Advanced Nanolubricants for Improved Energy Efficiency and Reduced Emissions in Engines

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Project ID # FT018

Overview

Timeline

- Project start date: 3/23/2012
- Project end date: 3/22/2015
- Percent complete: 70%

Budget

- Total project funding
  - DOE share: $800K
  - Contractor share: $215K
- Funding received in FY13: $268K
- Funding for FY14: $267K (expected)

Barriers

- 10-15% of fuel's energy is lost to overcome friction in engines despite the use of highly efficient lubricants (ILSAC GF-5, CJ-4, etc.)
- Advanced nanolubricants may improve efficiency further but their effectiveness and compatibility with existing lubricants/additives are not known.

Partners

- Valvoline (lubricant supply, formulation and testing)
- U.S. Borax (boron-based nanolubricant material R&D)
- Cummins (engine/emission testing)
- **Project lead: Argonne**

(View the PowerPoint "Notes" page for additional instructions)

Relevance

- **Objectives**
  - Develop and implement novel boron-based lubricant formulations to reduce engine friction by at least 10% compared to current lubricant technology without compromising on engine durability and emissions
  - Demonstrate scalability, lubricant compatibility, and commercial viability.
- **Objectives for last year**
  - Demonstration of larger-scale production/lubricant formulation
  - Completion of lubricant optimization and bench tribology studies
  - Initiation of screening test in engines
- **Relevance to DOE-VT Objectives**
  - Reduce dependence on imported oil by increasing fuel economy
  - Reduce carbon emissions
- **Impact**
  - New lubricant technology has the potential to reduce boundary friction by as much as 80% (can save ≈100 million barrels of oil/year)
  - It may allow:
    - uses of much lower viscosity engine oils
    - Increased catalyst life by reducing anti-friction and –wear additives.

Milestones

Month /Year	Milestone/Go-No-Go Decisions	Milestone Description	Status
Q1/13	Milestone	Nanolubricant compatibility studies	Completed
Q2/13	Milestone	Nanolubricant bench tribology studies	Completed
Q3/13	Milestone	Nanolubricant optimization studies based on bench tribology tests	Completed
Q4/13	Milestone	Nanolubricant scale-up demonstration	Completed
Q1/14	Milestone	Screening fired engine studies	In-progress
Q2/14	Milestone	Large-scale manufacture of improved nanolubricant formulation for engine test	In-progress
Q3/14	Milestone	Final/full engine testing of improved formulation	On-schedule
Q4/14	Milestone	Cost, commercial viability studies	On-schedule

Approach / Strategy

- **Conduct physical, chemical, and surface analytical studies to attain fundamental knowledge necessary for superior nanolubricant performance in both diesel and gasoline oils.**
  - Effect of nanolubricant concentration (size, shape, etc.)
  - Effect of surface functionalization (borate ester studies)
- **Conduct systematic bench tribological studies to confirm anti-friction and –wear properties**
  - Boundary lubrication behavior
  - Extreme pressure capability
- **Elucidate fundamental lubrication mechanisms through advanced surface/structure analytical techniques**
  - Nature of tribofilm (boundary film) providing low friction and wear
- **Conduct engine studies to confirm performance**

Combined knowledge gained from these studies will help close the gap in better understanding of those key barriers for more advanced lubricant formulations affording higher engine efficiency.

