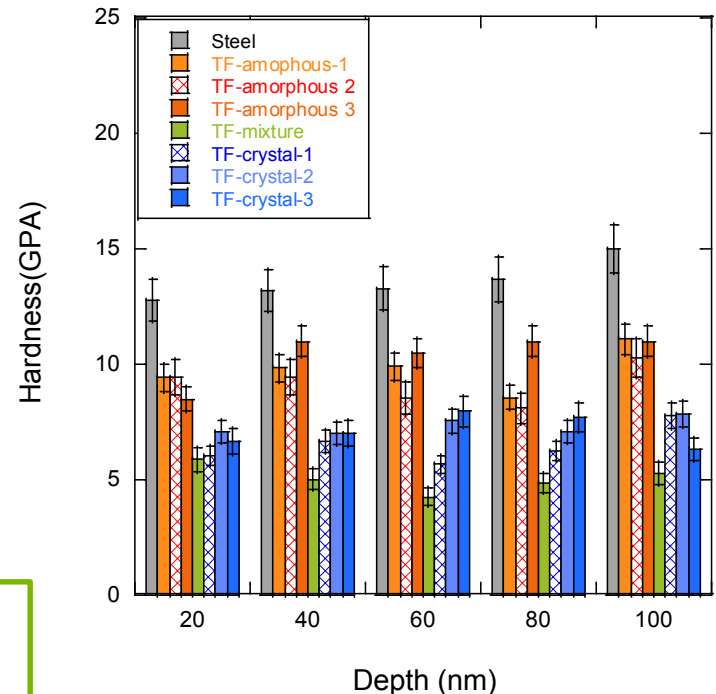
***Accomplishment/Progress:*** correlated mechanical properties (hardness/modulus) of tribofilms with structure

- Mechanical properties of hardness and elastic modulus dependent on structure of tribochemical films.
  - Amorphous films consistently showed higher hardness and elastic modulus than crystalline films.
  - Overall, tribofilms are softer and have lower elastic modulus than steel substrate.

## Future Directions – Tribofilm Phenomena

- Evaluate the basic mechanisms of scuffing in engine components.
- Formulate constitutive equations to enable friction prediction and modeling at lubricated interface.
- Develop empirical relationship between basefluid viscosity and boundary regime frictional behavior.

*Nanohardness of amorphous and crystalline tribofilms as a function of the indentation depth*



# TECHNOLOGY DEVELOPMENT

## Development of basefluids, additives and coatings to reduce asperity and hydrodynamic friction losses without sacrificing reliability

### Issues/Background

- Lubricants are balanced blends of basefluids and additives designed to achieve oil performance specifications.

### Basefluids

- Low viscosity, High VI

### Additives

- Colloidal friction modifiers and antiwear additives

### Coatings

- Low asperity friction, high wear resistance

**Approach: Develop basefluids, additives, and coatings that reduce friction without degrading wear performance.**

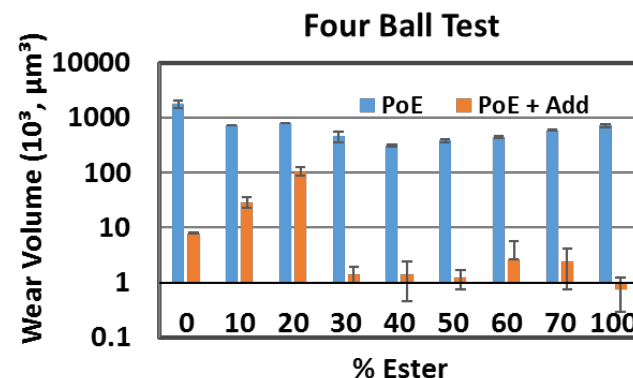
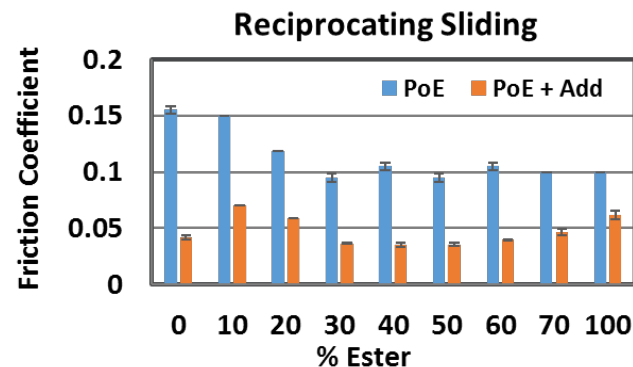
- Investigate rheological, friction and wear performance of hybrid basefluids—polyalphaolefin (PAO) and esters.
- Investigate nanotechnology platforms that invoke both physical and chemical mechanisms to improve tribological performance.
- Develop non-ferrous coating technologies that exhibit both low friction and wear performance.

