Examining Effects of Lubricant Composition in Engine Component Systems in Pursuit of Enhanced Efficiency under Environmental Constraints

2012 Directions in Engine-Efficiency and Emissions Research Conference

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Dearborn, MI

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Friction/efficiency improvement in engines require developments in multiple areas:

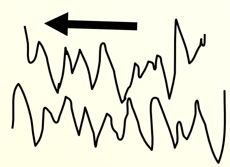
Mechanical Design, Operation:
- Power density
- Sliding, rotational speeds
- Component dynamics; contacts and loading
- Fluid-film vs metal-metal
- Distortions, clearances, film thicknesses

Material and Surface Characteristics:
- Coatings, roughness, textures, dimples, etc.

Lubricant Formulation
- **Base oil, additives:** **Advanced control of in-situ properties and composition**

CONSTRAINTS:
1. **Wear/Durability:**
   - **Film Thickness**
2. **Emissions/Oil Consumption**
3. **Cost: Material, manufacturing, user operating cost**

Engine-Component Lubrication/Friction Analysis and Design



Lubricant appears to be the key link to material & mechanical design

Lubricant formulation is an essential strategy in overall friction reduction and engine efficiency improvement

Cooperative Agreement #DE-EE0005445 (2011-2014)

Project: Lubricant Formulations to Enhance Engine Efficiency in Modern Internal Combustion Engines

Lubricant Formulation

- Base-oil, additives: requirements, optimization

DOE-NETL
Current Program

Goal: 10% mechanical efficiency improvement

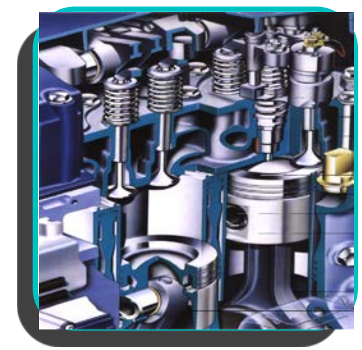
Among other approaches investigated previously/elsewhere:

- Mechanical Design, component micro-geometries, operation:
- Material and Surface Characteristics:

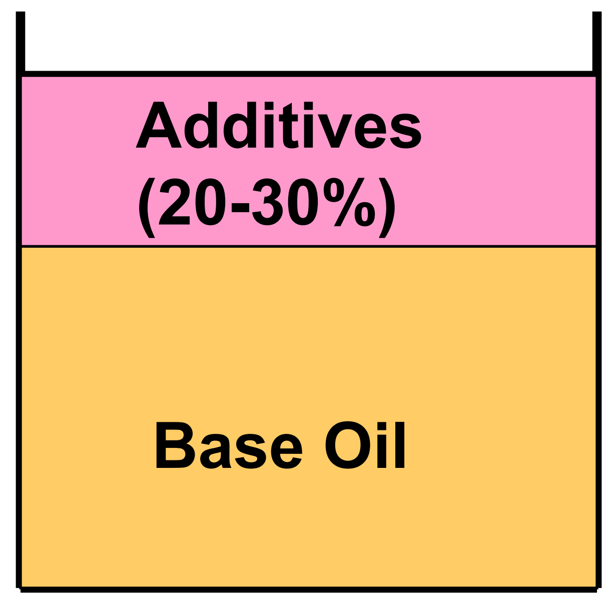
Our approach is to examine strategic control of lubricant properties and composition in engine in subsystems

1. **Base Oil: HC's providing basic lubrication**

   API Groups: I, II (low S), III (low S, high VI), IV: synthetic, V other



2. **Additives:**
   - **Detergents**
   - **Dispersants**
   - **Anti-Wear**
   - **Anti-oxidants**
   - **VI and Friction Modifiers**
   - **Anti-foam**
   - **Pour-point depressants**
   - **Extreme-pressure wear, etc**



Four lubricant technical themes that aim to work synergistically to advanced engine technologies:

1. Controlling oil/additive properties in local areas that matter most in specific engine subsystems

2. Interfacing with engine technologies that affect “in-situ” effective lubricant properties in action

3. Optimizing lubricant “formulation:” the complete package – viscous/boundary friction, wear

4. Ascertaining compatibility with lubricant/additive-emission control system: lubricant/additives affect fuel economy of engine operation beyond friction

Four lubricant technical themes that aim to work synergistically to advanced engine technologies:

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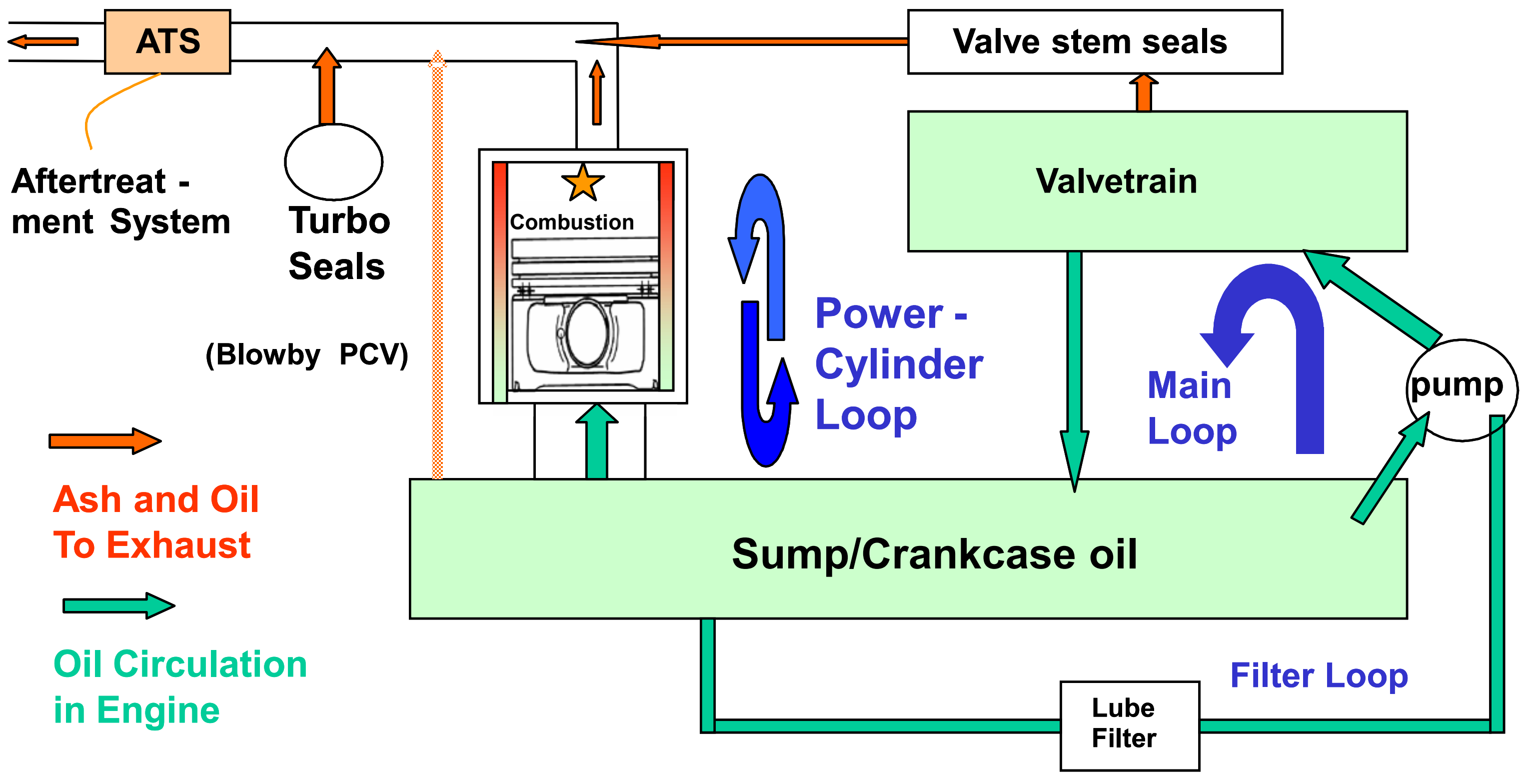
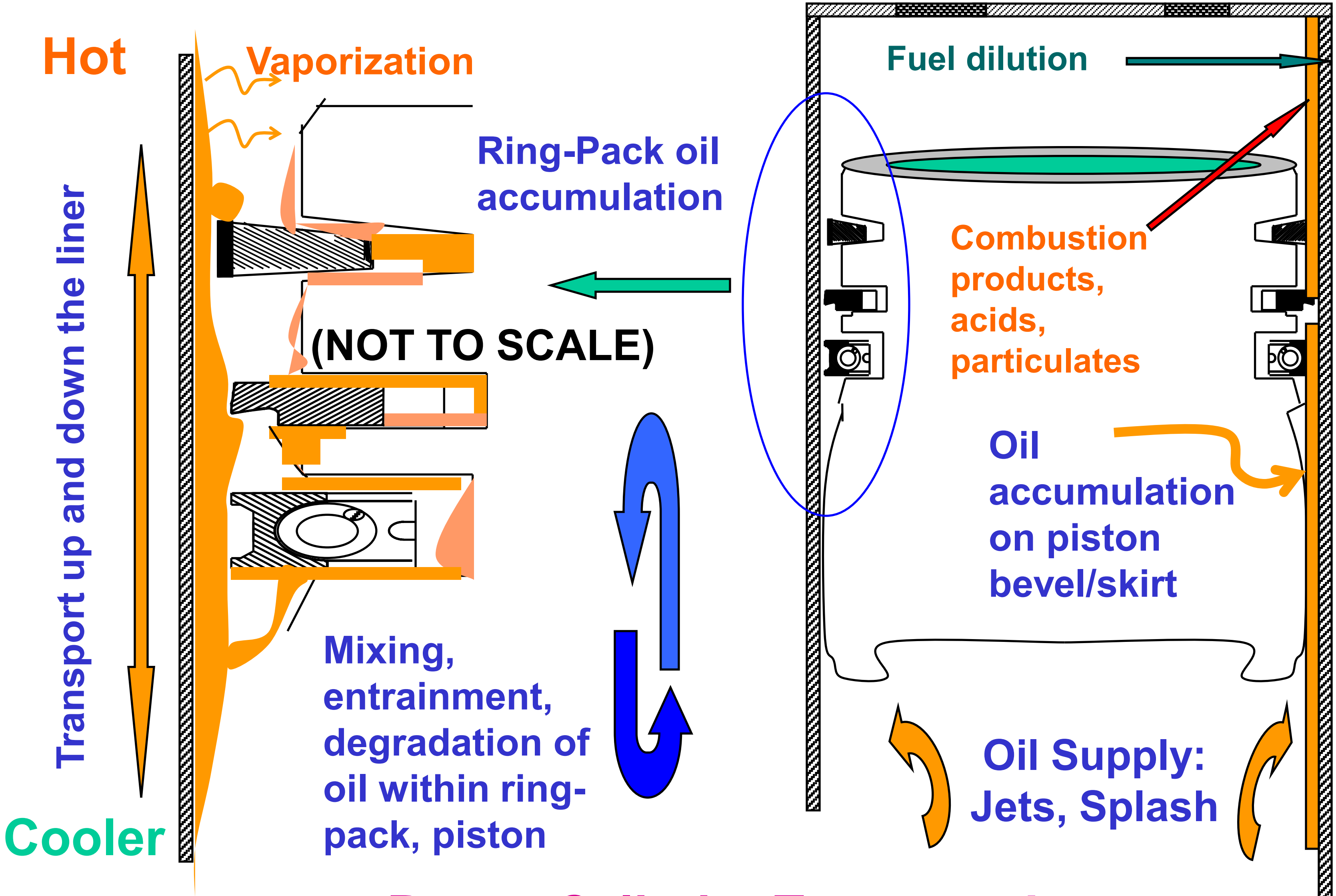
Lubricant behavior inside the engine: There are many processes between oil in the sump and oil in the upper-ring-pack/ valvetrain that affect the oil and additive conditions