Technical Accomplishments and Progress

Summary of Prior Year Activities

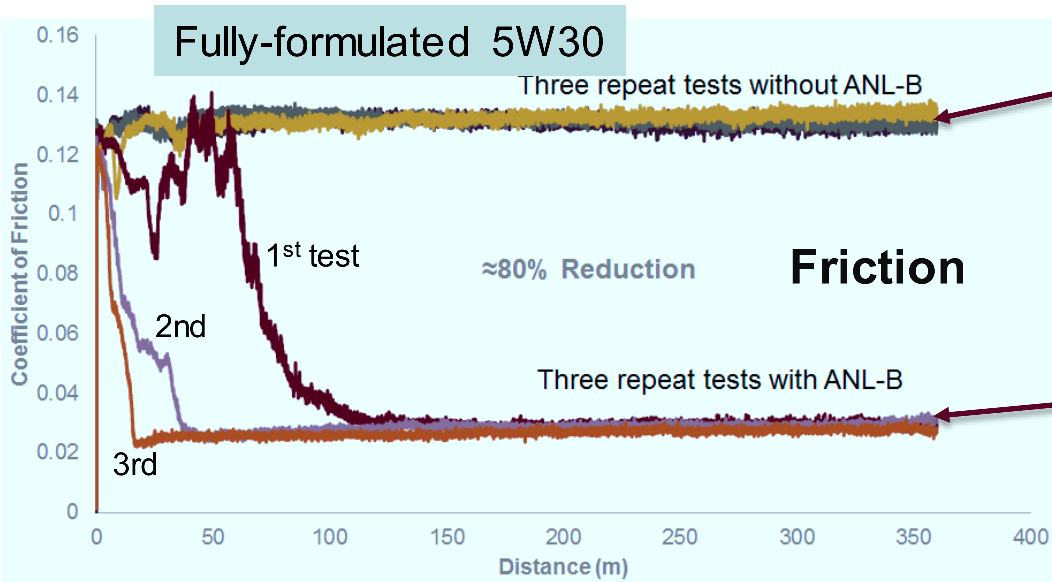
March 23, 2012 – September 30, 2012

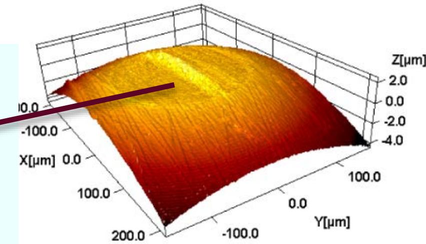
Optimization of New/Emerging Boron-based Lubrication Additives for Bench Studies (Argonne and US Borax)

- Preparation of appropriate borate materials and test samples for bench evaluation
  - Dispersability, lubricant/additive compatibility, concentration, etc.
  - Novel synthetic borate compounds (both liquid and solid) with much higher thermal and oxidative stability and potentially much better lubricity.
  - Surface functionalization (borate esters, etc.)
- Initiation of bench-friction and wear studies (Argonne and Valvoline)
  - Screening tests of boron-formulated oils over a range of test conditions using a variety of tribological test machines
  - Extreme pressure (scuffing) studies using block-on-ring test machine
- Characterization of boundary films to understand fundamental lubrication mechanism

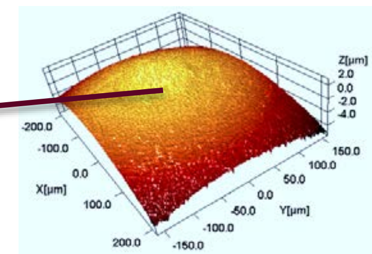
Technical Accomplishments and Progress

Bench Tribological Studies





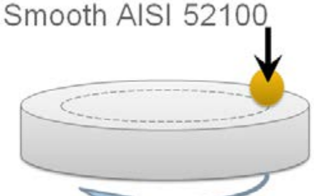
Wear



Boron-additized 5W30 oil showed 80% reduction in friction; wear was also dramatically reduced

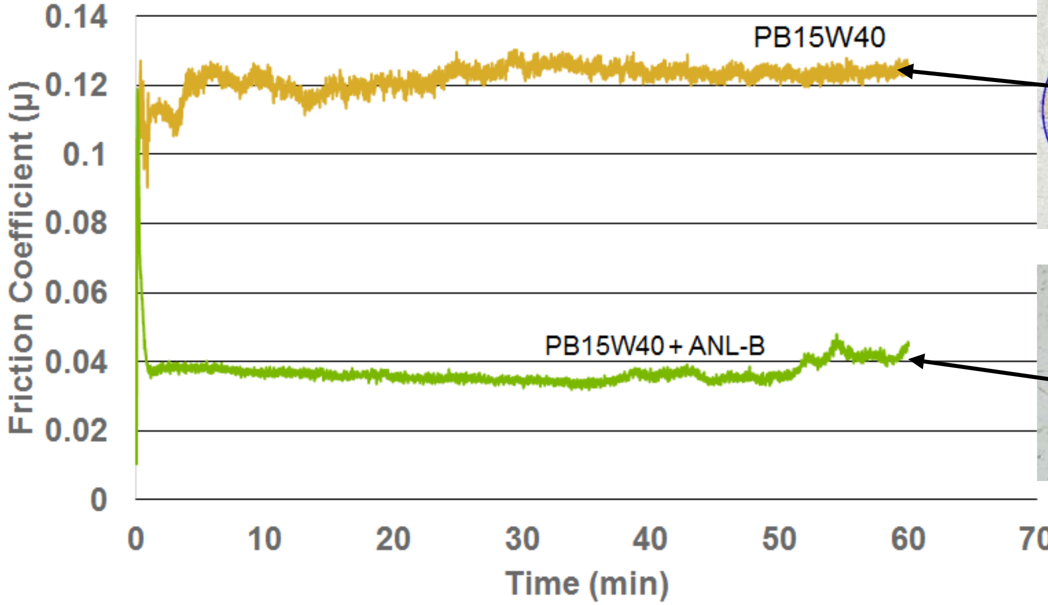
Temperature:	100°C
Load:	10 N
Contact Pressure:	1.05 GPa
Speed:	0.1 m/s
Distance:	360 m (3600s)
Ball:	3/8" Smooth AISI 52100
Flat:	Smooth AISI 52100