Milestone/Deliverable	Status
Characterize tribological performance of PAO/ester blends	Completed
Assess tribological performance of colloidal compounds	Completed
Evaluate tribological properties of novel catalytically active coatings	In progress

# HYBRID BASEFLUID DEVELOPMENT

**Accomplishment/Progress:** Demonstrated superior performance of hybrid basefluid (PAO/ester) blends with model additives (ZDDP & MoDTC)

- Friction and wear performance evaluated for model additives (ZDDP & MoDTC) in composite basefluids
  - In unidirectional sliding, additives did not change the friction behavior much except for low ester content.
  - In reciprocating sliding, additives reduced friction for all compositions.
  - In all cases of unidirectional, reciprocating, and 4-ball testing, the presence of additives reduced wear substantially in all composite basefluids.



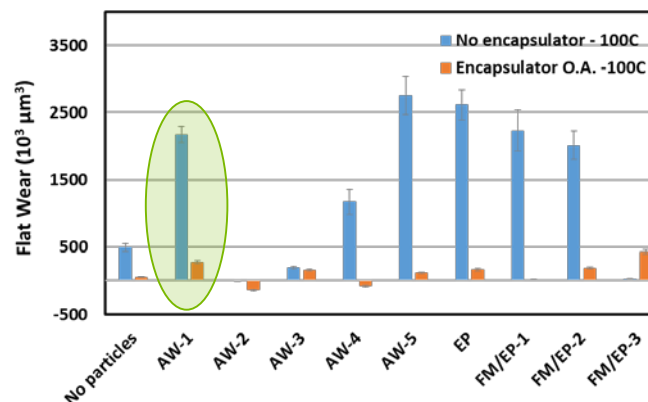
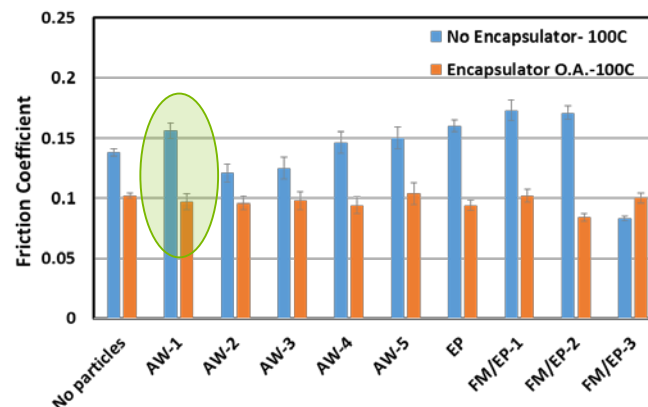
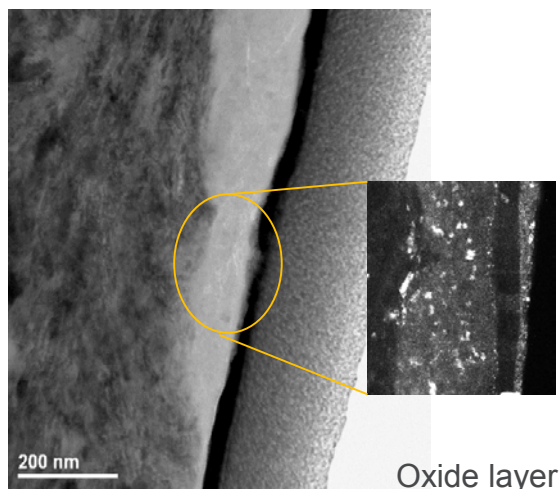
## Future Directions – Basefluid Development

- Extend ultra-low viscosity composite basefluid formulations to include advanced mineral-based fluids.
- Conduct comprehensive tribological evaluation of composite basefluids.
- Formulate thermodynamic model to predict rheological properties of binary and ternary fluid mixtures, including fuel dilution.

# COLLOIDAL PERFORMANCE EVALUATION

***Accomplishment/Progress:*** demonstrated superior performance of several candidate colloidal compounds and the impact of encapsulants on friction and wear

- In general, friction is reduced when particles are encapsulated.
- Overall, wear is considerably lower when the particulate additives are encapsulated.



