High-Efficiency Low-Toxicity Ionic Liquids as Lubricant Additives

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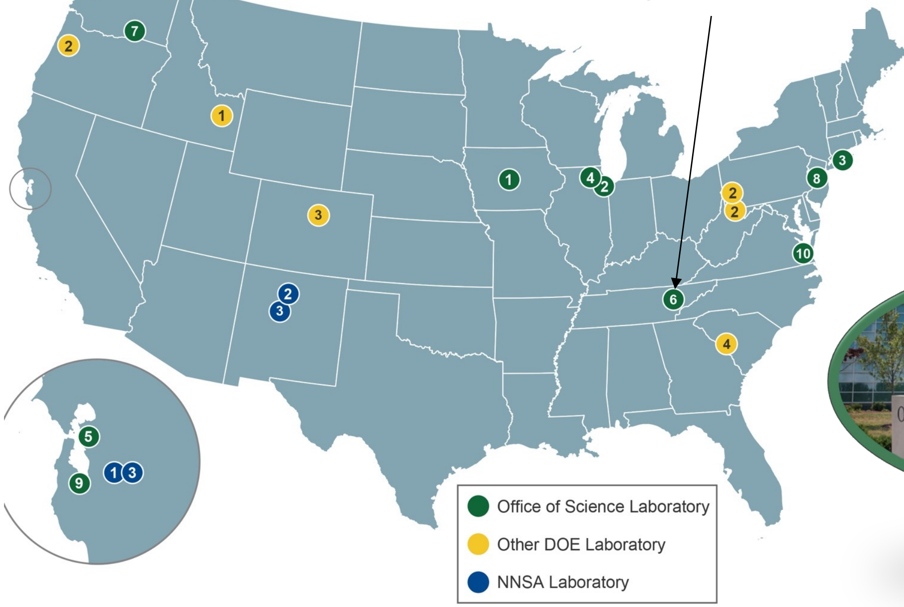
January 29, 2024

Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy

Oak Ridge National Laboratory, East Tennessee



Established in 1943 as part of the Manhattan Project

Great Smoky Mountains

ORNL Tribology Research Portfolio

Technologies

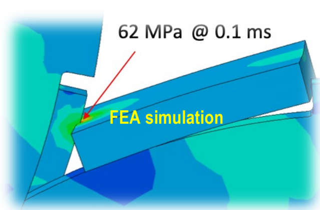
- **Advanced lubrication**
  - Ionic liquids (including eco-friendly)
  - Nanolubricants
  - Molten salts
- **Surface engineering**
  - Superlubricity and wear-resistant coatings
  - Surface functionalization
  - Additive surface compositing & structuring (FSP, LM, BJ)
- **Nanomaterials processing**
  - Organic/electrochemical synthesis
  - Chemical/physical vapor deposition (CVD/PVD)
- **Contact interface investigation**
  - Contact mechanics and lubrication modeling
  - Surface/tribofilm characterization
- **Bench testing & standardization**
  - Application-oriented testing and analysis
  - 4 ASTM standards developed at ORNL

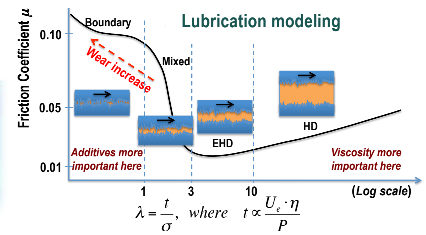
Applications

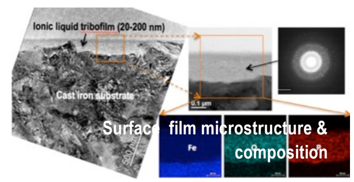
- **Vehicle (IC & EV)**
  - Energy-efficient engine and gear lubricants
  - Superlubricity bearings and seals
  - High-efficiency e-motor coolants
  - High-conductivity thermal interface material
- **Bioenergy**
  - Biomass/MSW preprocessing tool wear & mitigation
  - Biomass/MSW fouling & plugging
- **Concentrating solar power**
  - Wear/corrosion-resistant molten salt pumps
  - Self-lubricating high-efficiency seals
- **Hydropower & Hydraulics**
  - Eco-friendly tidal turbine lubricants/hydraulic fluids
- **Nuclear**
  - Grid-to-rod fretting of ATF claddings (PWR)
  - Wear and corrosion in molten salt and gas-cooled reactors
- **Building**
  - Advanced lubricants and coatings for HVACs

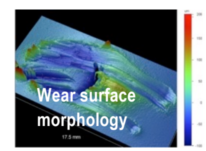
ORNL Tribology Research Capabilities

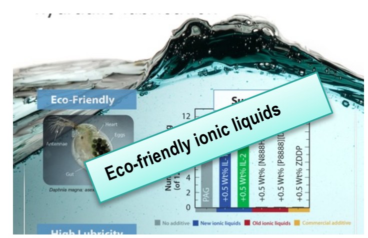
- **Tribosystem analysis for understanding the failure modes and wear mechanisms**
  - *Contact interface modeling*: Contact mechanics, heat transfer, and lubrication modeling
  - *Materials characterization:* Microstructure, composition, morphology, roughness, and mechanical and thermophysical properties
- **Materials development for mitigation**
  - *Novel lubricants and additives*: Ionic liquids, molten salts, and nanoparticles
  - *Advanced coatings/surface treatments*: CNT coatings, oxygen diffusion, friction stir processing, and additive manufacturing
- **Tribological testing and analysis for evaluation**
  - *Various wear modes*: Abrasive (2-body & 3-body) wear; Sliding wear; Rolling contact fatigue; Fretting
  - *Well-controlled conditions*: Ambient, vacuum, or controlled gas; RT – 1000 ºC; 0.1 – 1000 N load; 0.1 mm/s – 15 m/s velocity; Dry, wet, & lubricated
- **Standardization:** ***4 ASTM standards for tribo-testing***

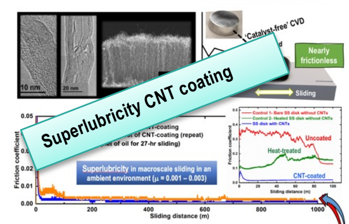


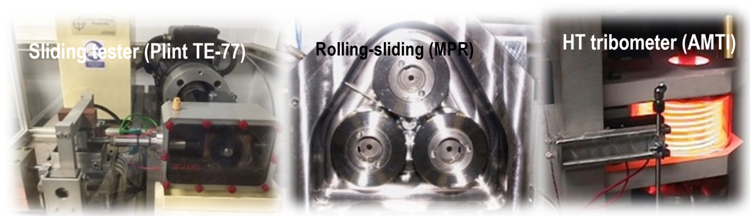












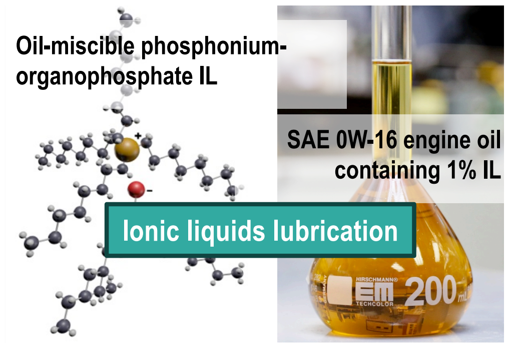
ASTM Standards

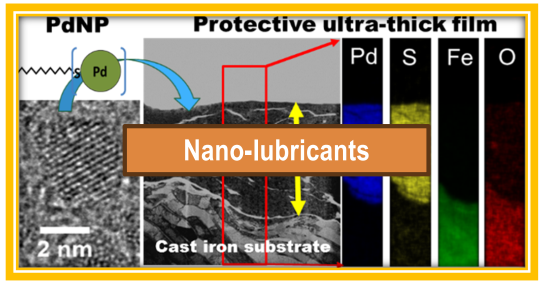
Oak Ridge National Laboratory

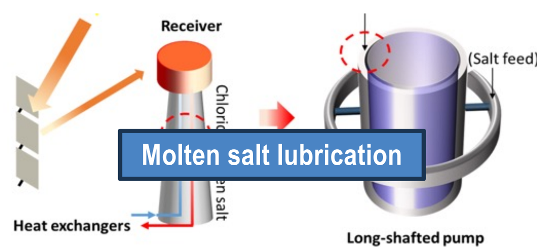
ORNL Advanced Lubrication

- Development and evaluation of new lubricant additives (**ionic liquids, nanoparticles, molten salts**, etc.)
- *Recent projects:*

1. **Organic-modified CNTs as lubricant additives for enhanced lubricity and thermal management of EVs (DOE VTO 2022-26, CRADA w/ Valvoline)**
2. **Eco-friendly ionic liquids as additives for environmentally-acceptable lubricants (DOE WPTO 2021-25**, ORNL TIP 2020-21, DOE VTO 2018-20)
3. **Molten salt lubrication for concentrating solar power and nuclear reactors (DOE NE 2021-25**, SETO 2018-20)
4. Ionic liquids for lubricating HVAC compressors (DOE TCF 2021-23)
5. Organic-modified nanoparticles as lubricant additives (Hyundai 2019-20, DOE VTO w/ UTK and UCM, 2015-17)
6. Ionic liquids as lubricants or multi-functional lubricant additives to improve fuel economy (Seed and VTO 2005-19, w/ GM, Shell, and DRO)
7. Compatibility of lubricant additives with non-ferrous coatings and alloys (VTO 2013-20)
8. Hyperbranched polymers for improved viscosity and enhanced lubricity (VTO 2014-16, w/ PNNL)
9. Tribological evaluation of aged diesel engine oils (DOE VTO 2002-05)
10. Diesel fuel injectors in ultra low sulfur fuels (DOE VTO 2002-05)