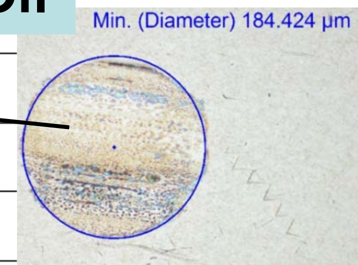
Pin-On-Disk Tribo-tester

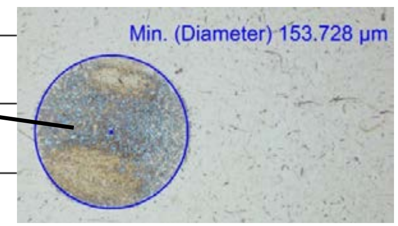


Technical Accomplishments and Progress Cont'd

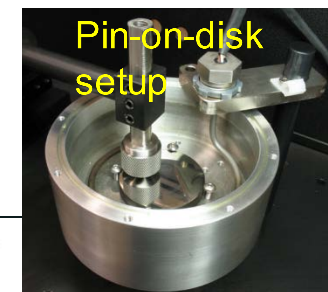
Current/conventional 15W40 Diesel Oil







Wear



Temperature:	100°C
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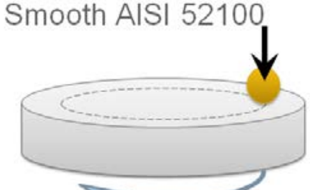
Pin-On-Disk Tribo-tester

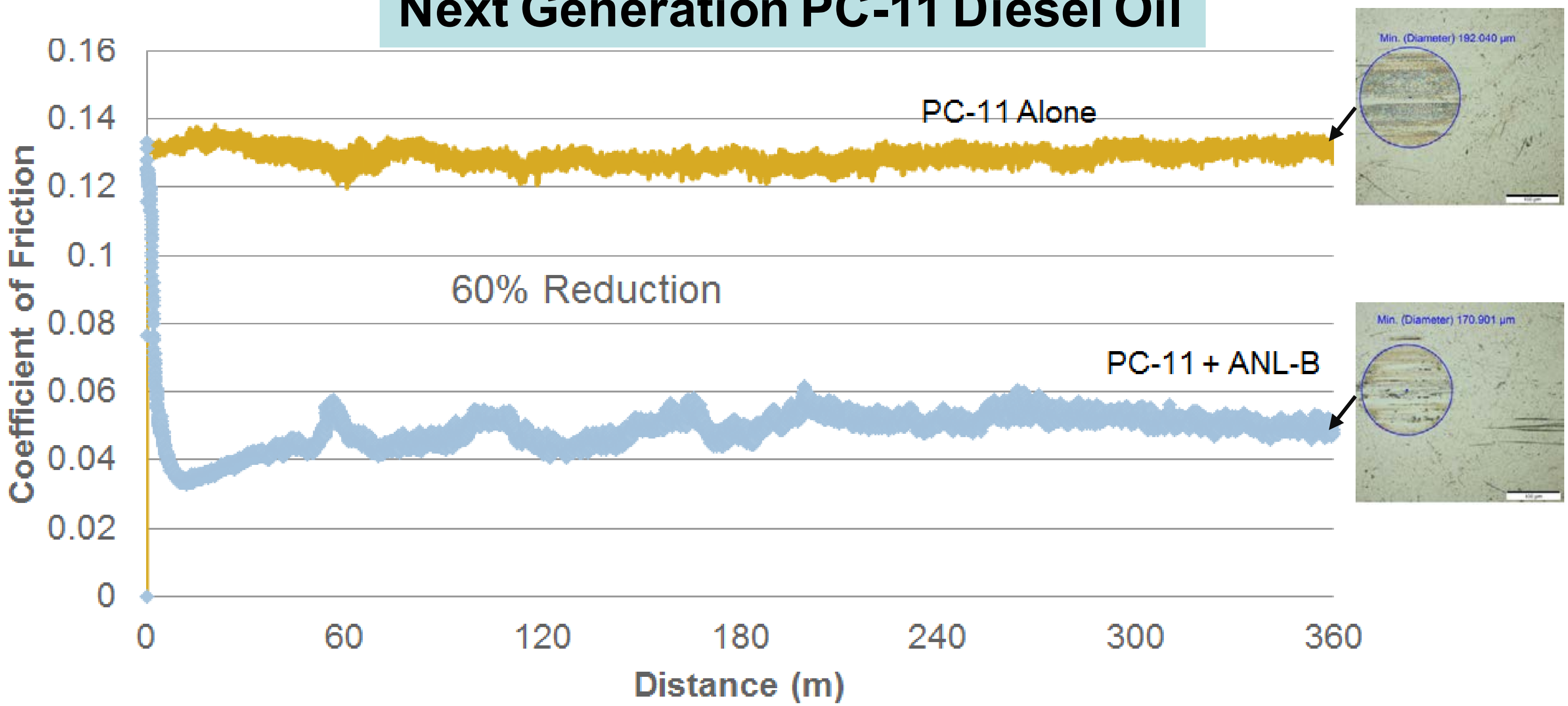


Boron-additized 15W40 conventional diesel oil showed 66% reduction in friction; wear scar diameter was reduced by 17% despite severe test condition.