## Future Directions – Colloid Development

- Evaluate load-carrying capacity of colloidal additives through scuffing performance evaluation.
- Conduct comprehensive characterization of structure and properties of tribofilms formed by colloidal additives.
- Engineer and optimize the structure of tribochemical films of colloidal additives.



# CATALYTICALLY ACTIVE COATINGS

## Development of catalytically active hard coatings that promote *in situ* formation of lubricious carbon films

### Accomplishments/Progress:

- Completed optimization of VN-Ni nanocomposite coatings.
- Finished tribological testing of the coated flat samples against uncoated steel cylinders in high frequency reciprocating rig using PAO-10 base stock oil.
  - Friction reduction of 40%
  - Negligible wear on coated surfaces
- Wear on coated samples was immeasurable while the wear on uncoated 52100 steel was substantial.

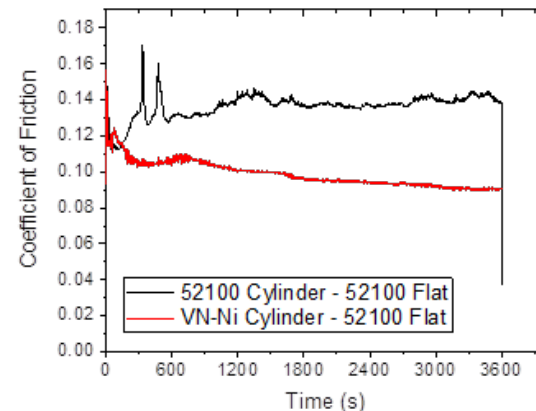
### Future Directions – Catalytic Coatings

- Confirm performance in ring-on-liner test.
- Evaluate performance in aged oil.
- Evaluate optimized coatings under engine test conditions.

Nanocomposite VN-Ni Coating



Coefficient of friction as a function of time during cylinder-on-flat tests.



# RESEARCH 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 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
  - Diamondlike carbon, Fe-boriding, nitrides
- Sample/components for testing
  - Engine blocks
  - Liners, rings, pistons
  - Bearings

## RESPONSE TO REVIEWERS' COMMENTS

- Comment: "...include some engine and vehicle modeling in order to predict how fundamental changes affect overall performance. The reviewer acknowledged that there is much hype about improving the legacy fleet with new lubricants. This should be demonstrated, including a study of durability, oil film thickness, and wear. The reviewer wonders how far we can really go..."
  - Response – The reviewer makes a good point. Argonne is currently supported under an FOA with Ricardo to answer these concerns – how much fuel savings can we expect if the viscosity is reduced, or if the boundary friction is reduced. The same models used by engine designers to predict friction power losses are being used to predict friction on a lab-scale rig. Many factors are being considered including load, speed, temperature, viscosity, surface finish (GWT), etc. Early results look promising.
- Comment: "... observed good participation and collaboration with OEMs, additive industries and other national laboratories. Participation in the Massachusetts Institute of Technology consortium adds extra value to predict critical frictional/wear/scuffing testing performance phenomena..."
  - Response – We highly value the wealth of experience brought to this project through our collaborations with industrial leaders and participation on the MIT and OSU consortia. The exchange of information is invaluable and helps guide the direction of our research activities to ensure they are relevant.
- Comment: "... that benchtop testing correlative to effective fuel economy is a large technical risk; however, developing more standardized ways to quantify tribological performance is definitely a fruitful effort..."
  - Response – Couldn't agree more, achieving a 1-to-1 correlation between lab and engine/vehicle performance would be great – but very challenging. The goal of the lab-engine correlation activity is to develop protocols that better replicate in-situ conditions, and to apply these protocols consistently.

# SUMMARY

- The Argonne project was structured to understand the complex mechanisms involved in lubricated contacts, and to use this knowledge to guide the development of advanced technologies (lubricants, additives, and materials/coatings) that can improve fuel economy, reduce emissions, and enable implementation of transformational technologies.
- Previous years' efforts focused on the development of lab-scale protocols that provide high-fidelity friction and wear data.
- Recent efforts are now focusing on lab protocols to replicate scuffing conditions – in particular, examining the role of oil supply at the scuffing interface using a tilted test configuration coupled with precise control of the oil supply rate.
- Advanced surface characterization techniques/protocols developed previously are now used routinely to assess the structure and chemical composition of thin, protective tribofilms.
  - Friction, wear, and mechanical properties can now be correlated with film structure.
- A catalytically active vanadium nitride coating was designed and developed. The catalysts were chosen to promote in-situ formation of lubricous carbon films. Little or no wear was observed, and this coating is now undergoing engine tests.
- The effect of traditional anti-wear additives and friction modifiers on a hybrid PAO/ester was studied, and the results indicate improvements in friction and wear.
- The effect of encapsulating colloidal compounds on friction and wear was studied. The results indicate little or no change in friction and wear under unidirectional sliding, but significant improvements under reciprocating and severe contact conditions.