- Affecting: Additive effective concentrations in ring pack/valvetrain versus in sump
- Residence time, oil supply/replenishment, vaporization

Oil properties at critical surfaces are different from sump composition



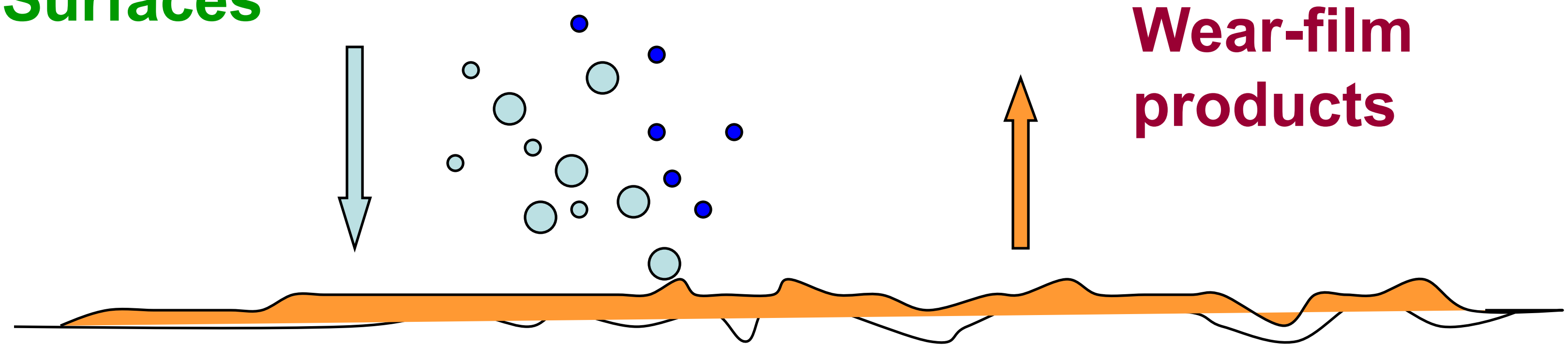
Power Cylinder Transport Loop

Changes of lubricant species also by lubricant-surface interfacial processes

Processes	Species
Anti-wear film formation	Zn, B, S, P, compounds
Wear process	Fe, Al
Anti-Corrosion, Deposits	Ca, Mg
Friction Modification	Organic molecules - GMO

Adsorption on Surfaces

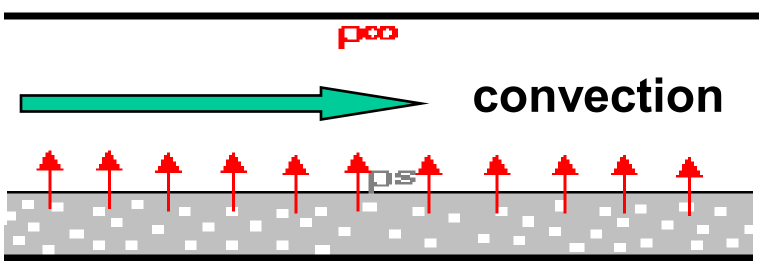
Tribochemical Wear-film products



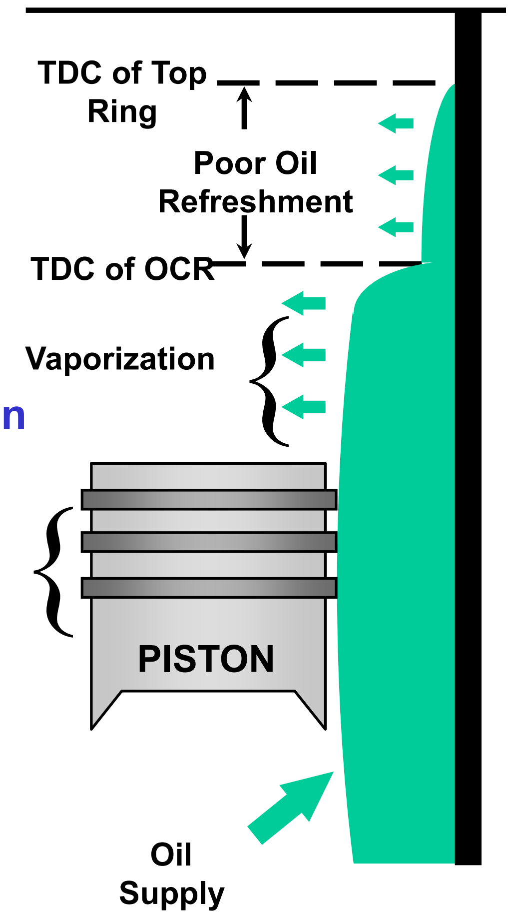
Vaporization Processes:

- **Mutli-Species: by carbon numbers**
- **In various regions: crown land, ring-pack, piston crevices, and on liner**

Heat transfer analogy:



Vaporization of oil from ring-pack and piston crevices

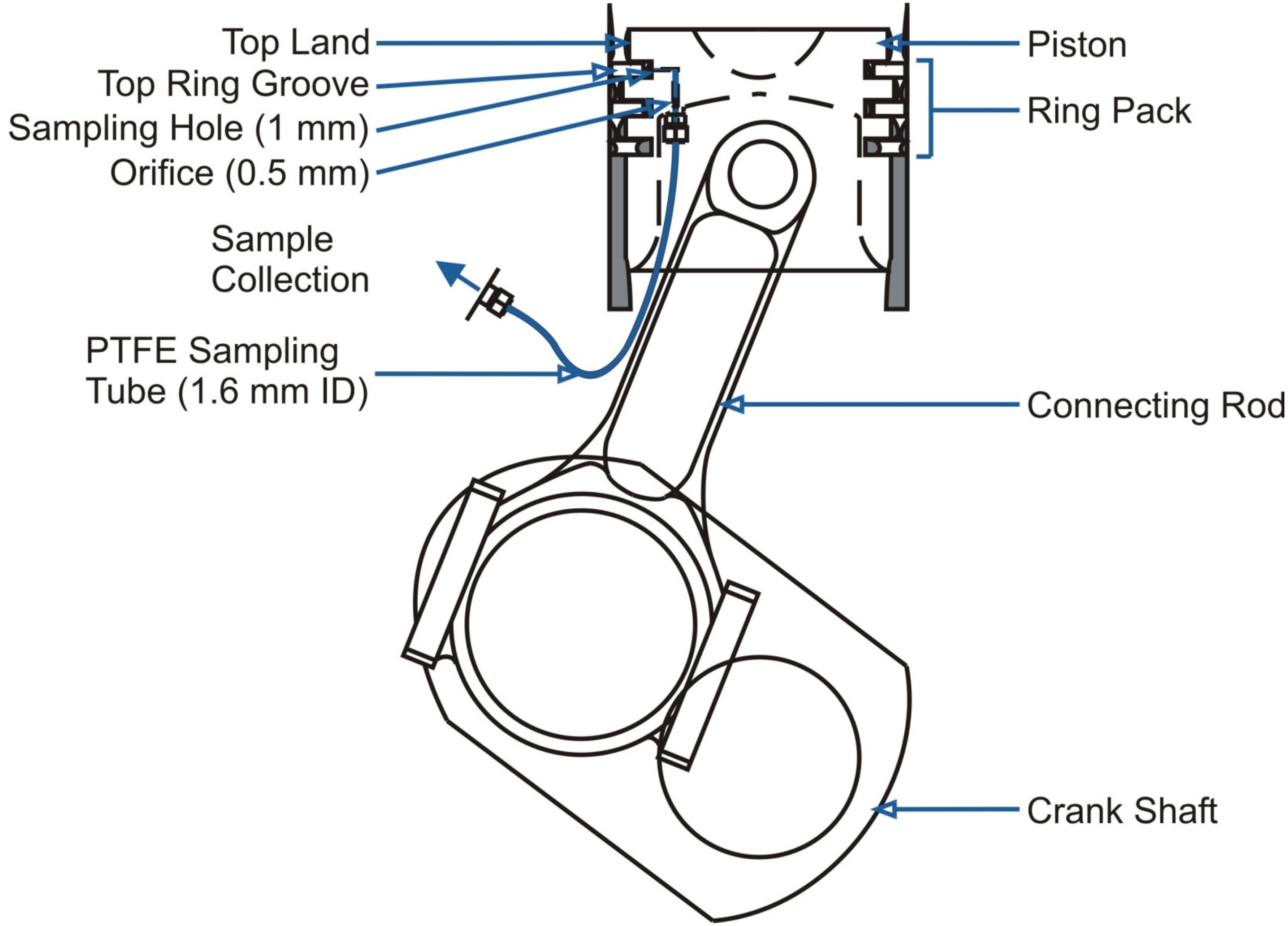


ρs : oil vapour surface density

$\rho\infty$: oil vapour free stream density

$$\dot{M}gen_j = \overline{h_{m_j}} S_j \left(\rho s_j - \rho\infty_j \right)$$

Ring Pack Sampling System

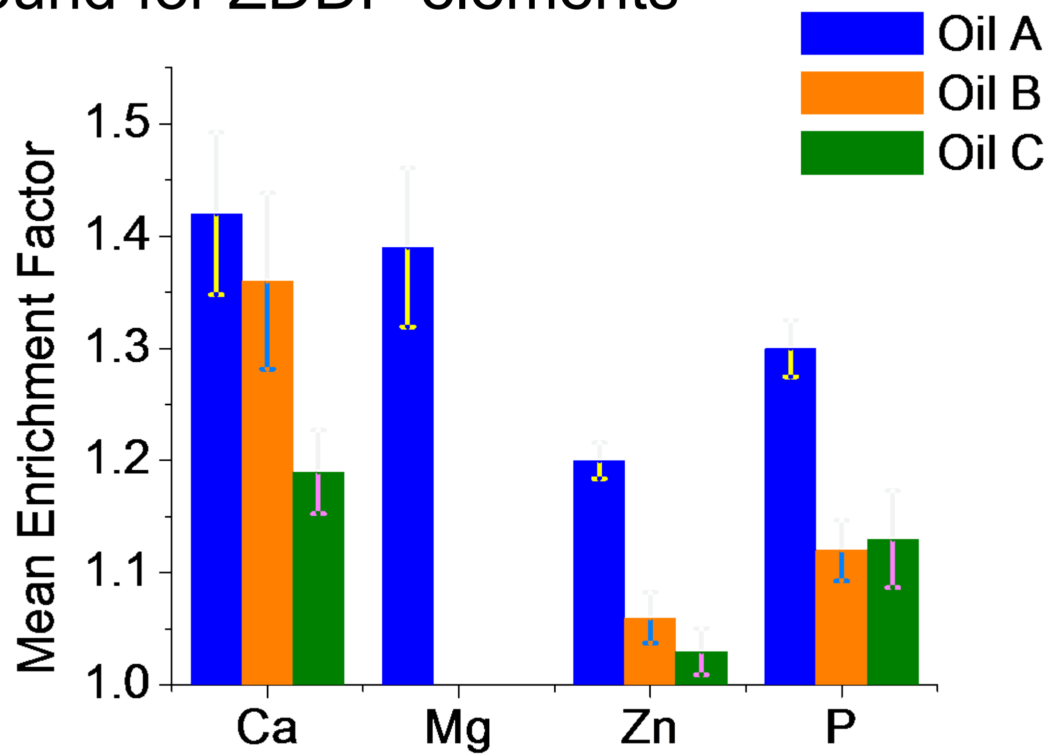


Top Ring Zone Enrichment

- All metals are concentrated in the top ring zone samples
- Degree of enrichment is different for each element
- Lowest enrichment found for ZDDP elements

Enrichment Factor =

Concentration of element in ring-pack zone relative to concentration of element in sump



1. *Controlling oil/additive properties at critical surfaces in local areas in specific engine subsystems (valvetrain, piston assembly, bearings..)*

Bottom Line:

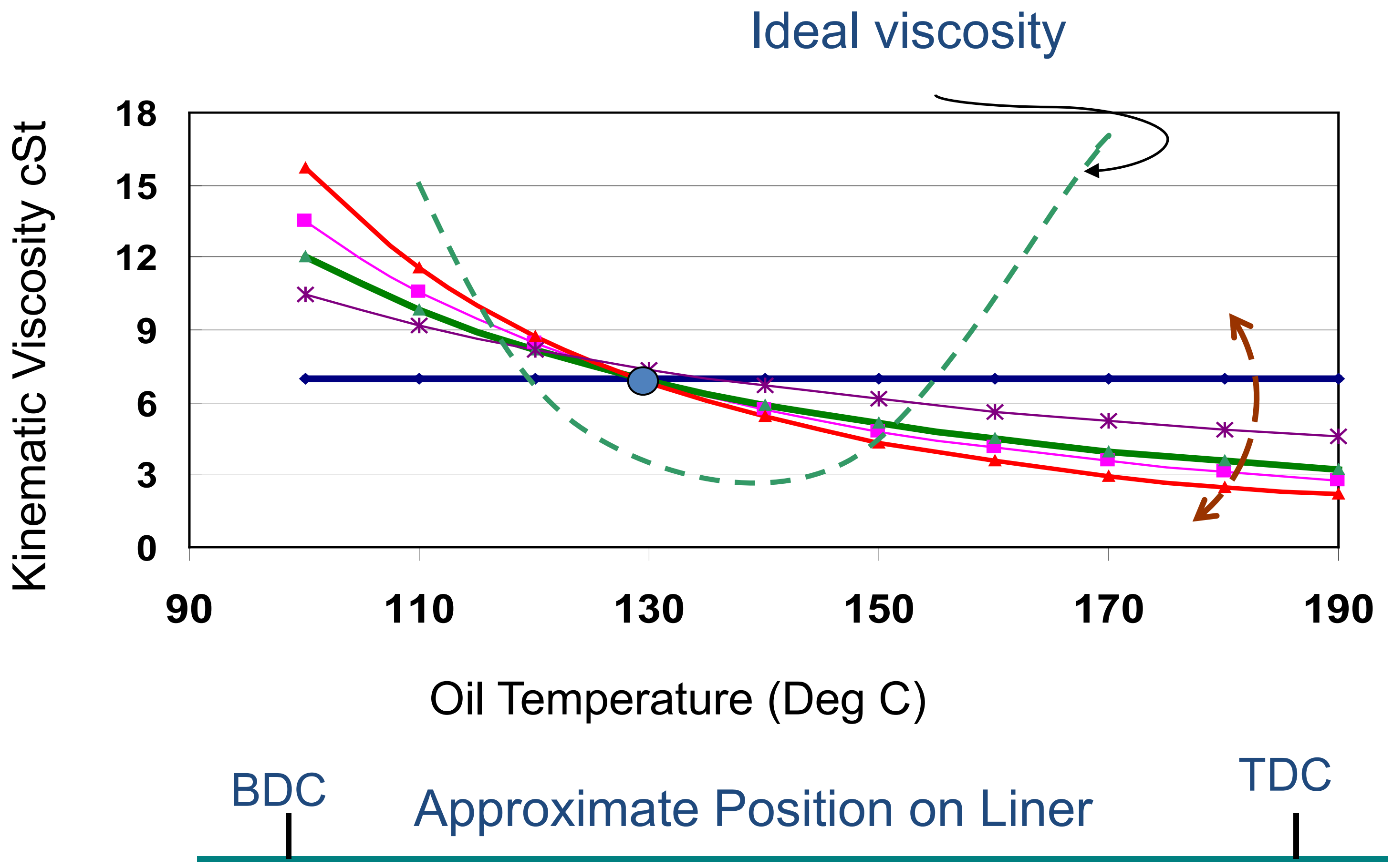
Opportunities in optimizing the “effective” lubricant composition “in operation” “at the most critical locations for best performance at surfaces – boundary friction, wear, detergency – that tailor to local conditions at engine subsystems