Technical Accomplishments and Progress Cont’d

Wear

Next Generation PC-11 Diesel Oil

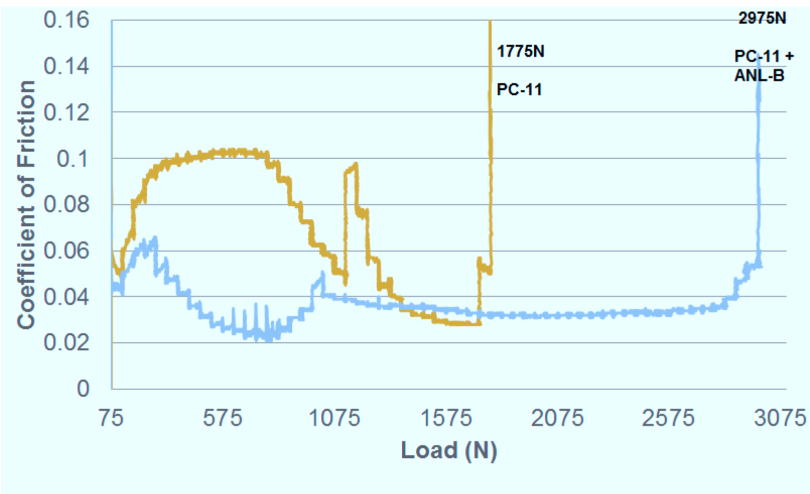


Boron-additized PC-11 diesel oil showed 60% reduction in friction; wear scar diameter on ball was also reduced (11%)

Technical Accomplishments and Progress (cont’d)

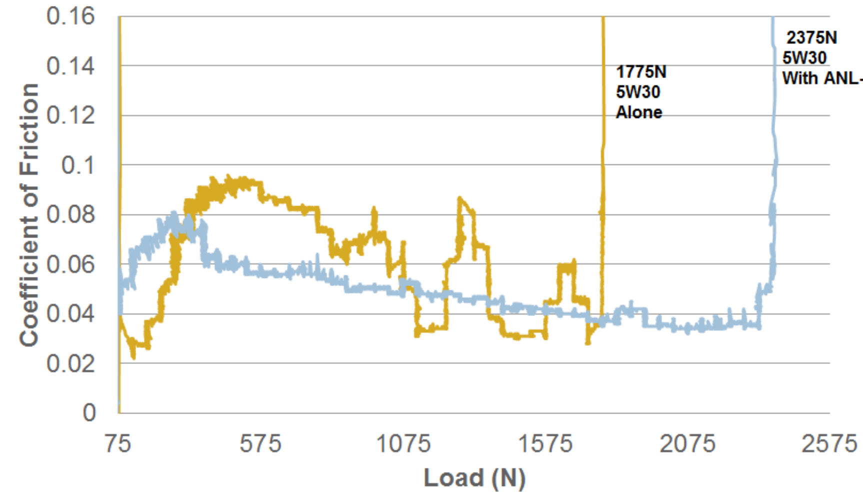
Scuffing Performance (Block-on-ring test)

PC-11 Diesel



67% Increase

5W30 Gasoline



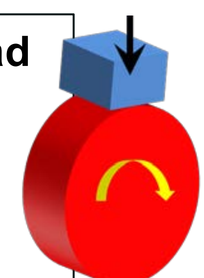
33% Increase

Boron-additized oils showed lower friction coefficients and significantly higher scuffing loads

Block-on-ring

Test condition/configuration

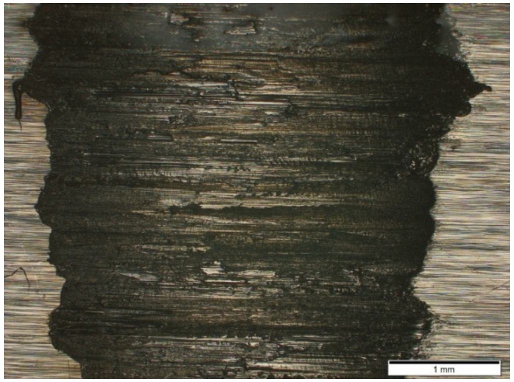
Load: 0 – Scuffing Load
Speed: 1000 rpm
Samples: Block and Ring
ASTM standard



Technical Accomplishments and Progress (cont'd)