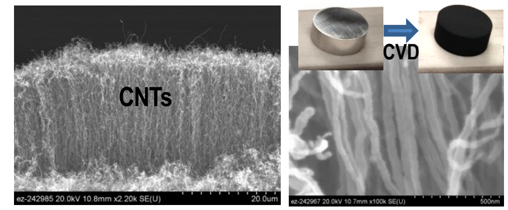


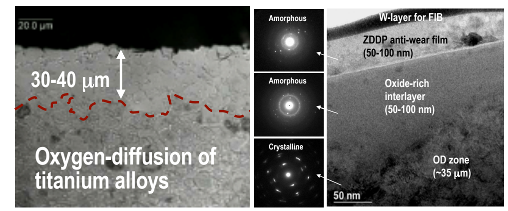


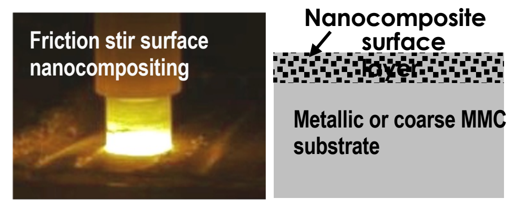


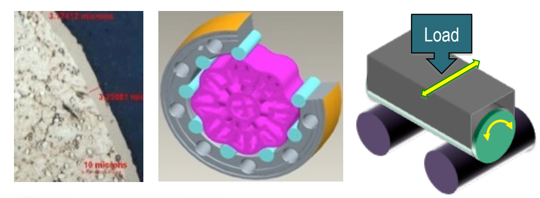
ORNL Surface Engineering

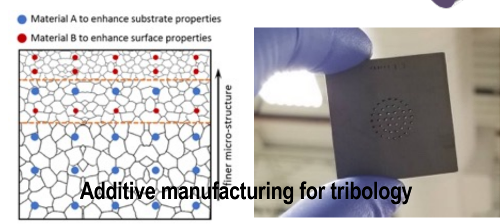
- Development of new **coatings and surface treatments**
- *Recent projects*
  1. **Surface modifications to enhance printability of US banknotes (BEP 2024-26)**
  2. **Carbon nanotube-based coatings for friction and thermal management (DOE VTO 2022-26**, ORNL Seed 2018-19)
  3. **Tool wear characterization and mitigation in biomass preprocessing (DOE BETO 2018-26, CRADAs with Rawlings** and Forest Concepts**)**
  4. **Graphite wear in molten salt and gas-cooled reactors (DOE NE 2021-25)**
  5. **Carbon nanotube-coated mesh seal (DOE SETO 2020-24)**
  6. Grid-to-rod fretting of candidate accident-tolerant fuel claddings (DOE NE FOA 2018-23, CASL 2014-17)
  7. Additive manufacturing for tribology (Ford, 2018-20)
  8. Advanced diesel engine piston skirt coatings (DOE VTO 2015-16, CRADA w/ Cummins)
  9. $AlMgB_{14}$-based superhard coatings for hydraulic & tooling (DOE ITP 2007-10, w/ Eaton, Greenleaf, and Ames Lab)
  10. Surface nanocompositing of aluminum alloys using friction stir processing (ORNL LDRD 2006-08)
  11. Oxygen diffusion case-hardening for titanium alloys (DOE VTO 2004-08)
  12. Low-temperature carburization of austenitic stainless steels (DOE ITP 2005-08, w/ Swagelok and CWRU)











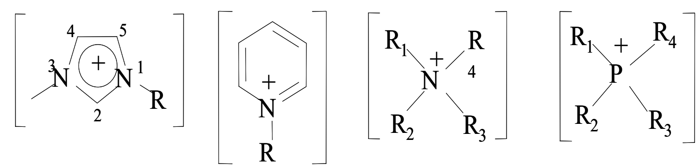
OAK RIDGE National Laboratory

Ionic liquids for lubrication (since 2005)

- **ILs as neat lubricants or base stocks**
  - High thermal stability (up to 500 ^{o}C)
  - High viscosity index (120-370)
  - Low pressure-viscosity coefficient → low EHL friction
  - Strong surface adsorption → low boundary friction
  - Strong tribo-film formation → excellent wear protection
  - *Technical problem: Many earlier ILs corrosive*
    - **ORNL developed non-corrosive ILs in 2006 (*U.S. patent #7,754,664*)**
- **ILs as oil additives for engine/gear lubrication**
  - Potential multi-functions: AW/EP, FM, etc.
  - Ashless → low sludge
  - Allow the use of lower viscosity oils
  - Advantage: cost effective and easier market penetration
  - *Technical problem: most ILs insoluble in oils (<<1%)*
    - **ORNL invented 1st group of oil-soluble ILs in 2010 (*U.S. patent #9,957,460, 2014 R&D 100 Award*)**
- **ILs as eco-friendly lubricant additives for hydropower/hydraulics**
  - *Problem: many ILs as toxic as traditional additives*
    - **ORNL invented eco-friendly ILs in 2019 (*U.S. Patent #11,760,766*)**

2014 R&D 100 Oak Ridge National Laboratory — Ionic Liquid Anti-wear Additives for Low-Viscosity Engine Lubricants

Ionic liquids are 'room temperature organic molten salts', composed of cations & anions, instead of neutral molecules.



1-alkyl-3-methyl-imidazolium | *N*-alkyl-pyridinium | Tetraalkyl-ammonium | Tetraalkyl-phosphonium ($R_{1,2,3,4}$ = alkyl)

Common Cations

$[PF_6]^-$
$[(CF_3SO_2)_2N]^-$ (Tf_2N)
$[(C_2F_5SO_2)_2N]^-$ (BETI)
$[BR_1R_2R_3R_4]^-$
$[P(O)_2(OR)_2]^-$ (phosphate)
$[P(O)_2(R)_2]^-$ (phosphinate)

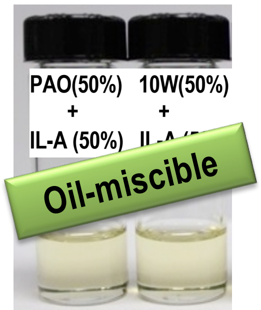
$[BF_4]^-$
$[CF_3SO_3]^-$

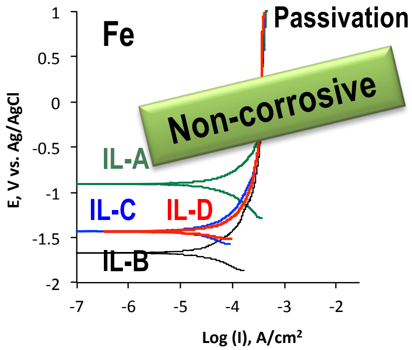
$[CH_3CO_2]^-$
$[CF_3CO_2]^-$, $[NO_3]^-$
Br^-, Cl^-, I^-
$[Al_2Cl_7]^-$, $[AlCl_4]^-$

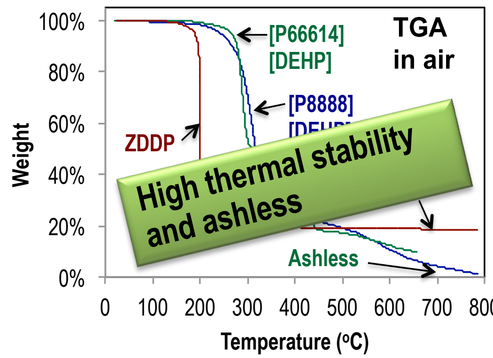
Common Anions

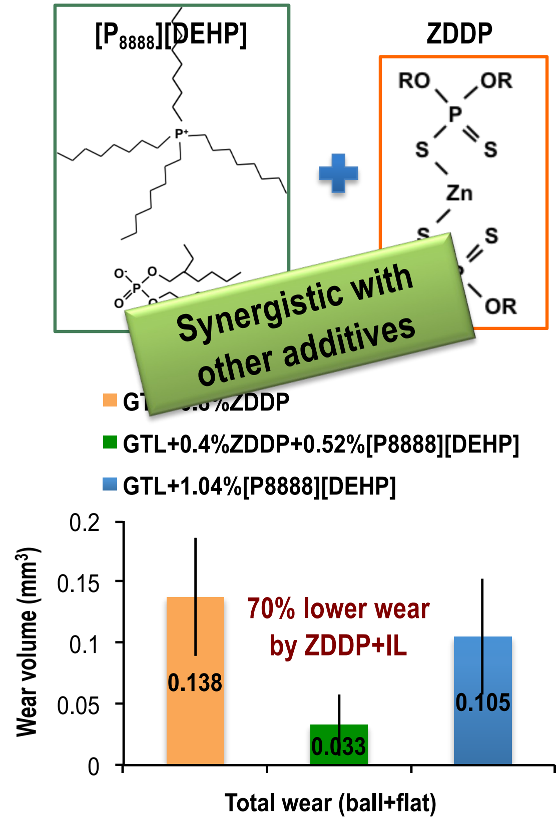
Y. Zhou and J. Qu*, **Ionic liquids as lubricant additives – a review**, *ACS Applied Materials & Interfaces* 9 (2017) 3209.

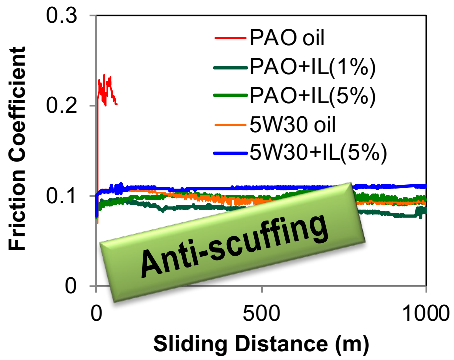
2010 Invented oil-miscible ionic liquids as lubricant additives

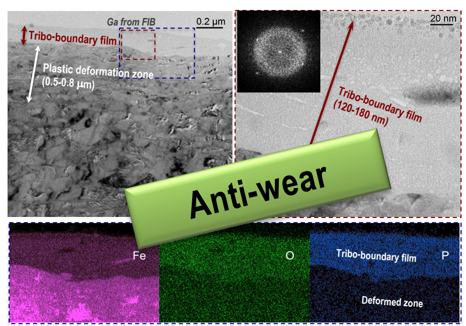








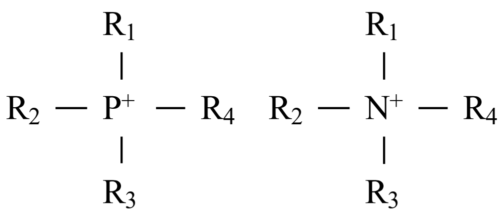




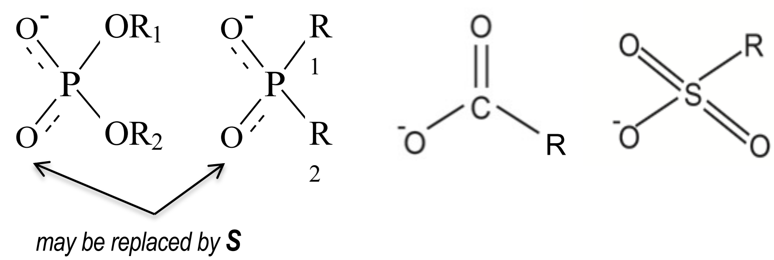
1. J. Qu, et al., ***U.S. Patent #10,435,642***.
2. J. Qu, et al., ***ACS Appl. Mater. Interfaces*** 4 (2012) 997.
3. J. Qu, et al., ***Advanced Materials*** 27 (2015) 4767.

Multiple groups of oil-soluble ILs have been developed

Cation structures



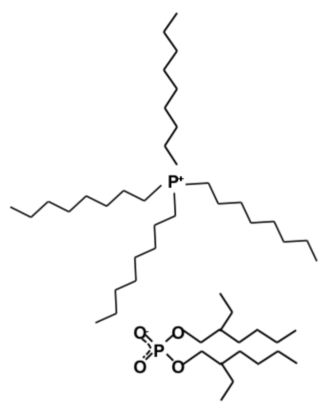
Anion structures



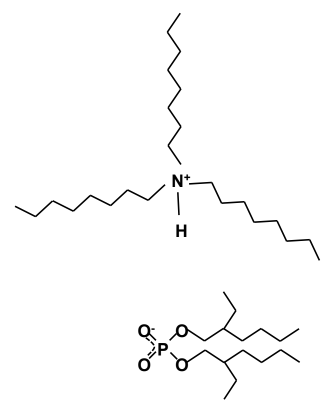
Examples of oil-soluble ILs:

ORNL has developed six groups of ILs fully miscible (>5%) in non-polar base oils.