Four lubricant technical themes that aim to work synergistically to advanced engine technologies:

1. Controlling oil/additive properties in local areas that matter most in specific engine subsystems
2. Interfacing with engine technologies that affect "in-situ" effective lubricant properties in action
3. Optimizing lubricant "formulation:" the complete package – viscous/boundary friction, wear
4. Ascertaining compatibility with lubricant/additive-emission control system: lubricant/additives affect fuel economy of engine operation beyond friction

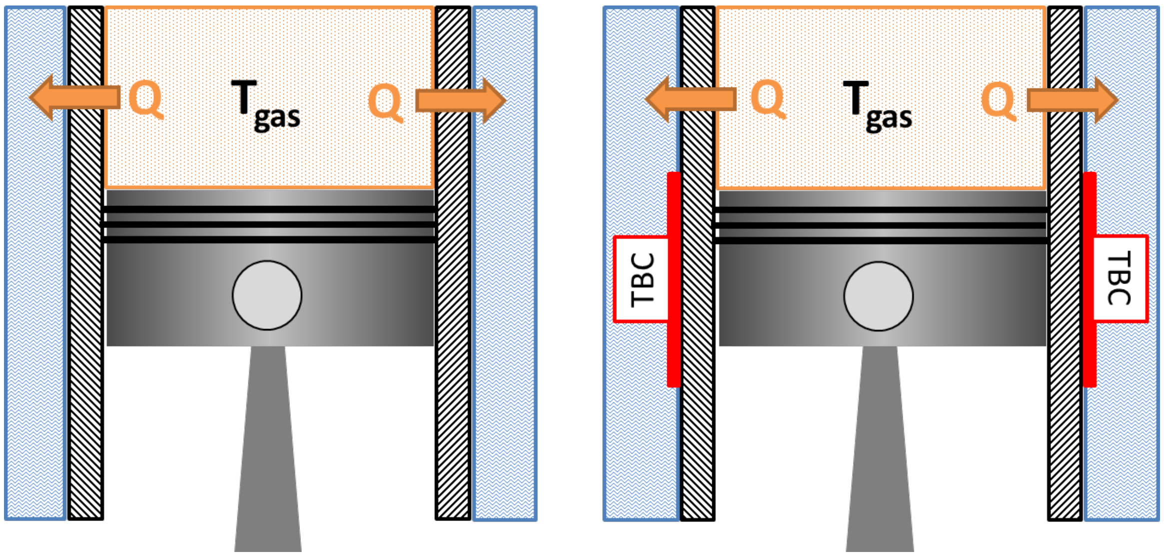
Viscosity Index: In-situ Lubricant Properties Control

Effects of Temperature Sensitivity of Viscosity



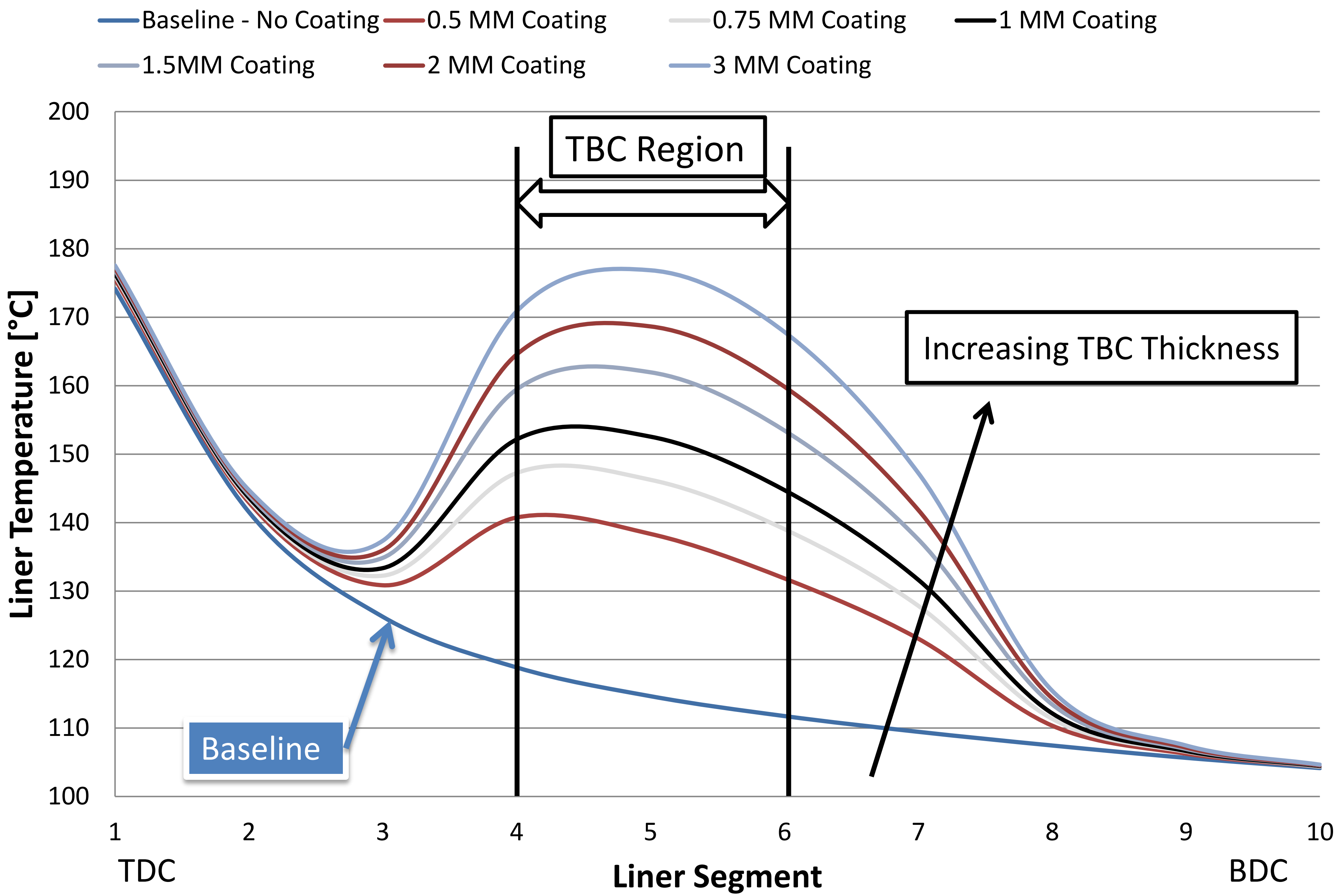
- Ideal viscosity should be low at mid-stroke and high at end strokes: either via lubricant design or component thermal management

Strategic Application Of Thermal Barrier Coatings (TBC)