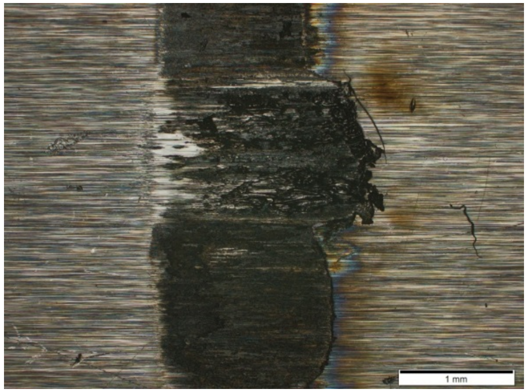
Wear Damage on Ring

PC-11 Diesel Oil



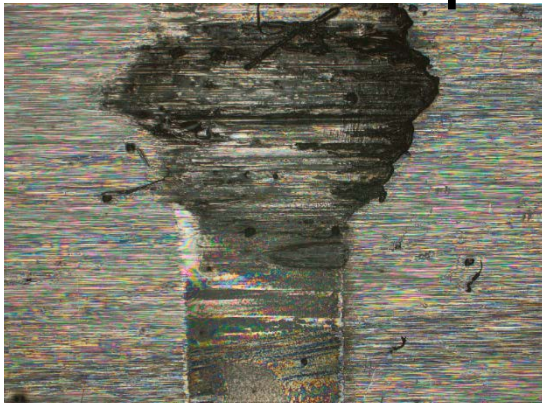
At 1775 N Load

PC-11 + ANL-B



At 2975 N Load

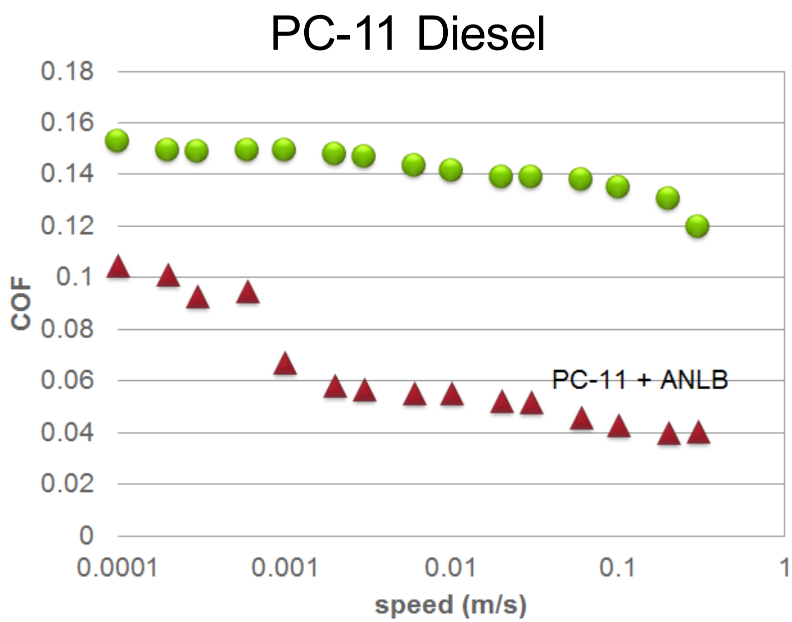
PC-11 + ANL-B Repeat

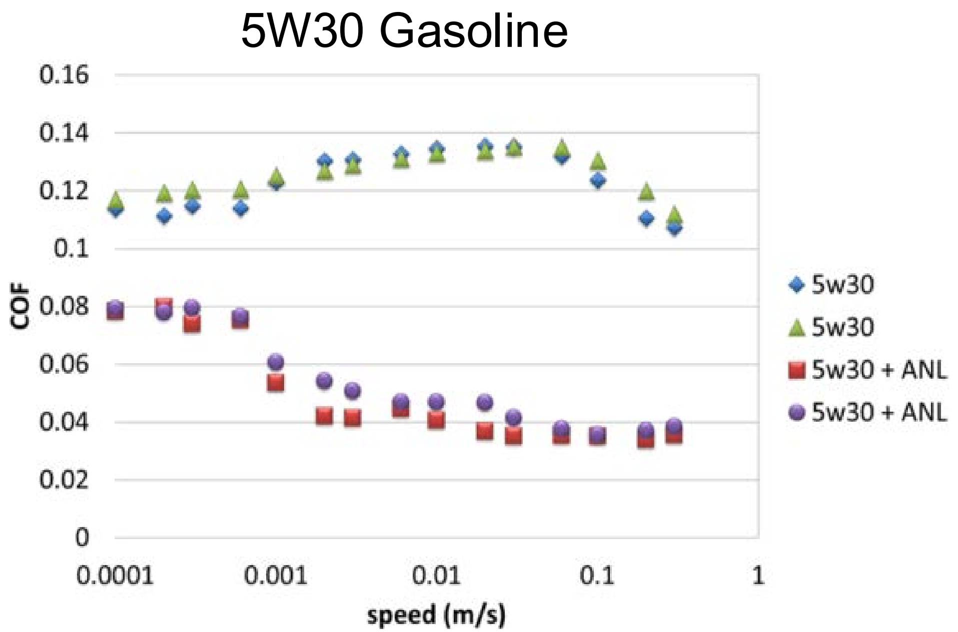


Boron-additized PC-11 caused less wear damage on ring upon scuffing

Technical Accomplishments and Progress (cont'd)