**THANK-YOU**

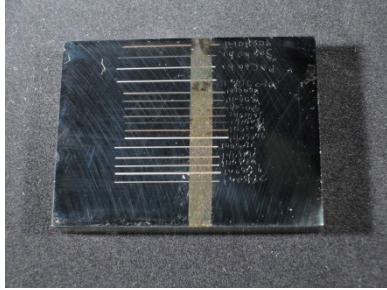
**QUESTIONS?**



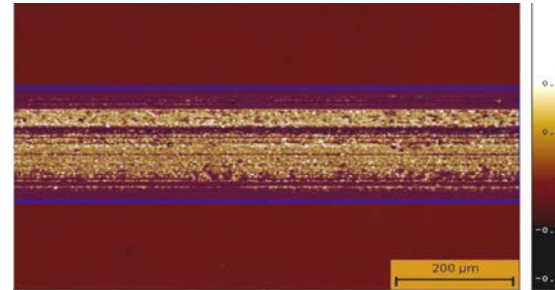
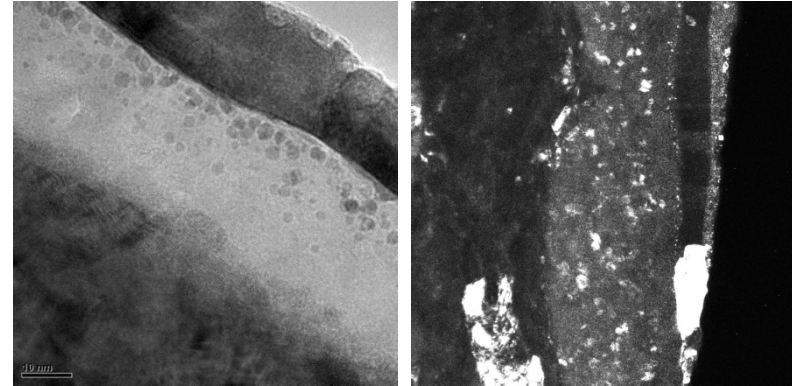
# BACKUP SLIDES

# DIFFERENT WAYS TO IMAGE TRIBOFILMS

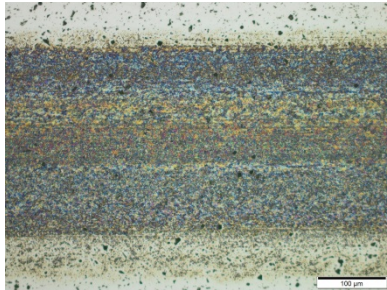
Naked Eye



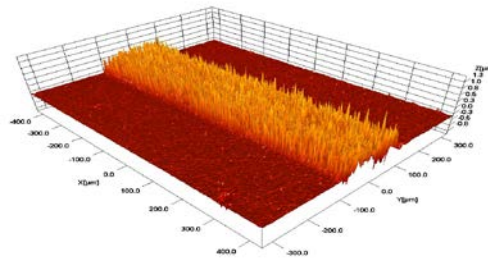
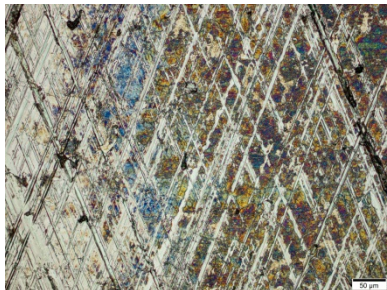
TEM Bright Field TEM Dark Field