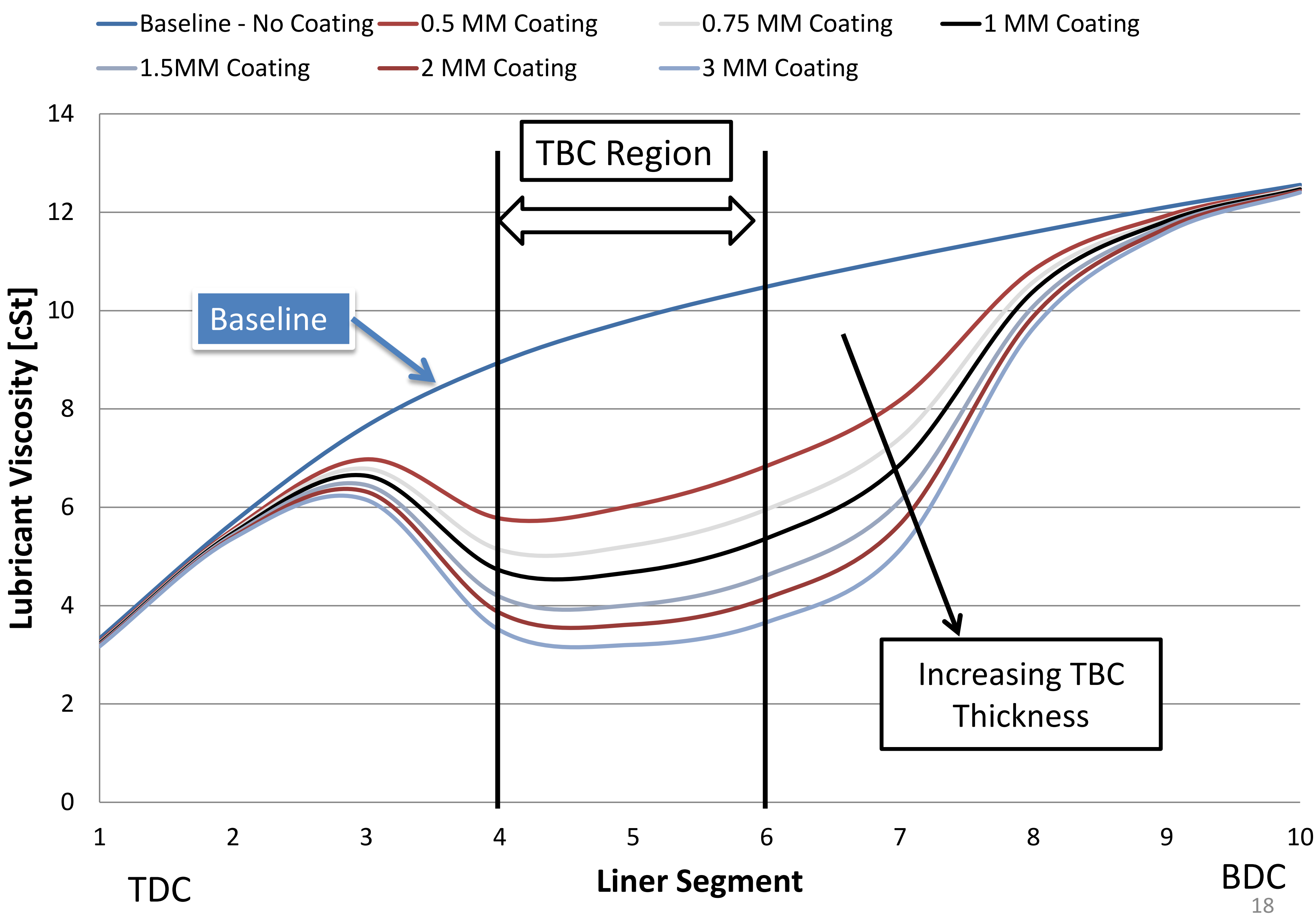


- Applied to mid-stroke to not affect lubricant properties at TDC or BDC

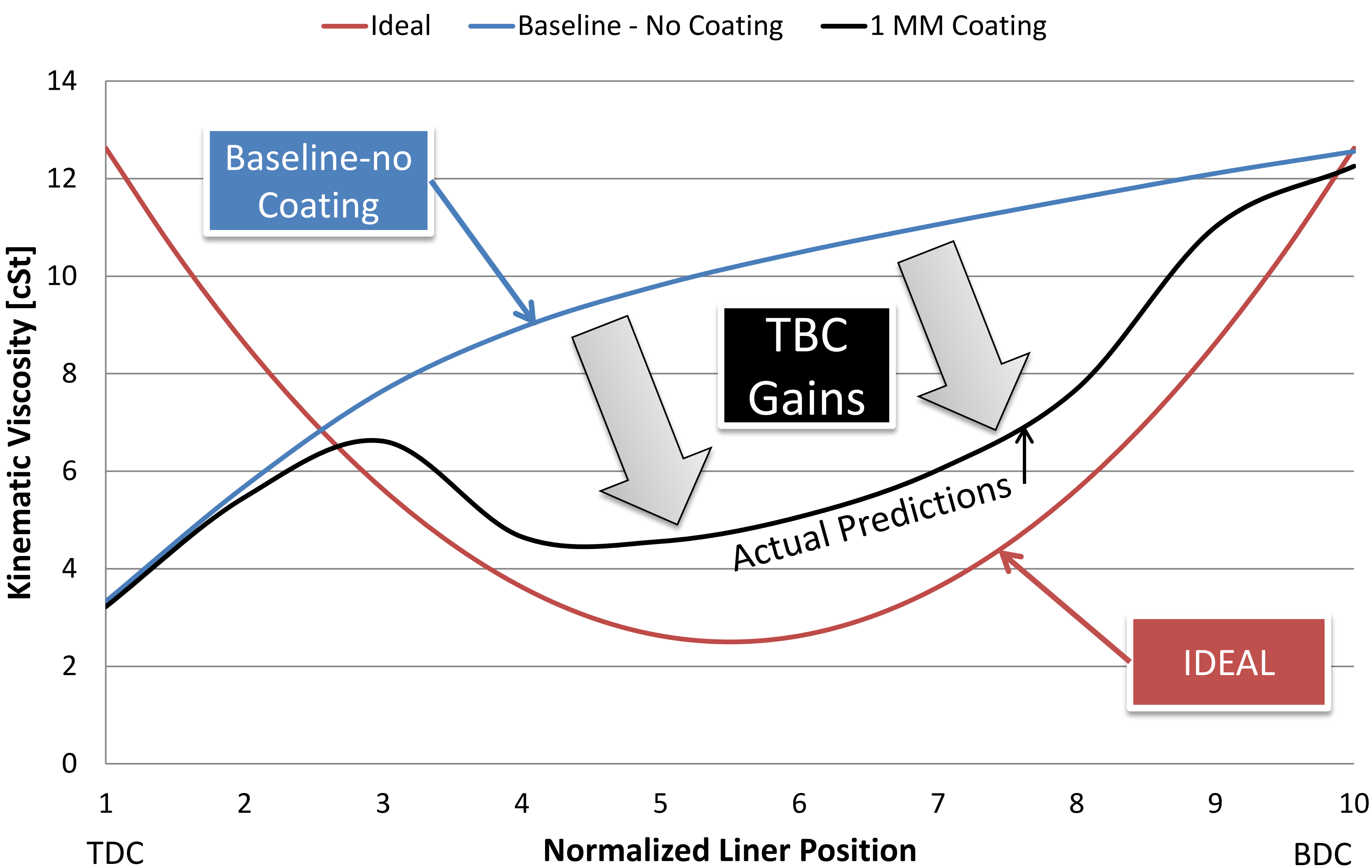
Liner Temperature with Coating On Segments 4,5,6



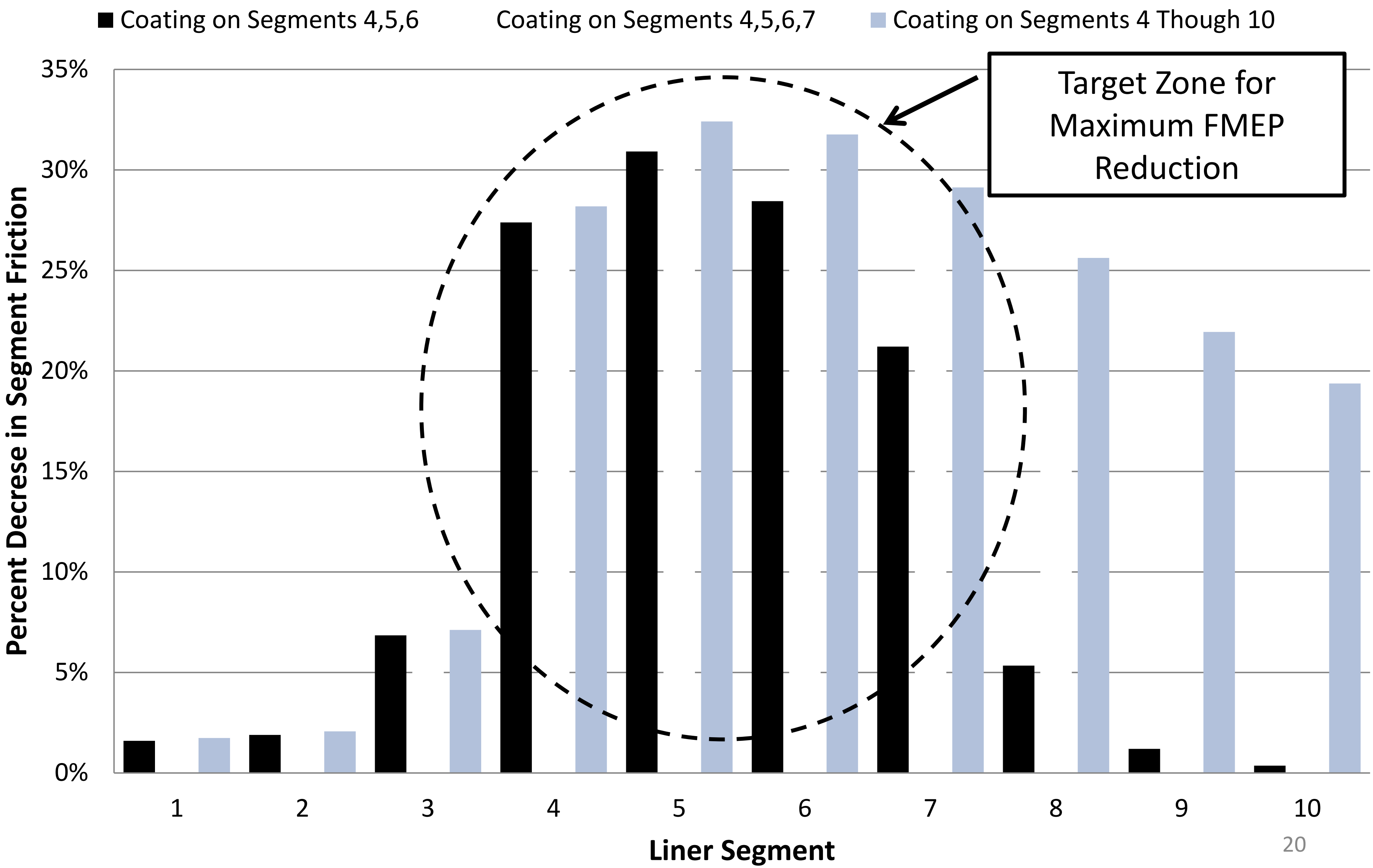
Local Viscosity of 15W-40 with Coating on Segments 4,5,6