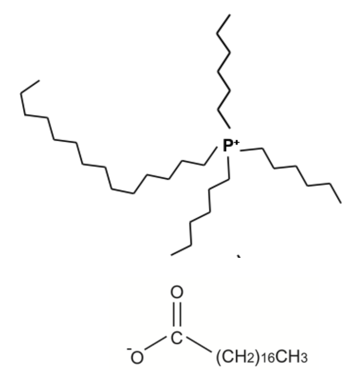
[P_{8888}][DEHP]



[N_{888}H][DEHP]

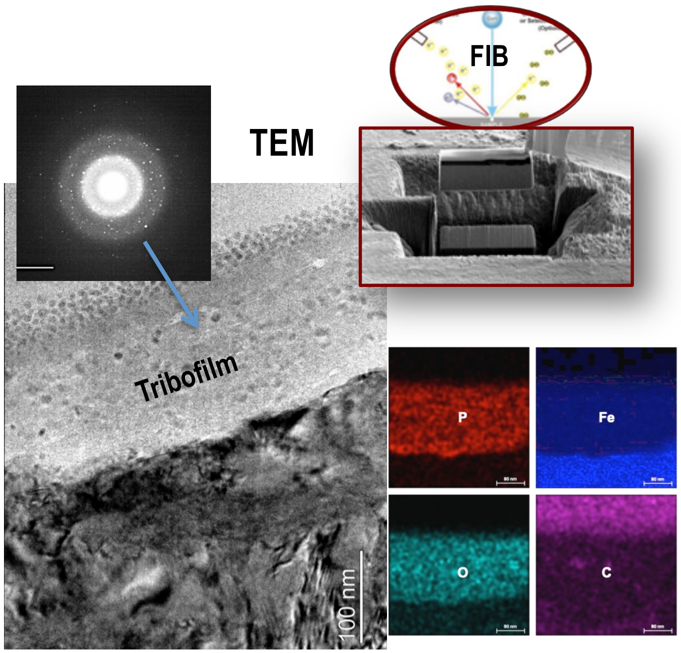


[P_{66614}][$C_{17}H_{35}$COO]

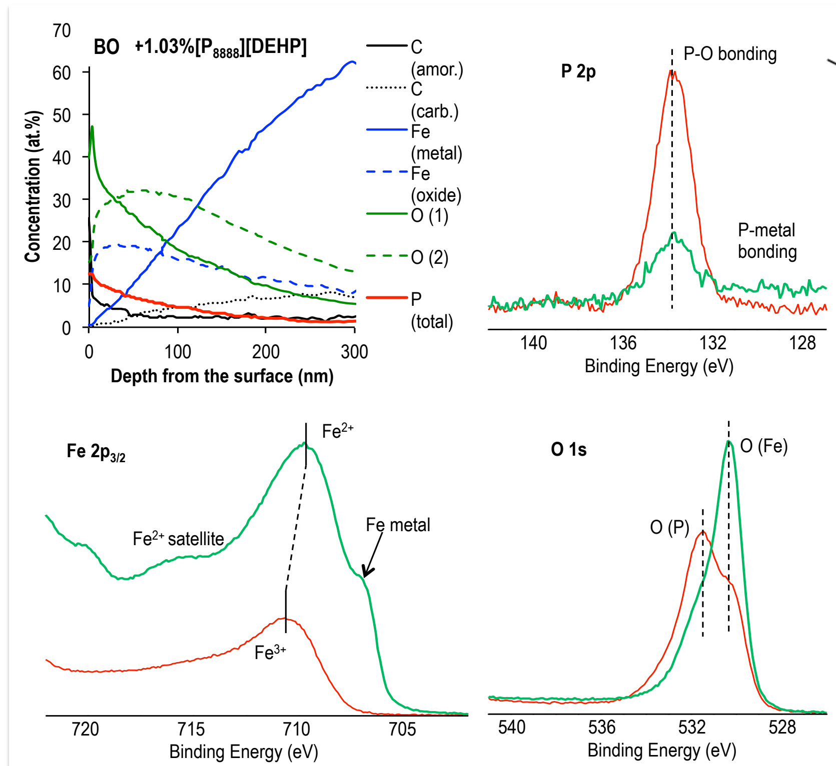


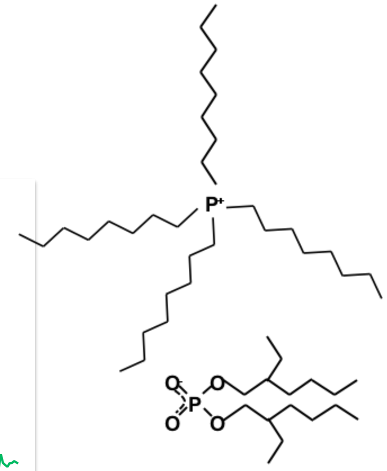
1. J. Qu, H. Luo, ***U.S. Patent #10,435,642,*** 2019.
2. J. Qu, H. Luo, Y. Zhou, J. Dyck, T. Graham, U.S. ***Patent Application 14/444,029***, 2014.

Tribofilm by phosphonium-phosphate [P_{8888}][DEHP]



XPS





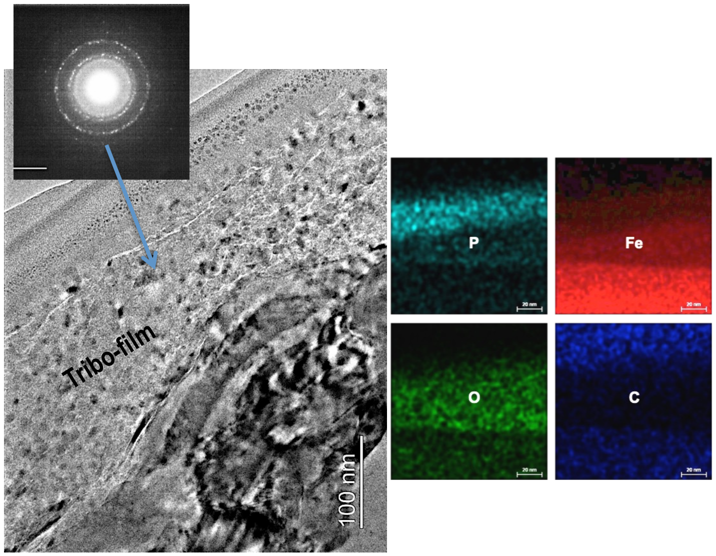
Tribofilm (up to 300 nm) on iron:

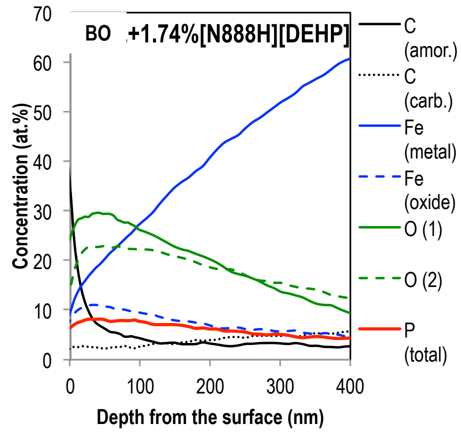
- Iron phosphates (~50 at%),
- Iron oxides (~50 at%),
- Metallic iron (<1 at%).

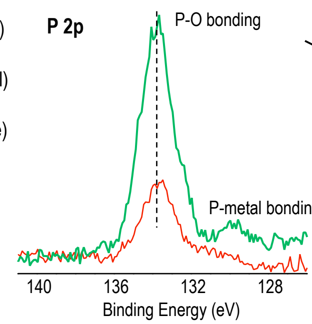
OAK RIDGE National Laboratory

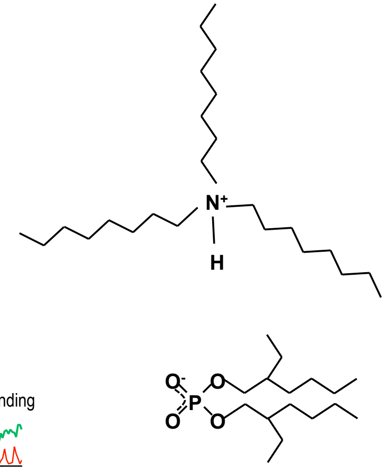
W.C. Barnhill and J. Qu*, et al., ***ACS Applied Materials & Interfaces*** 6 (2014) 22585.

Tribofilm by ammonium-phosphate [N_{888}H][DEHP]



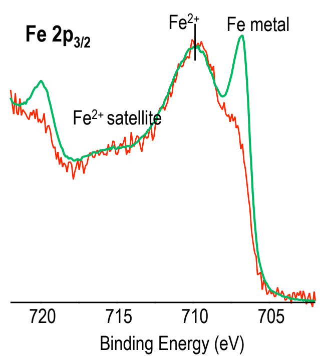


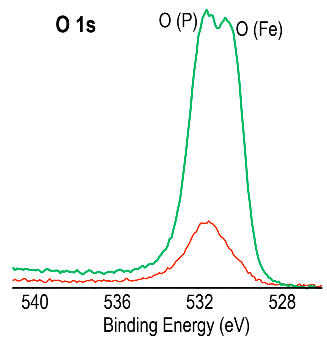




Tribofilm (up to 400 nm) on iron:

- Iron phosphates (30-40 at%),
- Iron oxides (40-50 at%),
- Metallic iron (10-15 at%).