Speed Effect (Stribeck behavior)

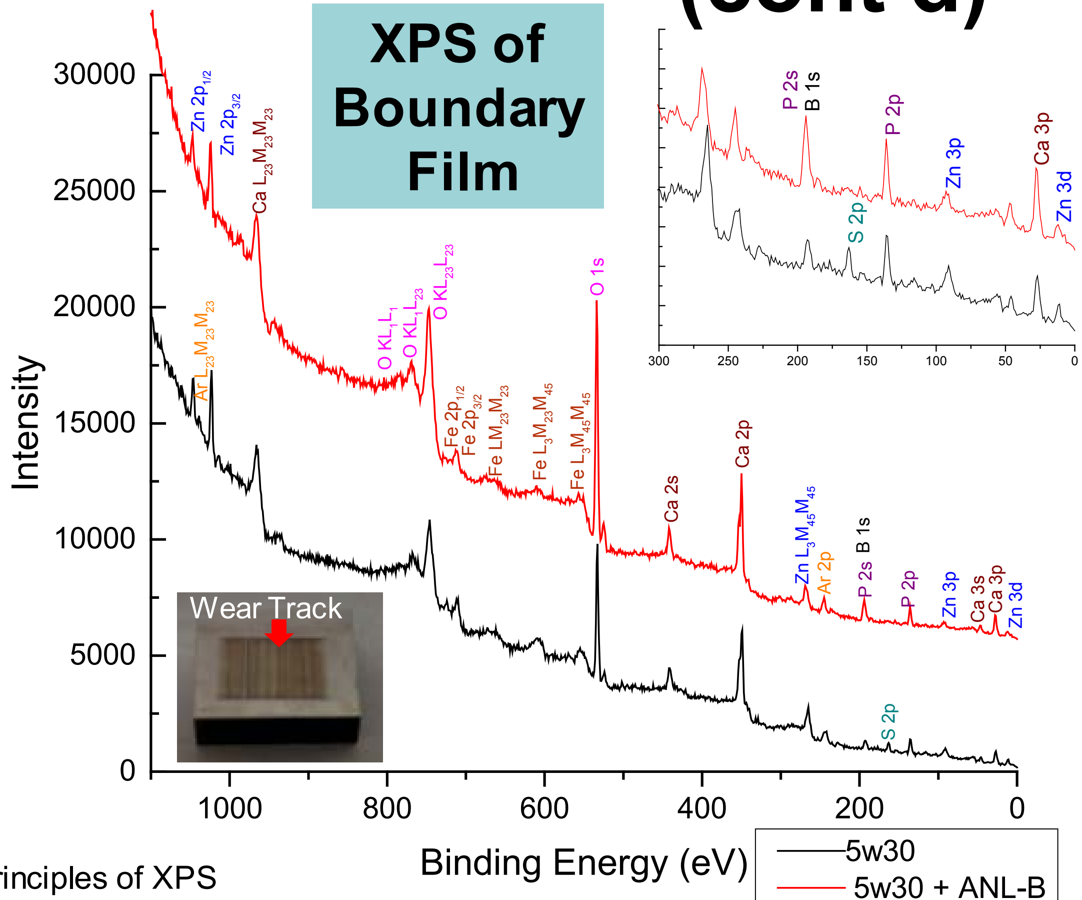


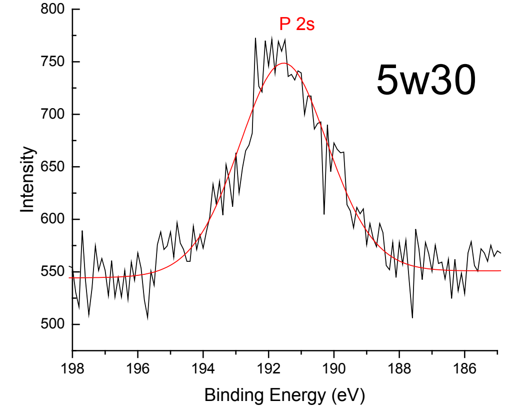


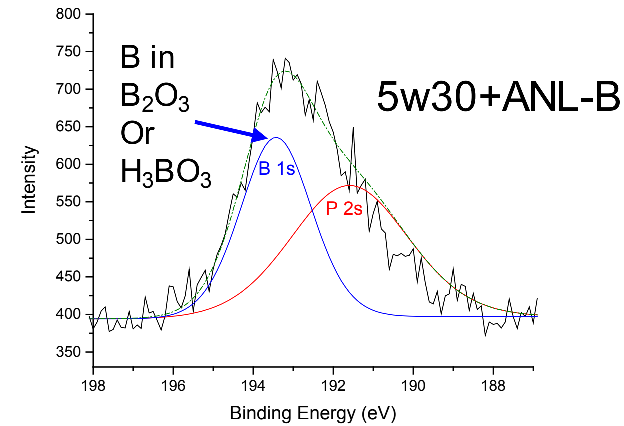
Boron-additized oils showed lower friction coefficients in boundary and mixed lubrication regimes

Technical Accomplishments and Progress (cont'd)

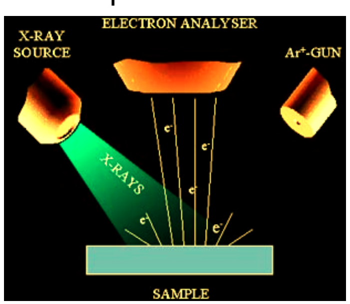