Lubricant Viscosity verus Liner Position



Percent Decrease in Friction for TBC Applications
1mm Coating, 15W-40 Reference Oil



2. *Interfacing with engine technologies that affect “in-situ” effective fuel & lubricant properties in action*

Bottom Line:

Potential opportunities in further viscosity-temperature sensitivity (VI improvers) optimization in base oil that match advanced engine technologies

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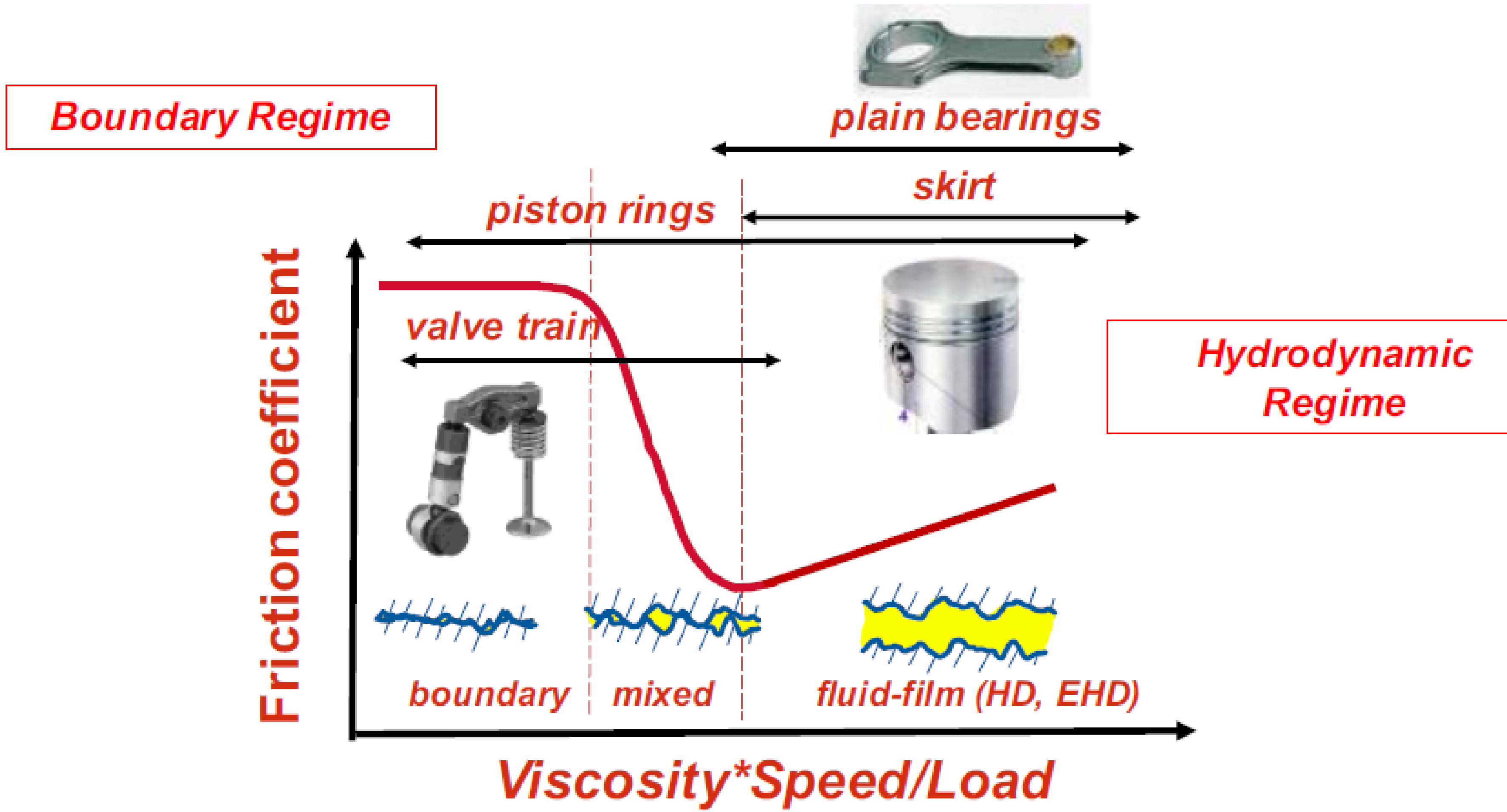
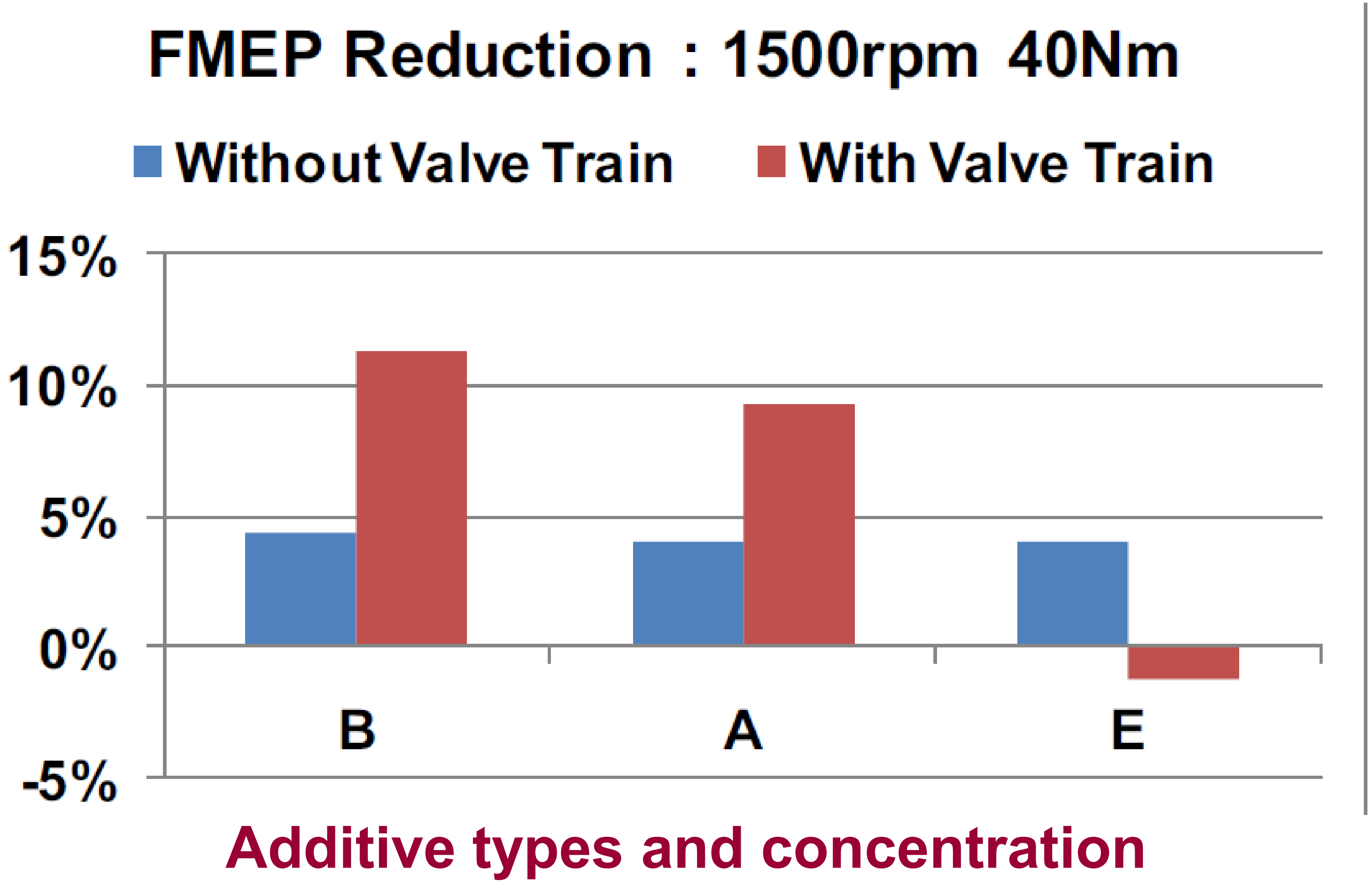


Stribeck Diagram

From e.g. 2011-01-2134 Nattrass, S.R et al

Different additives show varying effects to different engine subsystems in split valvetrain lube system



From e.g. 2011-01-2134 Nattrass, S.R et al

Ford Zetec 2l I4 gasoline

Program Phases and Major Tasks:

Phase 1:

Investigate the ideal lubricant formulations tailored to each major engine component subsystem for the best performance

- Modeling the effects of lubricant parameters on friction and wear for subsystems
- Parametric experiments to determine lubricant & additive effects on subsystems

Phase 2, 3:

Develop composite lubricant formulations, tradeoffs and implementation strategy for optimal lubricant formulation for the overall engine. Demonstrate the mechanical efficiency improvement. Determine impact if any on emission control system.