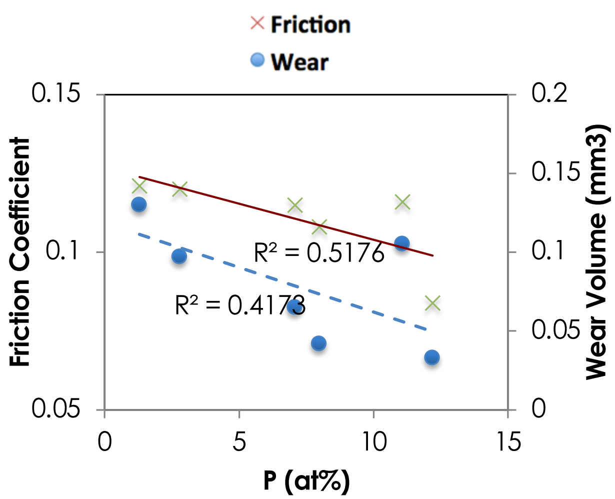


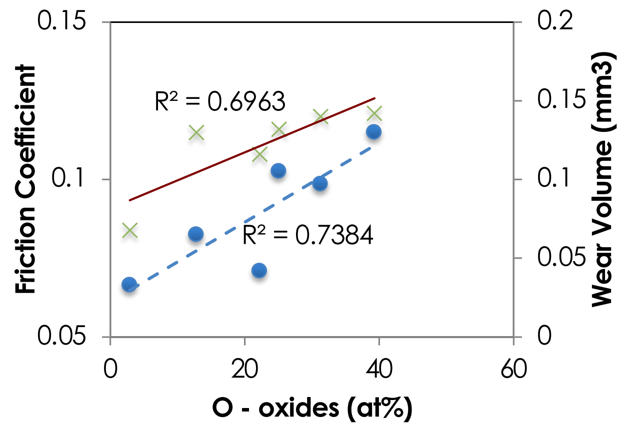


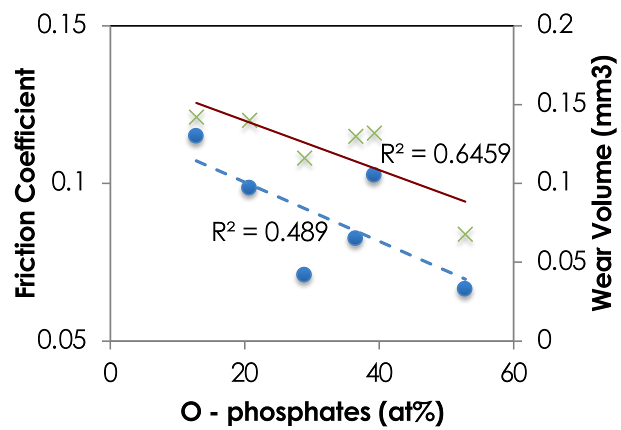
W.C. Barnhill and J. Qu*, et al., ***Tribology Letters*** *63 (2016) 22.*

Correlating friction and wear performance to the tribofilm chemical composition

- Higher content of metal phosphates → lower friction and wear
- Higher content of metal oxides → higher friction and wear

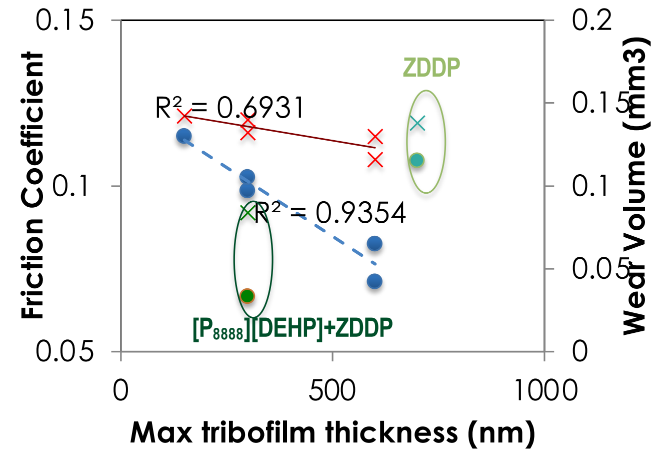


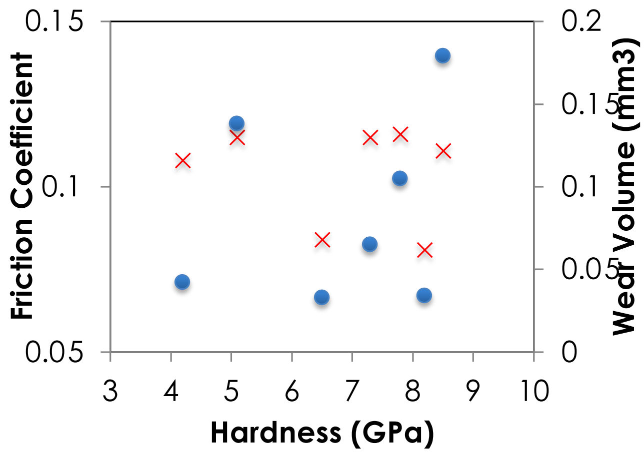


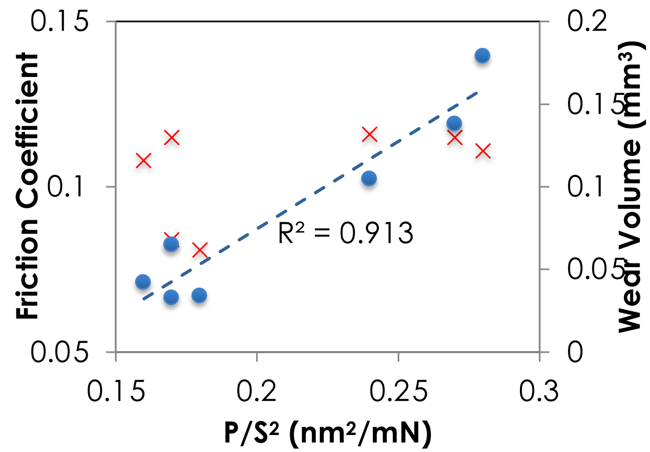


Correlating to the tribofilm thickness and mechanical properties

- Thicker tribofilm often leads to lower friction and wear
- No correlation between tribofilm hardness with friction or wear
- **Lower ratio of load to stiffness squared (P/S^2) leads to less wear**
  - P/S^2 representing the resistance to plastic deformation
  - Opposite trend to literature reports for bulk or coating materials
  - Attributed to the dynamic, sacrificial and self-healing nature

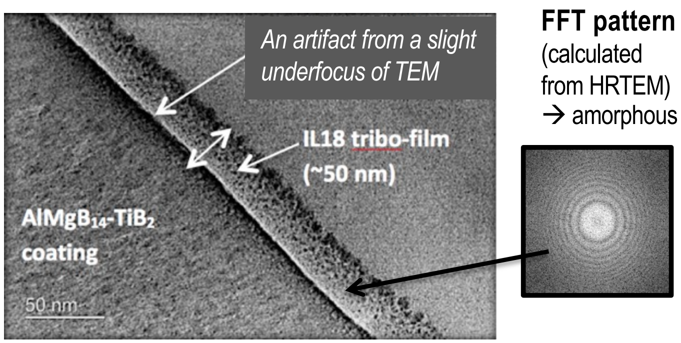




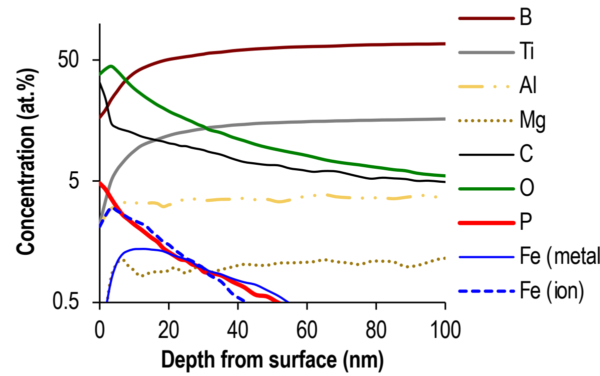


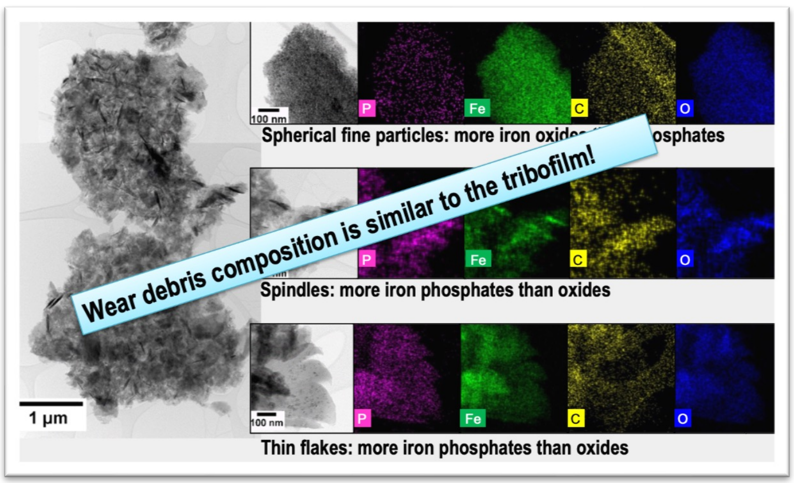
A.K. Landauer, W.C. Barnhill, J. Qu*, ***Wear*** 354-355 (2016) 78.

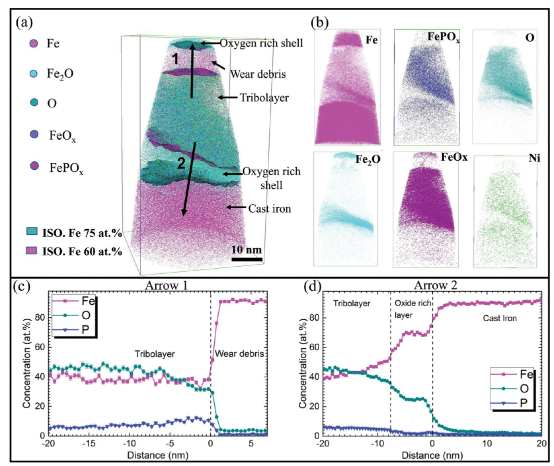
Understand the IL tribofilm formation process



The iron-free coating surface eliminates the ambiguity of the source of Fe in the tribofilm.