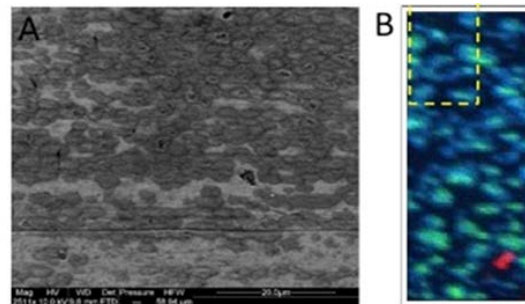
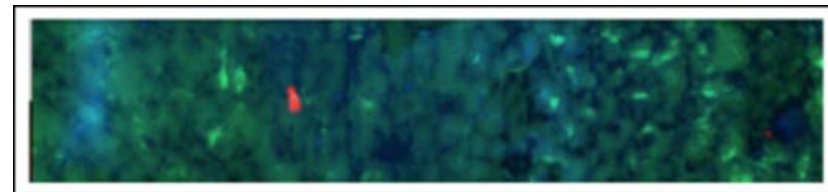
White Light Interferometry



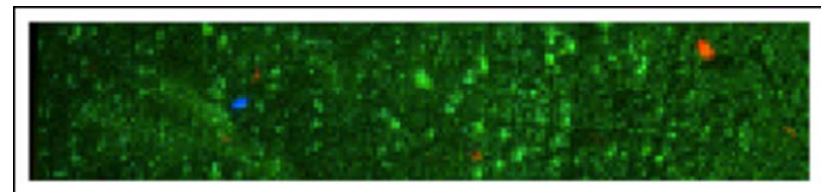
Optical



Micro Xray Fluorescence

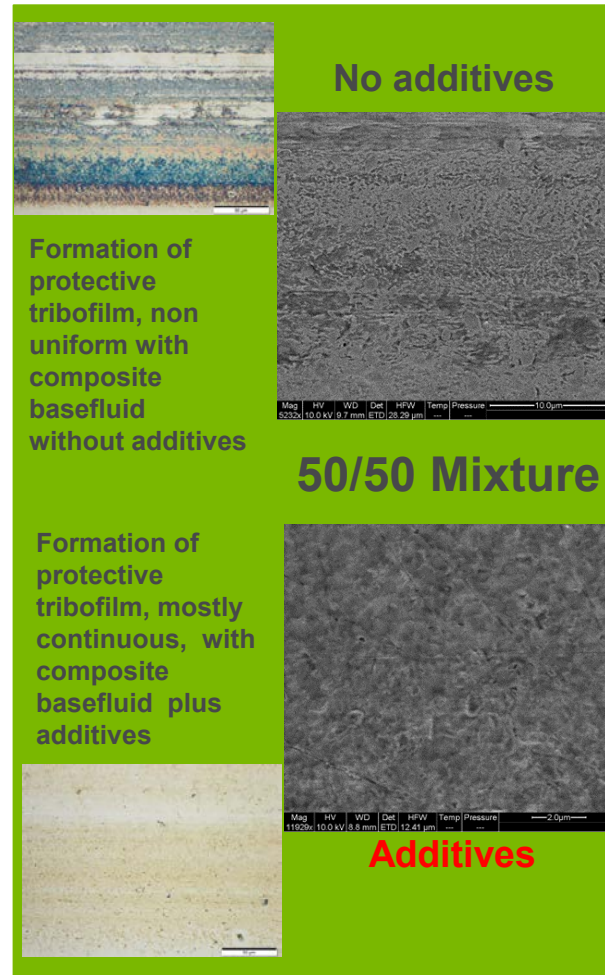
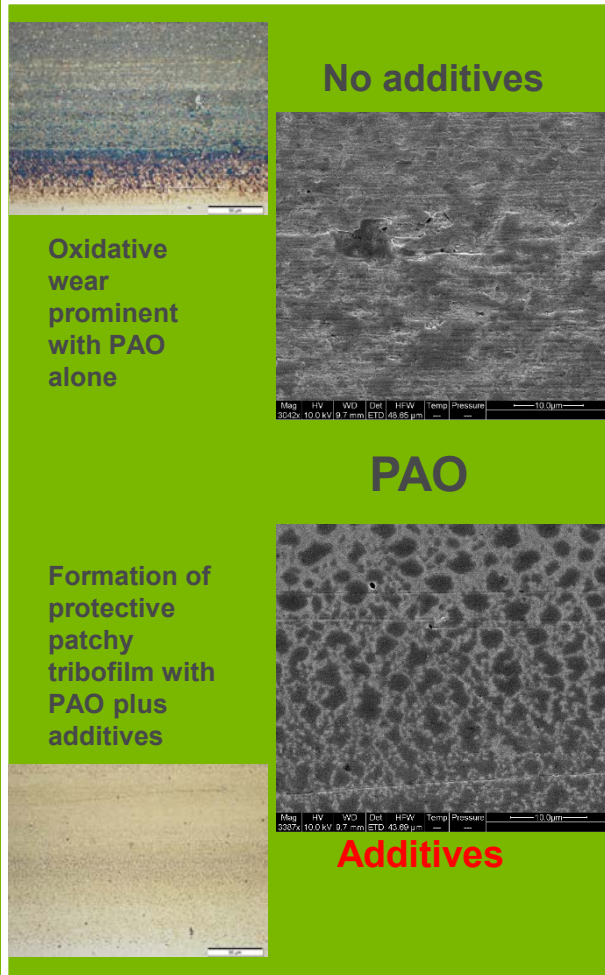