Major tasks to examine lube composition effects

- **Modeling the effects of lubricant parameters on friction and wear for subsystems**

  - Extend single-component models to include lubricant composition variations, including additives. Semi-empirical models on boundary-friction vs additives
  - Develop and apply a lubricant compositional model to the power cylinder and valvetrain subsystems

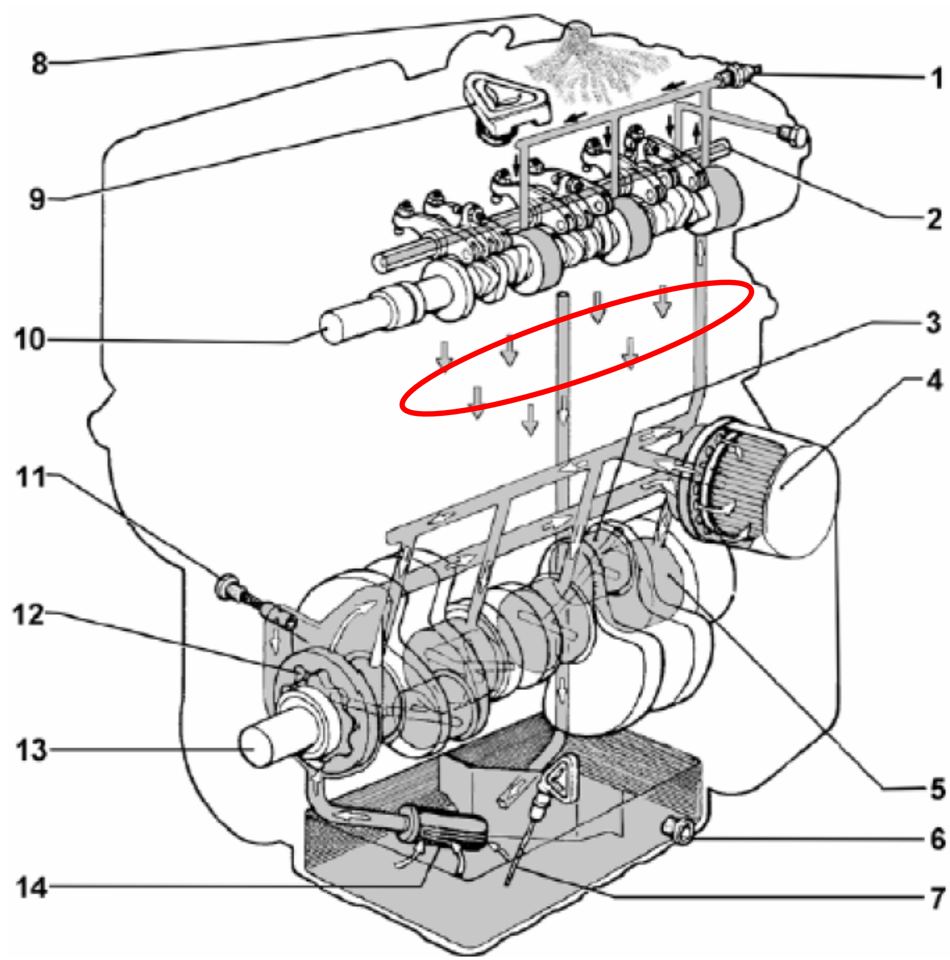
- **Parametric experiments to determine lubricant & additive effects on subsystems**

  - Lubricant sampling and composition measurements
  - Lubricant and additive effects on piston assembly and bearings
  - Lubricant and additive effects on cam/valvetrain friction

Lubrication Circuit and Subsystem Separation

- **Overhead camshaft configuration enables the separation of the valvetrain and crankcase lubrication circuits**

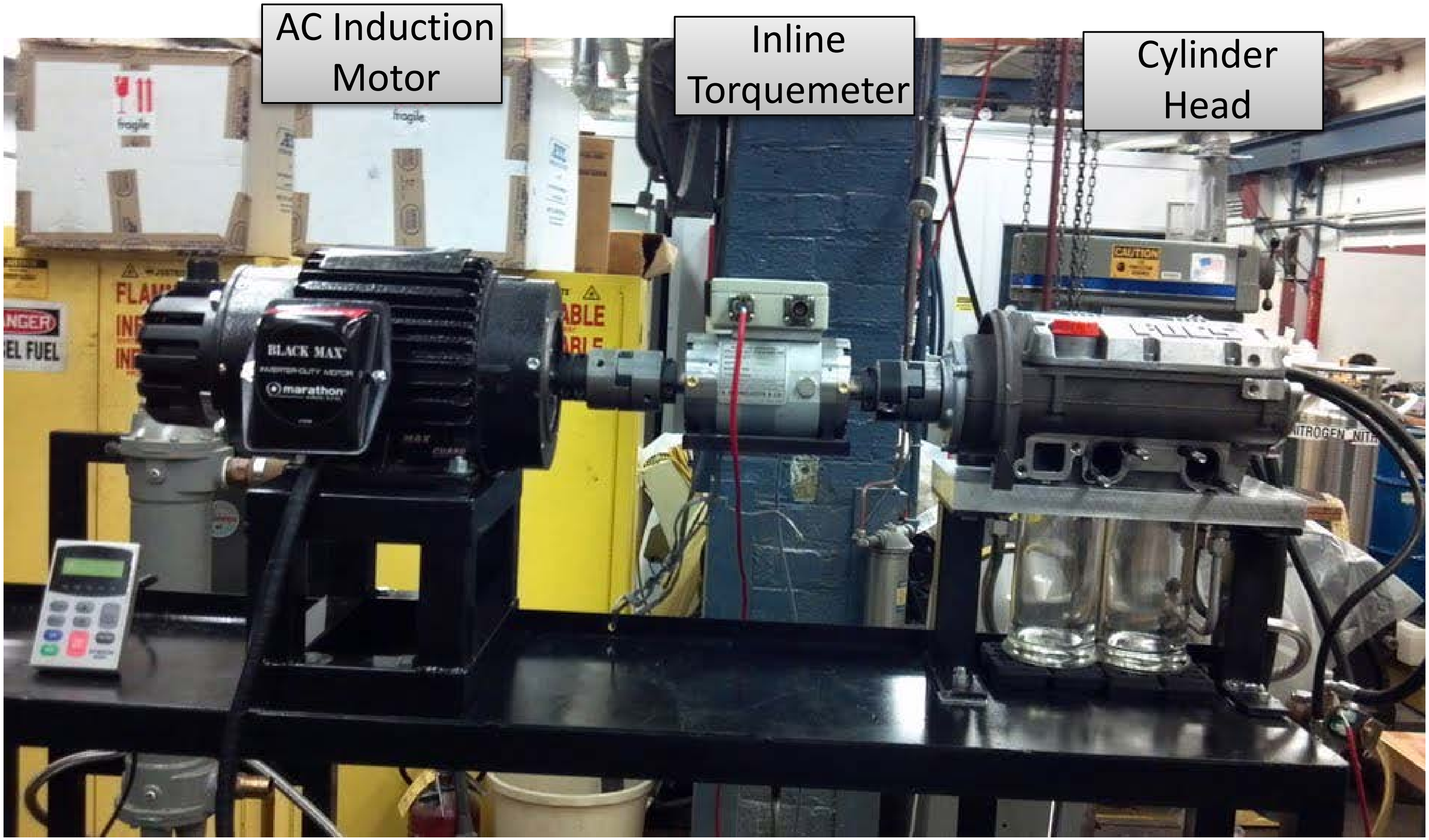
- **Dedicated torque sensor to determine camhaft torque and power**