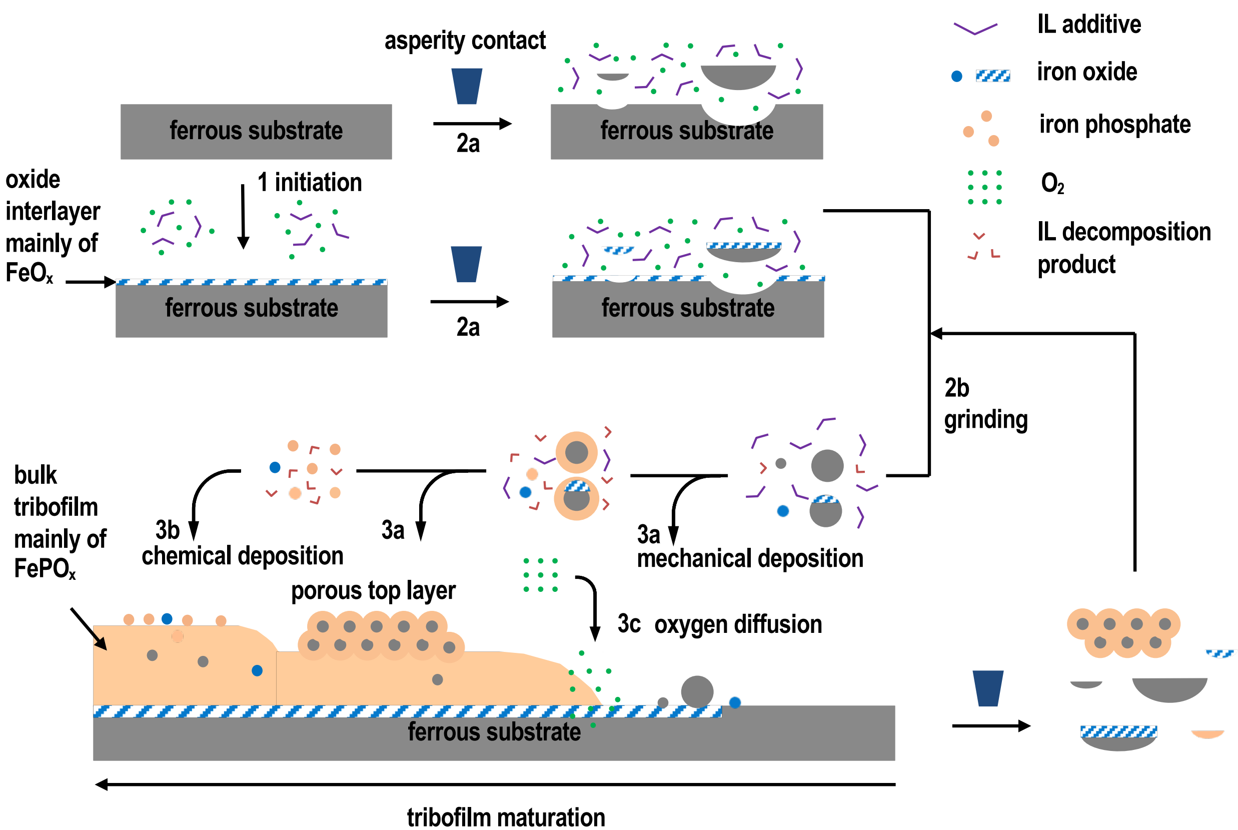




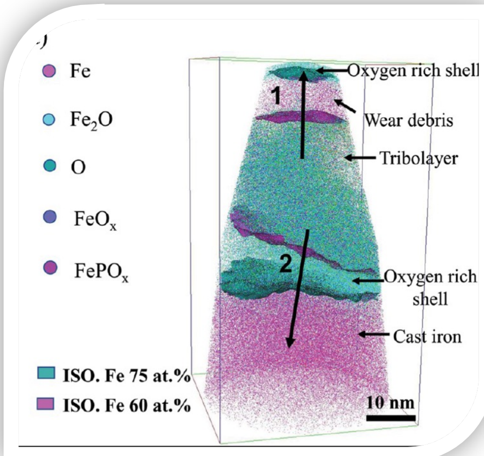
3D atom probe tomography (APT) reconstruction of the IL tribofilm showing a layered structure.

J. Qu*, et al., ***Wear*** 332-333 (2015) 1273.
Y. Zhou*, D.N. Leonard, W. Guo, J. Qu*, ***Scientific Reports*** 7 (2017) 8426.
W. Guo*, Y. Zhou, and J. Qu*, et al., ***ACS Applied Materials & Interfaces*** 9 (2017) 23152.

Wear debris evolution-based tribofilm growth model for ILs



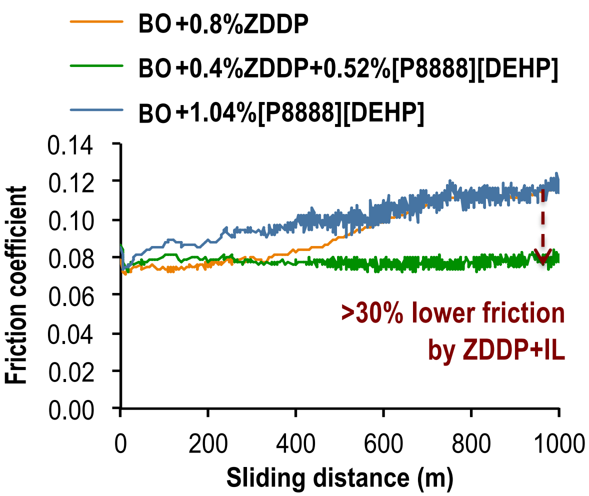
Good correlation with the APT revealed IL tribofilm structure

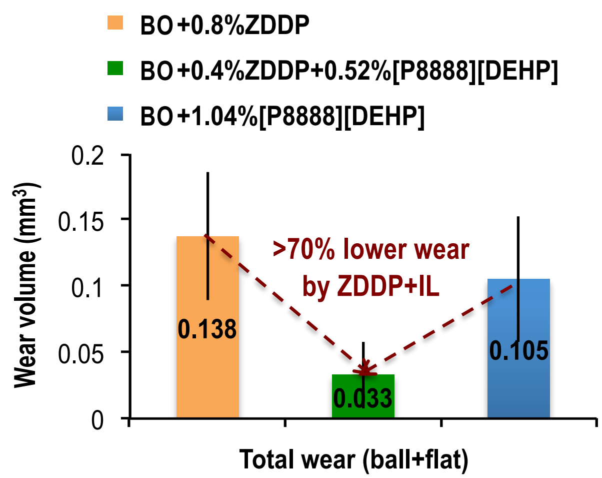


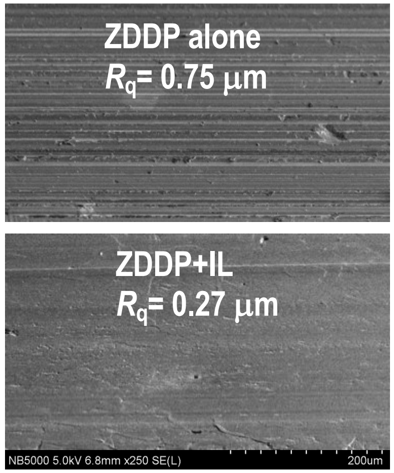
Y. Zhou* and J. Qu*, et al., ***Scientific Reports*** 7 (2017) 8426.
W. Guo*, Y. Zhou, and J. Qu*, et al., ***ACS Applied Materials & Interfaces*** 9 (2017) 23152.

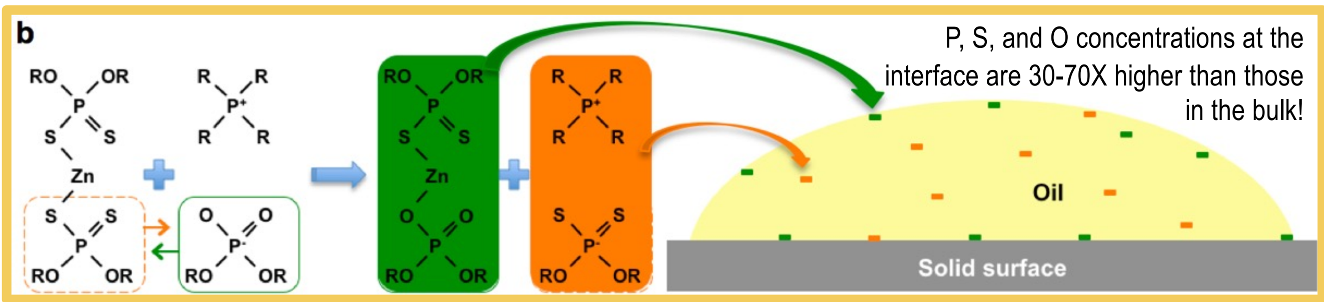
OAK RIDGE National Laboratory

2013 discovered synergistic effects between phosphonium-phosphate ILs and ZDDPs





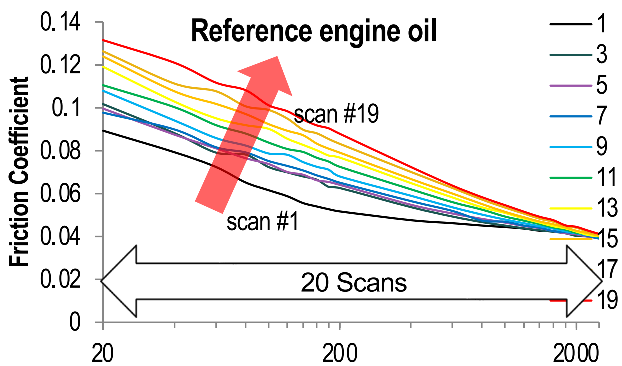


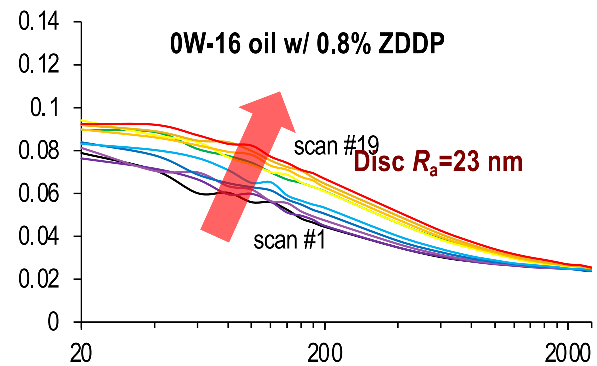


No synergy between ammonium-phosphate ILs and ZDDP though…

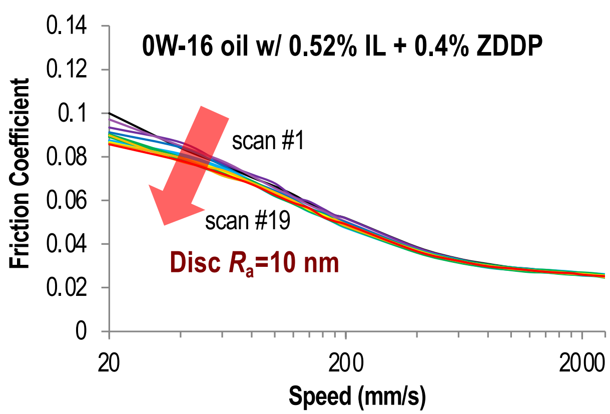
J. Qu, et al., ***Advanced Materials*** 27 (2015) 4767.