XPS of Boundary Film







Principles of XPS

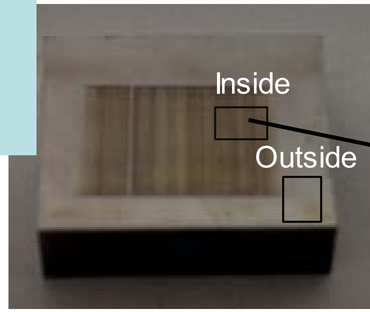


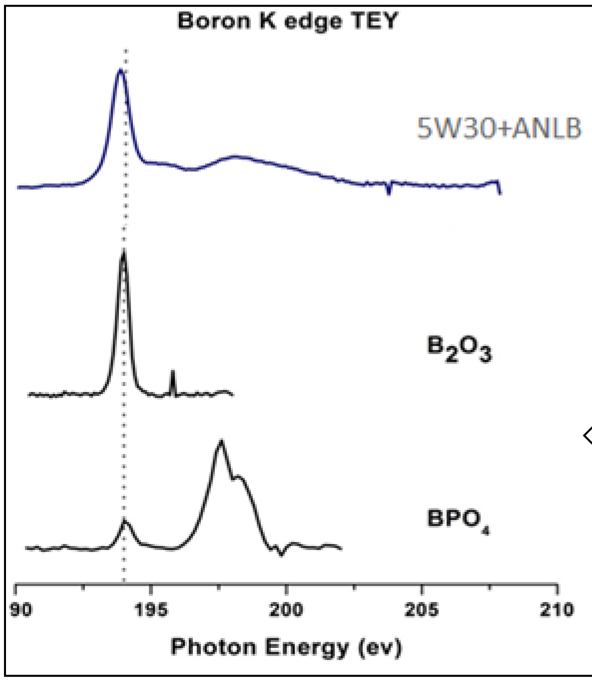
Significant amount of boron (≈20 at.%) detected in boundary film

Element	At.% FFO 5w30	At.% FFO 5w30+ANLB
O	44.24	54.40
Fe	2.56	1.33
Ca	31.23	15.10
Zn	4.26	2.28
P	12.64	6.98
S	5.07	-
B	-	19.90

Technical Accomplishments and Progress (cont'd)