SEM



Micro XANES

# HYBRID BASEFLUID DEVELOPMENT



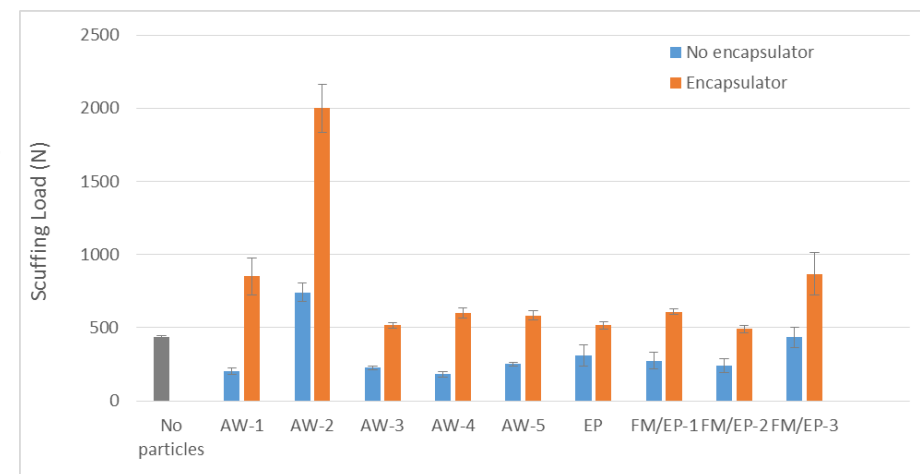
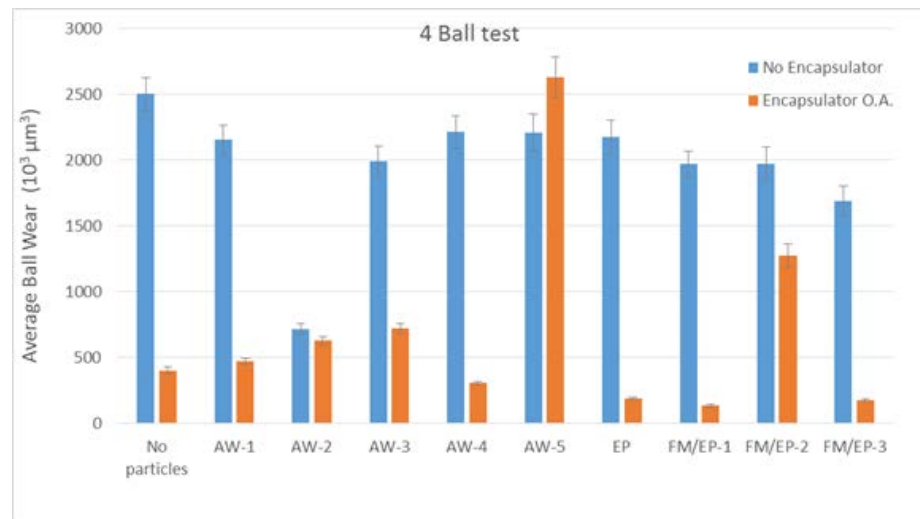


# COLLOIDAL PERFORMANCE EVALUATION

**Significant improvements in wear and scuffing performance occur when colloidal compounds are encapsulated.**

Tribological performance evaluated for candidate colloidal additives under extreme pressure conditions of 4-ball and scuffing testing.

- In 4-ball test, colloidal additives provided only a marginal reduction in wear (except for AW-2).
- Addition of encapsulator reduced wear in all cases (except for AW-5).
- Wear mechanism in all cases is by abrasion.
- In scuffing test with block-on-ring contact configuration, 3 nano-additives increased scuffing load, and the others reduced scuffing.
  - More work needed and in progress to further elucidate the role of colloidal additives in scuffing mechanism and performance.



**WE START WITH YES.  
AND END WITH THANK YOU.  
DO YOU HAVE ANY BIG QUESTIONS?**