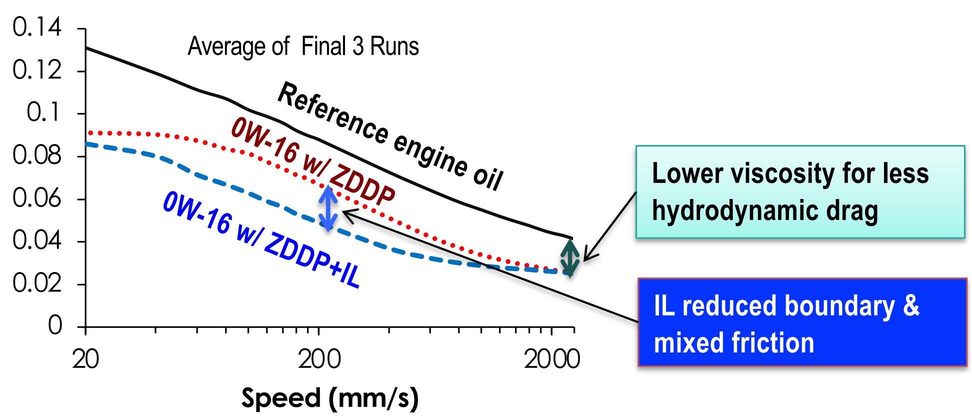
Prototype IL+ZDDP additized engine oil demonstrated lower boundary and mixed friction





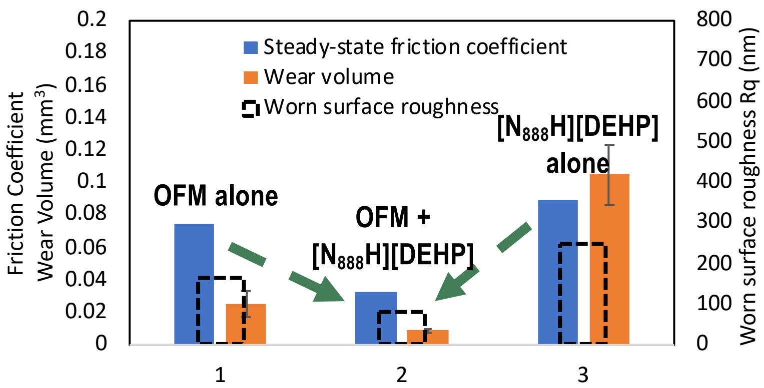
- 30 N load
- 100 ºC
- Slide-roll ratio: 100%





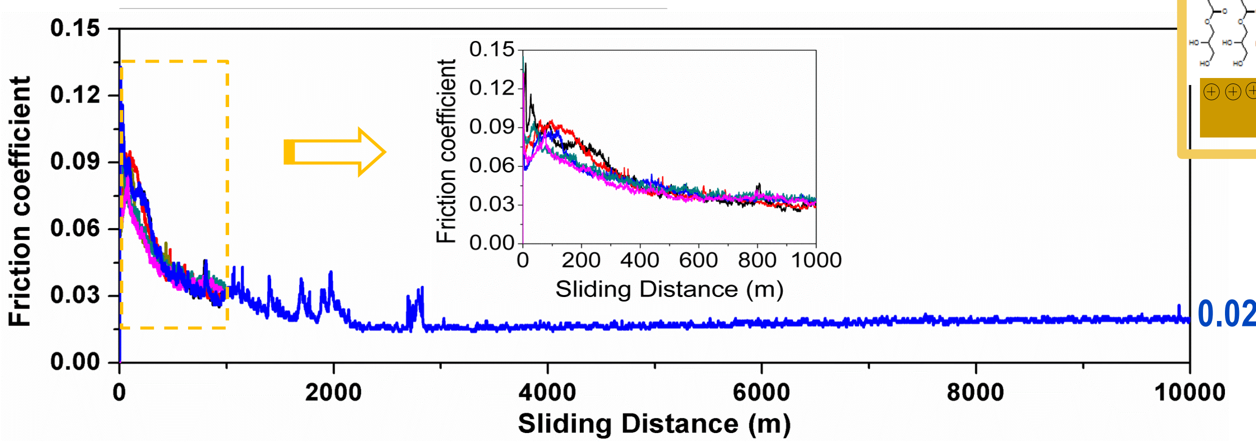
W.C. Barnhill and J. Qu*, et al., ***Frontiers in Mechanical Engineering***, 1 (2015) 12.

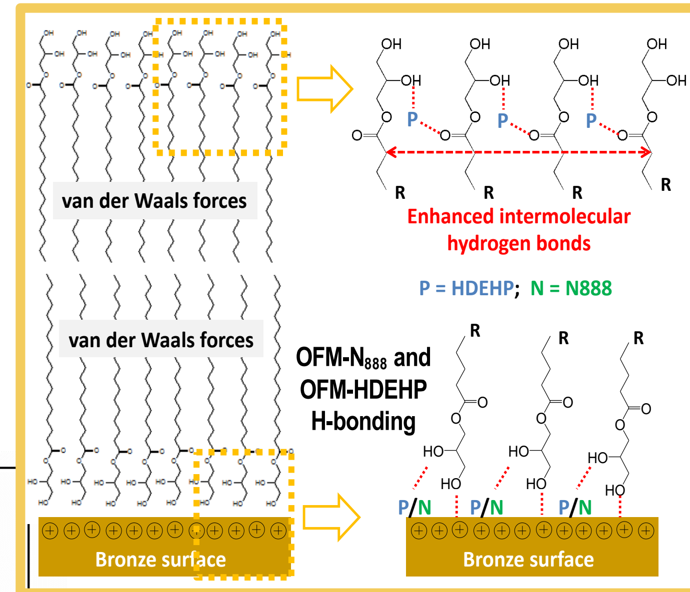
2018 ORNL discovered synergistic effects between ammonium-phosphate ILs and OFM



>60% reduction in friction coefficient

>65% reduction in wear volume of bronze



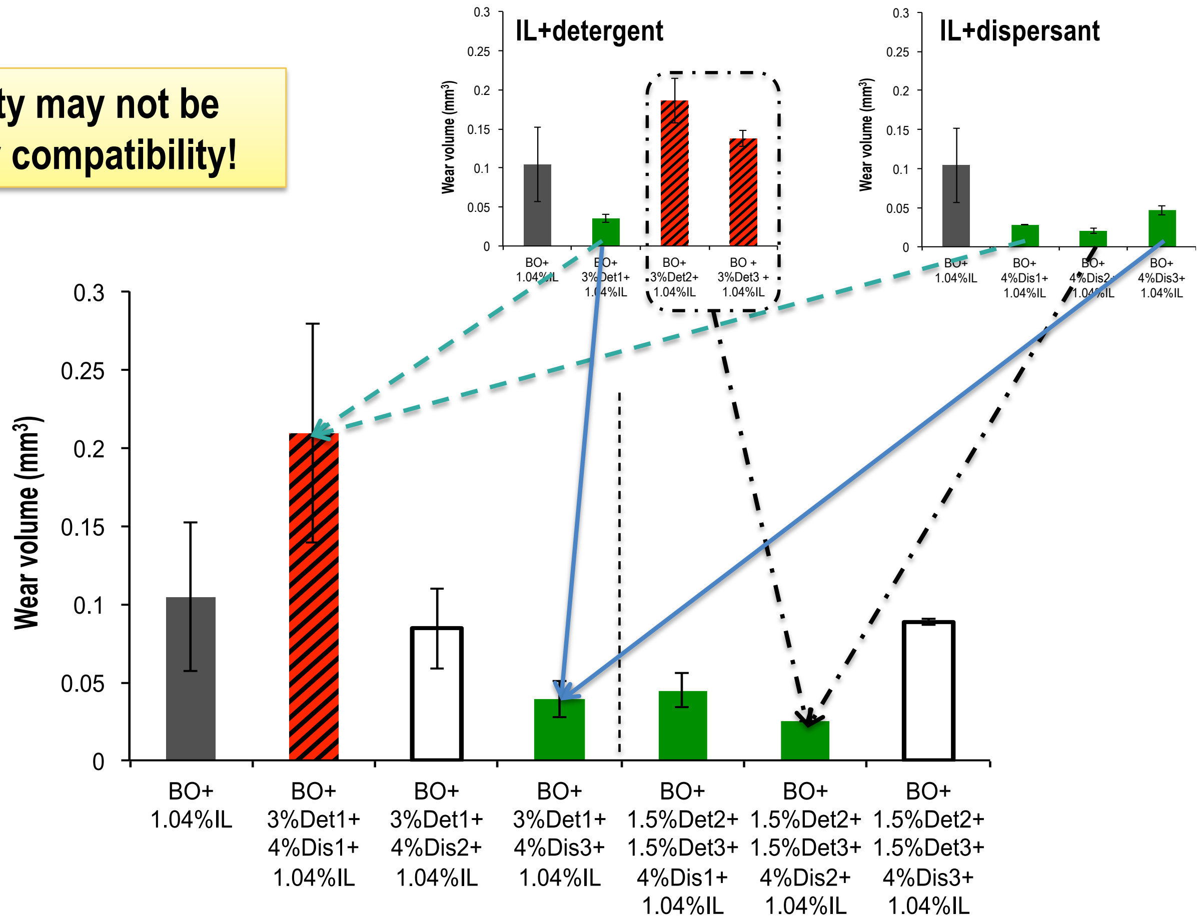


No synergy between phosphonium-phosphate ILs and OFM though…

W. Li, J. Qu*, et al., ***Langmuir*** 34 (2018) 10711.

Introducing ILs into a fully-formulated lubricant is rather complex…

2-way compatibility may not be translated to 3-way compatibility!

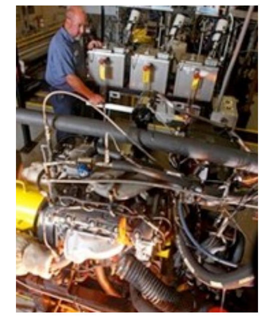


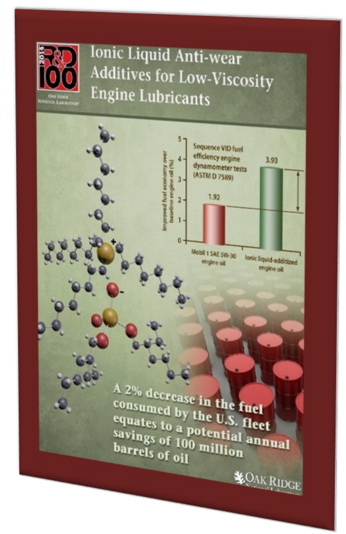
2013 Demonstrated improved fuel economy in engine dyno tests for IL-additized experimental oil

Sequence VIE (ASTM D7589) FEI 1 fuel economy engine dyno tests at InterTek

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Engine condition	2000 rpm, 105 N-m, 115 °C	2000 rpm, 105 N-m, 65 °C	1500 rpm, 105 N-m, 115 °C	695 rpm, 20 N-m, 115 °C	695 rpm, 20 N-m, 35 °C	695 rpm, 40 N-m, 115 °C
Lubrication regime	Dominated by **HD/EHD** lubrication			More **boundary & mixed** lubrication		
0W-16 w/ ZDDP vs. BLB	2.36%	2.84%	1.66%	3.72%	5.98%	3.03%
0W-16 w/ ZDDP+IL vs. BLB	**2.54%**	**2.91%**	**1.77%**	**4.48%**	**6.46%**	**3.81%**
ZDDP+IL vs. ZDDP only	**0.17%**	**0.07%**	**0.11%**	**0.76%**	**0.48%**	**0.79%**

1.77 – 6.46% fuel economy improvement (FEI) for the prototype IL+ZDDP additized experimental oil over the standard baseline





- J. Qu, et al., ***U.S. Patent #10,435,642*** licensed to Driven Racing Oil, 2019.
- J. Qu, et al., ***2014 R&D 100 Awards.***
- J. Qu, et al., ***Frontiers in Mechanical Engineering***, 1 (2015) 12.