XANES (X-ray Absorption Near Edge Structure) Spectroscopy: Boron K edge



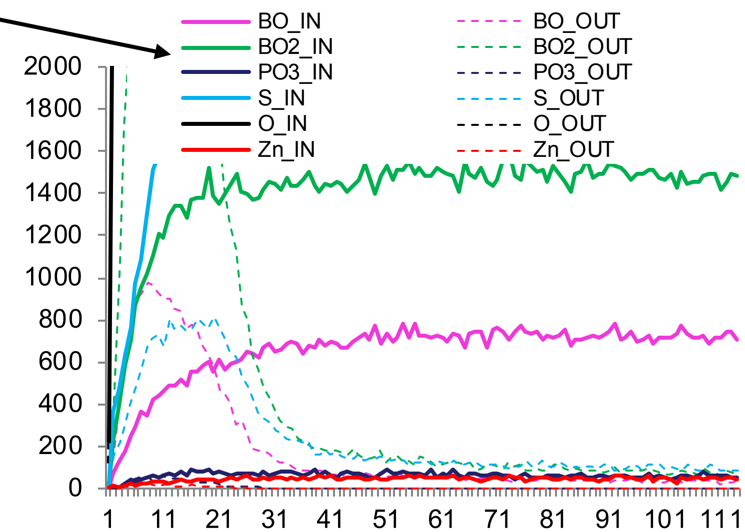


Primarily B_2O_3 with small presence of BPO_4

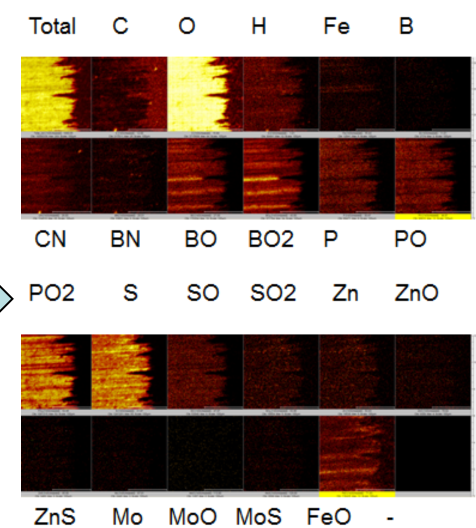
Courtesy of Prof. P. Aswath/ V. Sharma

Boron in boundary film is in the form of complex boron oxide/ boron phosphate compound

TOF-SIMS Chemical Analysis of Wear Track



TOF-SIMS chemical mapping of region near the edge of wear track

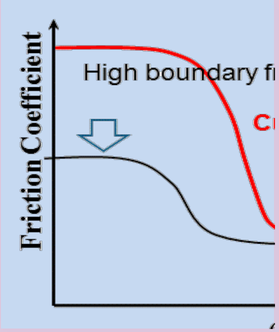


Brighter the contrast higher the concent-ration

Technical Accomplishments and Progress (cont'd)

Screening fuel efficiency engine test with ANL-B additized oil

Boundary/mix lubrication portion of Stribeck curve



Fuel Economy Measurement and Aging Condition					
FE Stage	Speed (r/min)	Torque (N-m)	Oil Temp. (°C)	Coolant Temp. (°C)	
1	2000	105	115	109	
2	2000	105	65	65	
3	1500	105	115	109	
4	695	20	115	109	2.5% Savings
5	695	20	35	35	
6	695	40	115	109	1.5% Savings

Aging Stage	Speed (r/min)	Torque (N-m)	Oil Temp. (°C)	Coolant Temp. (°C)
1 & 2	2250	110	120	110

- Under FE stages (low-speed, high-temp) where mixed/boundary conditions prevail, 1.5 to 2.5% fuel efficiency improvements have been achieved. Very encouraging result!

More engine tests are planned with a highly optimized/stable boron additive to confirm the results of initial (screening) test.

Responses to Previous Year Reviewers' Comments

Our project was not reviewed last year

Collaboration and Coordination with Other Institutions

- NDAs have been signed with major oil, additive, and engine companies (Infineum, Evonik, TRD).
  - Sample exchanges and testing have been going on
  - Excellent results were obtained in bench tests
  - More relevant component/dyno tests will follow
  - SwRI® is another collaborator testing boron-based lubricants
- Key project collaborators are:
  - Valvoline (cost-sharing lubricant partner)
  - US. Borax (cost-sharing material partner)
  - Cummins (cost-sharing engine partner)

Remaining Challenges and Barriers

- Longer-term stability (both thermal, chemical), lubricant compatibility, performance/life-time.
  - Currently addressing these with some specialty tests under more prototypical conditions (i.e., thermal cycling; repeat testing after intermittent or long aging periods on shelf; moisture sensitivity; settlement, etc.)
  - Emission/after-treatment compatibility (more detailed engine tests are needed)
- Scalability, cost and economic/commercial viability.
  - Availability at reasonable cost
  - Alternative ways to achieve in-situ formation of boron-based nanolubricants.

Proposed Future Work

- **Argonne:** Demonstration of large-scale blending/formulation of oils for engine testing (Milestone Q3/14)
  - Completion of bench tribological studies
  - Further fundamental studies of boundary films (3D atom probe tomography) (Milestone Q3/14)
  - Cost-benefit analysis and commercial viability study (Milestone Q4/14)
- **RTM-US Borax:** Explore synthesis of more stable/effective boron-additives (Milestone Q2-Q3/14)
- **Valvoline:** Validation of improved fuel economy and wear performance (Milestone Q3/14)
- **Cummins:** More extensive engine studies on highly optimized diesel oil blends (Milestone Q4/14)

Summary Slide

- Consistent with the tasks/milestones of our project, we have made remarkable progress in developing novel boron-based nanolubrication additives that can:
  - Reduce friction by as much as 80% under severe boundary conditions
  - Increase resistance to wear and scuffing
  - Improve fuel economy (under engine running conditions involving mixed/boundary regime).
- Much improved tribological performance is related to the formation of a slick and highly protective boron-rich boundary film as confirmed by XPS, XANES, TOF-SIMS data.