Prototype IL-additized low-viscosity engine oil demonstrated 9.9% increased fuel economy in a racing engine

Engine dyno running stages (V8, 90 mins)

1. 15 minutes @ 1,500 RPM - 140 ft lbs, Dyno Sweep To 6,000 RPM at max 140-500 ft lbs, stop-start
2. 15 minutes @ 2,900 RPM - 140 ft lbs, Dyno Sweep To 6,000 RPM
3. 15 minutes @ 1,750 to 4,500 RPM (5 second acceleration and 10 second deceleration) – 100-300 ft lbs, Dyno Sweep To 6,000 RPM
4. 15 minutes @ 4,500 RPM - 175 ft lbs, Dyno Sweep To 6,000 RPM

IL replacing half ZDDP with IL to maintain P content @ ~800 ppm	Oil temp (ºC)	Torque (lb-ft)	Fuel consump. (lb)	FEI vs. SN 5W-30	Metal in used oil (ppm)		
					Fe	**Cu**	**Al**
SN SAE 5W-30	121	n/a	31.85	-	5	6	1
Synthetic SAE 0W-20	121	506	n/a	n/a	3	0	2
CPO 334 w ZDDP alone SAE 0W-12	120	505	30.4	4.4%	2	1	3
CPO 334+ZDDP+IL SAE 0W-12	**117**	**510**	**28.7**	**9.9%**	**3**	**1**	**3**

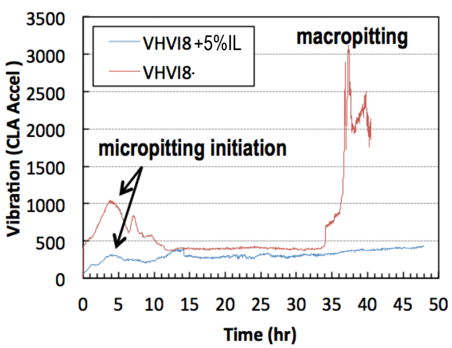
Such a significant FEI reflected the benefits of using the IL-additized oil at harsh engine operation conditions when boundary/mixed lubrication friction has high impact.

C. Kumara* and J. Qu*, et al., ***ACS Sustainable Chemistry & Engineering*** 9 (2021) 7198.

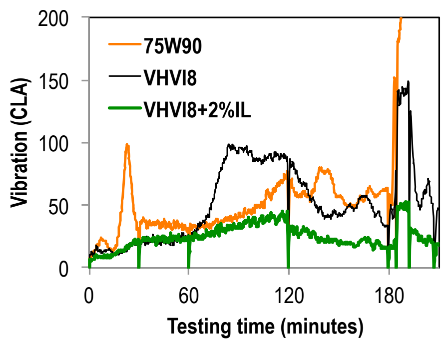
ILs as Gear Oil Additives to Improve Durability and Efficiency

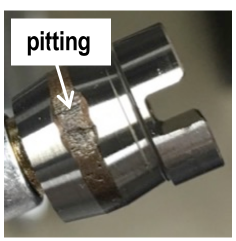
Adding 2-5% IL to oil significantly reduced rolling contact fatigue, sliding wear, and vibration

Case 1. Extreme conditions:
500 N,100 °C, 3.5 m/s, 3% SRR
48 hr (42 million cycles)



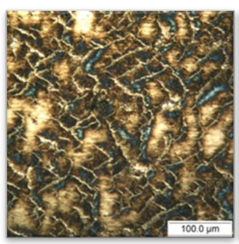
Case 2. Moderate conditions:
165-350 N, 55-120 °C, 3.5 m/s, 1.5% SRR
3.5 hr (2.6 million cycles)



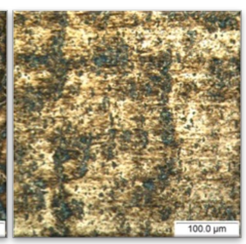


Roller tested in base oil

Roller tested in base oil + 5% IL



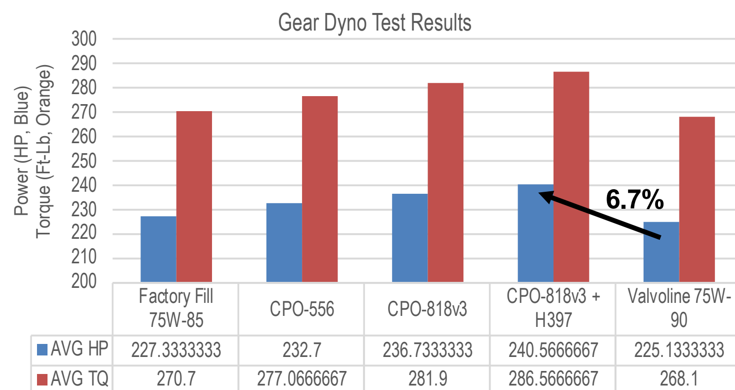
Roller surface tested in base oil



Roller surface tested in base oil + 2% IL

2018 Gear dynamometer tests increased 6% of the power output by using an IL-additized gear oil

Oil	Viscosity @ 40 C (cSt)	Viscosity @ 100 C (cSt)	Viscosity index	Iron in used oil (PPM)
80W-90 GL-5, Mineral				13
Valvoline Synpower (Racing) 75W-90	100	15	150	3
CPO-818v3	**34.7**	**7.8**	**210**	**4**



OAK RIDGE National Laboratory

2020 developed new ILs with much lower toxicity than ZDDP and previous ILs

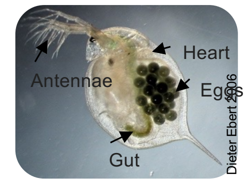
Survival in acute toxicity test (5 days)

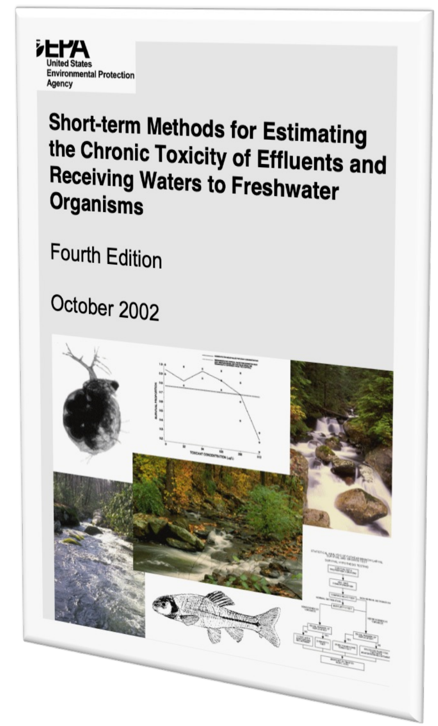
ILs previously developed for automotive engines

# of survivals	Neat PAG	PAG + 5% IL-1	PAG + 5% IL-2	PAG + 5% [N888H][DEHP]	PAG + 5% [P8888][DEHP]	PAG + 5% ZDDP
Day 1	10	10	10	10	10	10
Day 2	10	10	10	6	0	0
Day 3	10	10	10	0	0	0
Day 4	10	10	10	0	0	0
Day 5	**10**	10	10	**0**	**0**	**0**

Reproduction in chronic toxicity test (7 days)

# of neonates per day	Neat PAG	PAG + 5% IL-1	PAG + 5% IL-2	PAG + 5% [N888H][DEHP]	PAG + 5% [P8888][DEHP]	PAG + 5% ZDDP
Day 1	0	0	0	0	0	0
Day 2	0	0	0	0	0	0
Day 3	32	36	45	0	0	0
Day 4	2	0	13	0	0	0
Day 5	91	98	82	0	0	0
Day 6	128	159	141	0	0	0
Day 7	175	201	172	0	0	0
Grand Total	**428**	494	453	**0**	**0**	**0**




EPA
United States Environmental Protection Agency

Short-term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms

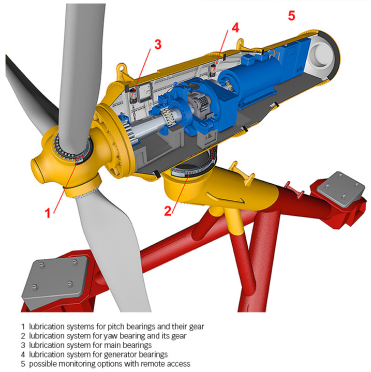
Fourth Edition

October 2002

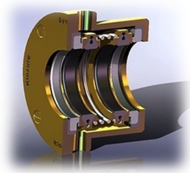
J. Qu, H.M. Luo, X. He, ***U.S. Patent #11,760,766***, 2023.

Eco-friendly ILs for tidal turbine lubrication

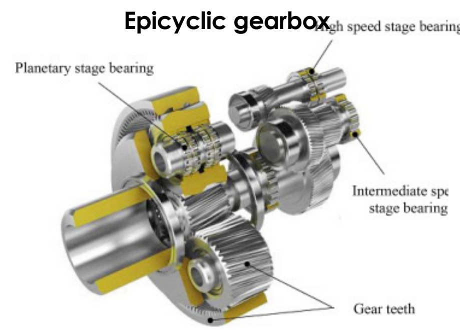
- Current lubricants for tidal turbines are basically borrowed from those for wind turbines, **however lubricating a tidal turbine are far more challenging:**
  - **Slower speed and higher force** and thus no full-film lubrication, leading to higher wear risk, which largely **rely on the protection of the anti-wear additives in the lubricant.**
  - **Lubricant more prone to a high water/moisture content,** causing degraded lubricity.
  - **Longer maintenance intervals of up to 6 years,** because the difficulties to access and maintenane.
- **Conventional gear oils are harmful and pose a significant threat to the marine ecosystems,** because they would contaminate the water directly upon spill or leak and violate the U.S. Clean Water Act's 'non-sheening rule'.
- While EPA has approved multiple groups of EAL base fluids, **there is lack of additives that are both non-toxic and effective in friction reducing and wear protection**.



Seal



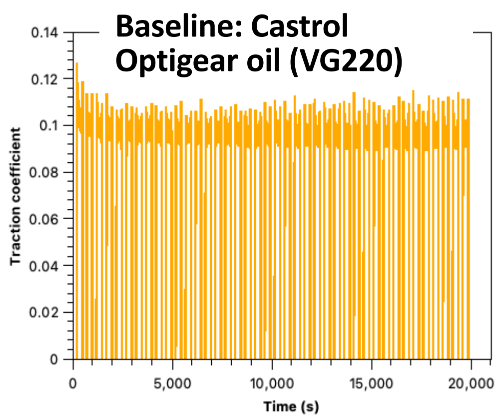
Epicyclic gearbox



Roller bearing

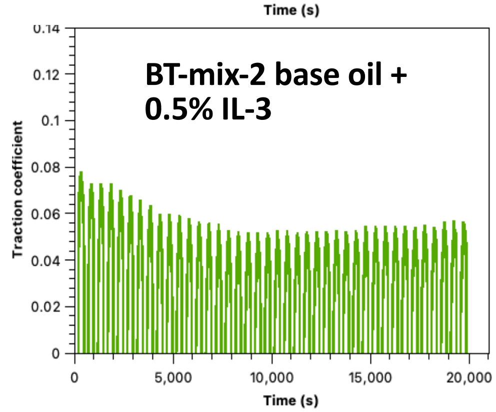
Oak Ridge National Laboratory

Lubricity: ORNL's new ILs demonstrated 50% reduction in friction and wear compared with the baseline gear oil



Steady-state
μ ~0.1

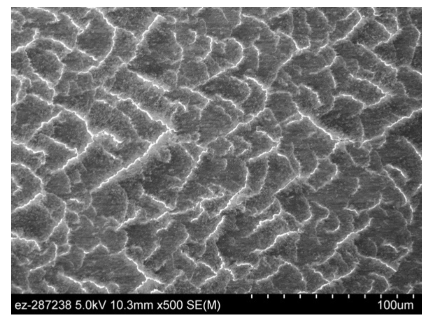
~50% friction reduction



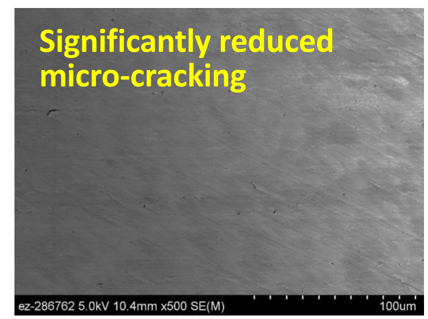
Steady-state
μ ~0.05

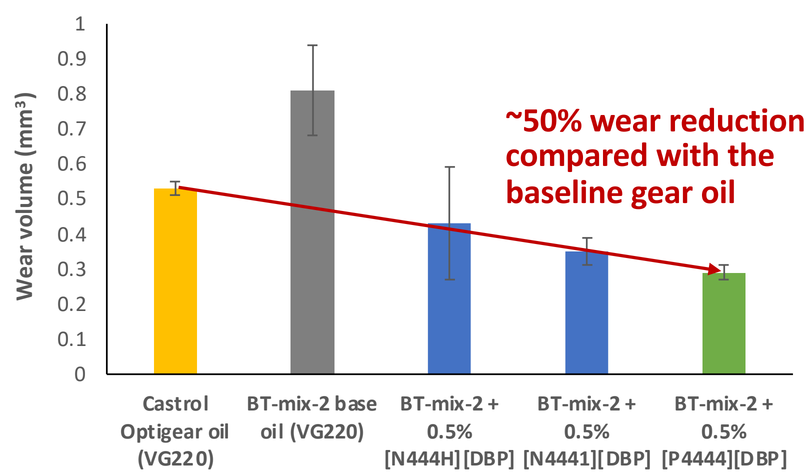
*Simulating the front bearing @ 100 ºC

Castrol Optigear oil (VG220)



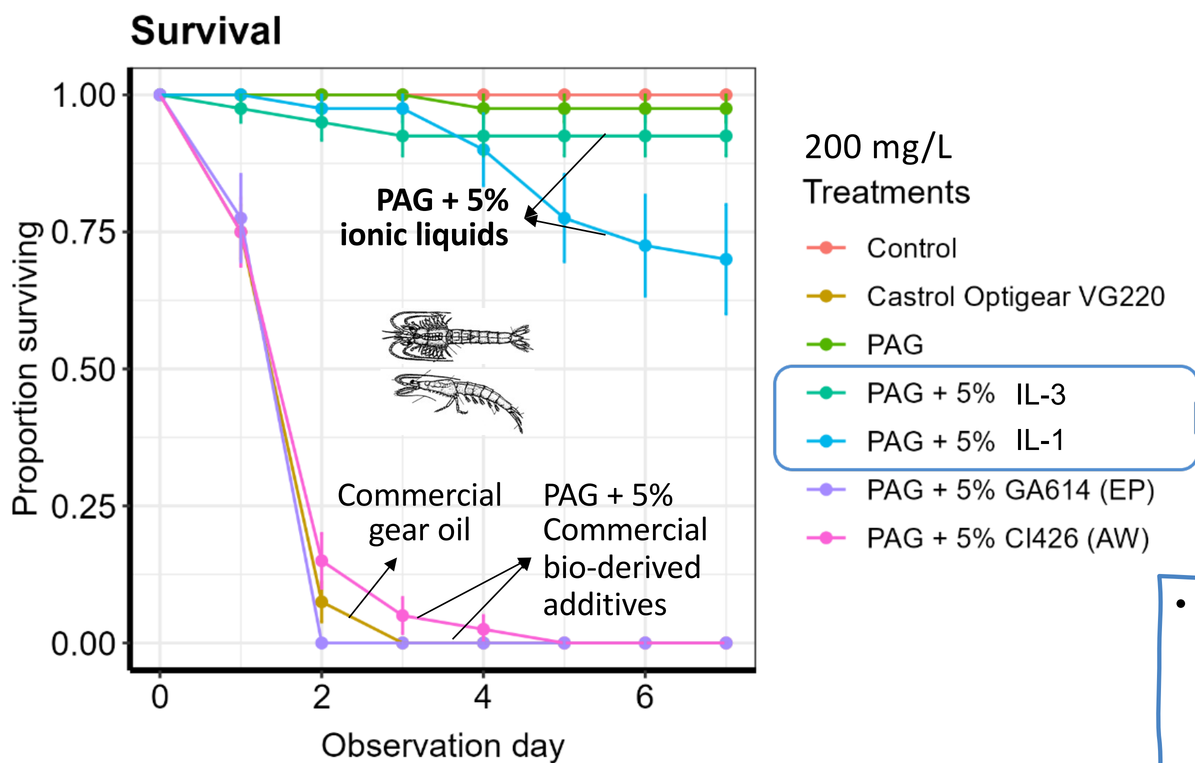
BT-mix-2 + 0.5% IL-3





OAK RIDGE National Laboratory

Toxicity: ORNL's new ILs can be classified as '*Not Toxic to aquatic organisms*' based on on-going sea water toxicity tests



Acute Toxicity Categories for aquatic environment based on 48-hr EC_{50} (crustacea)

- Very toxic (<=1 mg/L)
- Toxic (1-10 mg/L)
- Harmful (10-100 mg/L)
- **Not toxic (>100 mg/L)**

- **Potential impact**
  - Reduce the environmental impact
  - Improve the energy conversion efficiency
  - Enhance the turbomachinery durability and reliability

Oak Ridge National Laboratory

[2] Chemical hazard classification and labeling: comparison of OPP requirements and the GHS, 2004.

Key fundamental questions remained to be answered

- **Impact of marine water/moisture content in the lubricant?**
  - **Marine water/moisture getting into the tidal turbine oil is inevitable** during the multi-year operation.
  - What's **the impact on the viscosity, lubricity, and corrosion of the ionic liquid-enhanced eco-friendly lubricants** in comparison with that on the commercial baseline oils?
- **Effects of lubricant aging?**
  - **The promising results in Phase 1 were from fresh lubricants**; **however, lubricant aging** involving oxidation, decomposition, and reactions with the bearing/gear surfaces, **is inevitable** in the tidal turbine operation.
  - What's the **aging behavior of our ionic liquid-enhanced eco-friendly lubricants** in comparison with that of the commercial baseline oils?
- **Feasibility of lower-viscosity lubricants**?
  - **The promising results in Phase 1 were based on the same viscosity grade** with the baseline gear oils.
  - **A lower oil viscosity is expected to reduce the hydrodynamic drag and environmental impact**; however, it inevitably posts a higher risk of wear – **would the ionic liquids provide adequate wear protection to allow the use of lower viscosity lubricants?**

Team and Collaborators

- **My current tribo-team**: C. Kumara, T. Grejtak, W. Wang
- **Internal collaborators** (long term):
  - CNMS: M. Chi, R. Unocic, K. Xiao, K. An
  - CSD: S. Dai, H. Meyer, N. Gallego
  - ESD: T. Mathews, L. Stevenson, P. Ku
  - MDF: A. Elliot, N. Niyanth, R. Dehoff
  - MSD: H. Luo, T. Toops, B. West
  - MSTD: P. Blau, J. Keiser, J. Truhan, H. Wang, L. Lin, T. Watkins, Z. Feng, H. Bei, M. Lance, D. Leonard, B. Armstrong, A. Shaym, D. Pierce, M. Brady, E. Lara-Curzio
- **Other national labs**:
  - ANL: G. Fenske, O. Ajayi
  - INL: J. Lacey, M. Kuns, D. Hartley, V. Thompson, D. Thompson
  - NREL: E. Wolfrum, R. Elandar, S. Sheng
  - PNNL: L. Cosimbescu, R. Cavagnaro
  - SNLs: M. Dugger, V. Neary
- **Academia**:
  - Central FL: L. An
  - PSU: K. Seong
  - TAMU: H. Liang
  - Temple: F. Ren
  - U Iowa: H. Ding
  - UTK: B. Zhao
- **Industrial partners** (formal collaborations):
  - Biosynthetic: M. Woodfall, M. Miller
  - Cummins: R. England, C. Wang
  - Danfoss: T. Li, A. Rezaei, N. LaTray
  - Driven Racing Oil: L. Speed, J. Coleman
  - Eaton: D. Zhu, A. Elmoursi, C. Higdon
  - Ford: A. Gangopadhyay, H. Ghaednia, D. Uy
  - Forest Concepts: D. Lanning, C. McKiernan
  - GM: S. Tung, M. Viola
  - Hayward Tyler: K. Oldinski
  - Hyundai: I. Lyo
  - Lubrizol: E. Bardasz
  - Rawlings: J. Rawlings
  - Shell: B. Papke, H. Gao, D. Uy
  - Solvay: J. Dyck, E. Conrad, C. Chretien
  - Swagelok: P. Williams
  - Trane: W. Akram, M. Herried, A. Poslinski
  - Valvoline: R. England, N. Ren, J. Bonta, E. Murphy
  - Westinghouse: R. Lu, M. Conner

The key to success is collaboration!

Postdoc openings at ORNL

- Postdoc position 1: **Surface Science and Engineering**
  - https://jobs.ornl.gov/job/Oak-Ridge-Postdoctoral-Research-Associate-Surface-Science-and-Engineering-TN-37830/1085481400/
  - **Polymer surface characterization and modification**
  - Including but not limited to plasma treatment, as well as investigation and mitigation of adhesion and transfer of third-body material at contact interfaces under pressure and shear
  - **Subject to export control requirements: Yes**
- Postdoc position 2: **Thermal Degradation**
  - https://jobs.ornl.gov/job/Oak-Ridge-Postdoctoral-Research-Associate-Thermal-Degradation-TN-37830/1088612800/
  - **Organic thermal degradation in energy conversion and storage**
  - Development of a unique thermal-sensitive coating for alarming thermal runaway of energy storage systems including electric vehicle batteries
  - Investigation and mitigation of biomass fouling under combined thermal and mechanical stresses in biofuel preconversion
  - **Subject to export control requirements: No**

- ***Contact****: Jun Qu, Group Leader of Surface Engineering and Tribology, ORNL qujn@ornl.gov*