Kohler

Separate engine and valvetrain rig

Engine to be operational end of Oct



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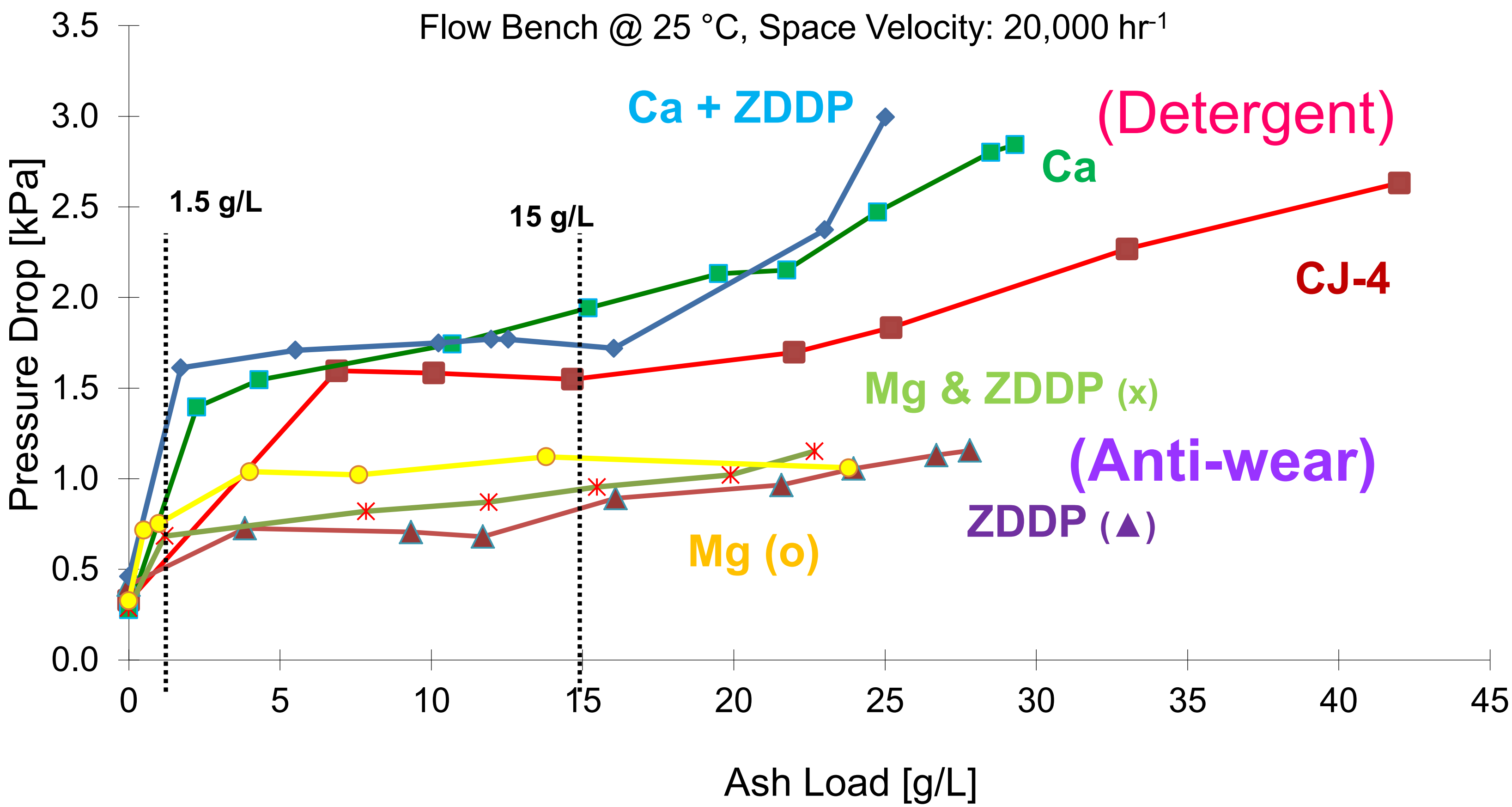
Different lube additives (ash) affect both engine and DPF differently and will have both emission and efficiency impact



- Lubricant additives composition affects ash properties and pressure drop
- Ca-based ash shows much larger effect on pressure drop than Zn ash

Summary

- **Opportunities exist in optimizing the “effective” lubricant composition “in operation” for best performance at surfaces – boundary friction, wear – that tailor to local conditions at engine subsystems**

- There are potential opportunities in further viscosity-temperature sensitivity (VI improvers) optimization in base oil that match advanced engine technologies

- **Convergence of lubricant chemistry and mechanical analysis will be helpful in developing and applying advanced lubricants for efficiency improvements**

- **Modeling and tests on lubricant composition effects on friction are challenging but will extend efficiency frontiers**

Thank you!

Supplementary slides

DOE-NETL

Cooperative Agreement #DE-EE0005445

Project: Lubricant Formulations to Enhance Engine Efficiency in Modern Internal Combustion Engines

with
Massachusetts Institute of Technology
Cambridge, Massachusetts

Prof. Wai K. Cheng
Principal Investigator
Dr. Victor W. Wong and Dr. Tian Tian
Co-Investigators

Kick-off Meeting
November 15, 2011
Washington DC

Program Objectives:

- The overall program goal is to investigate, develop, and demonstrate low-friction, environmentally-friendly and commercially-feasible lubricant formulations that would significantly improve the mechanical efficiency of modern engines by at least 10% (versus 2002 level) without incurring increased wear, emissions or deterioration of the emission-aftertreatment system

- The specific project objectives include identifying the best lubricant formulations for individual engine subsystems, identifying the best composite lubricant formulation for the overall engine system, and demonstrating the mechanical efficiency improvement for the optimized lubricant formulation via engine testing

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Definition of Program Phases/Budget Periods, Tasks, and Schedules

Program Duration: October 1, 2011 – September 30, 2014 (36 months)

- Budget Period 1 = Phase 1: October 1, 2011 – January 15, 2013 (Duration: 15.5 months)

- Budget Period 2 = Phase 2: January 16, 2013 – January 15, 2014 (Duration: 12 months)

- Budget Period 3 = Phase 3: January 16, 2014 – September 30, 2014 (Duration: 8.5 months)

Identification of Tasks in Each Phase:

Task 1.0 Project Management and Planning (continuous)

Phase 1: To investigate the ideal lubricant formulations tailored to each major engine component subsystem for the best performance

Task 2a: Modeling the effects of lubricant parameters on friction and wear for subsystems

Task 3: Develop experimental/analytical lubricant test parameters in consultation with team participant(s) from lubricant/additive industry

Task 4a: Parametric experiments to determine lubricant & additive effects on subsystems

Task 5a: Data analysis, interpretation, and iteration between modeling and testing

More details discussed for each task after overview of work planned for each Phase…

Identification of Tasks in Each Phase (continued):

Phase 2: *To investigate composite lubricant formulations that retain most of the frictional benefits for the subsystems identified in Phase 1. Identify the tradeoffs and compromises necessary for an optimal composite lubricant formulation for the combined subsystems*

Task 2b: Additional Modeling the effects of lubricant parameters on friction and wear for subsystems

Task 4b: Additional parametric experiments to determine lubricant & additive effects on subsystems

Task 5b: Additional data analysis, interpretation, and iteration between modeling and subsystems

Task 6: Modeling the effects of lubricant formulations with local variations in chemistry in overall engine with combined subsystems

Task 7: Engine experiments to determine lubricant and additive effects for the entire engine system

Task 8: Develop and design the enabling lubricant-handling technology and configuration in the engine, so that the best formulations can be implemented

Identification of Tasks in Each Phase (continued):

Phase 3: To demonstrate the mechanical efficiency improvement for the best optimized lubricant formulation in an actual engine over a range of operating conditions that both reflect those in standardized industry protocols and other driving conditions

Task 9: Demonstrate in an actual engine the quantitative improvements in the mechanical efficiency the best formulations from this study, in a production engine

Task 10: Evaluations of the impact on emission-control systems

Task 11: Technology transfer and interfacing with users and researchers

Task descriptions:

Task 1.0 Project Management and Planning

Task 1 will be a continuing effort throughout the program for monitoring the project status, tracking technical and financial reporting as required, and for reviewing and revising the on-going project plan with DOE periodically, as required

Task descriptions (continued):

Task 4.0 Parametric experiments to determine lubricant & additive effects on subsystems (Phase 1 + 2)

- Iterations between experiments and modeling (Task 2) will be expected

Four sub-tasks:

Sub-task 4.1: Engine installation

Sub-task 4.2: Lubricant sampling and composition measurements

Sub-task 4.3: Lubricant and additive effects on piston-ring-liner/crank friction

Sub-task 4.4: Lubricant and additive effects on cam/valvetrain friction

Task descriptions (continue):

Task 3.0 Develop experimental/analytical lubricant test parameters in consultation with team participant(s) from lubricant/additive industry (Phase 1)

- (a) Base oils: oils with different high/low shear viscosity characteristics, viscosity modifiers,
- (b) Other additives: boundary friction modifiers, anti-wear agents, detergents, anti-oxidants, and non-traditional additives such as nano-particles – particularly those carbon based particles that do not further add to ash emissions to the aftertreatment system. Actual formulations will be discussed with lubricant/additive partner

Task 4.0: Engine experimentation details: [Phase 1]

Engine criteria:

1. Diesel, as proposed, where lubricant contamination from combustion more severe.
2. Small, easy to work with, saves fuel when studying longer duration operation and cost of operation
3. Configuration common to most vehicles
4. Domestic manufacturer preferred due to easy of technical support and potential participation

→ Kohler diesel with belt driven overhead cam, inline 2, 3, or 4 cylinders

Lubrication System: Kohler KDW702, 1003, 1404 diesel with overhead cam

8) Breather
Sfiato
Reniflard
Entlüfung
Depresurisación
Respiradouro

9) Oil Filling
Rifornimento Olio
Remplissage Huile
Oleinfüllung
Tapon Llenado Aceite
Reabastecimento óleo

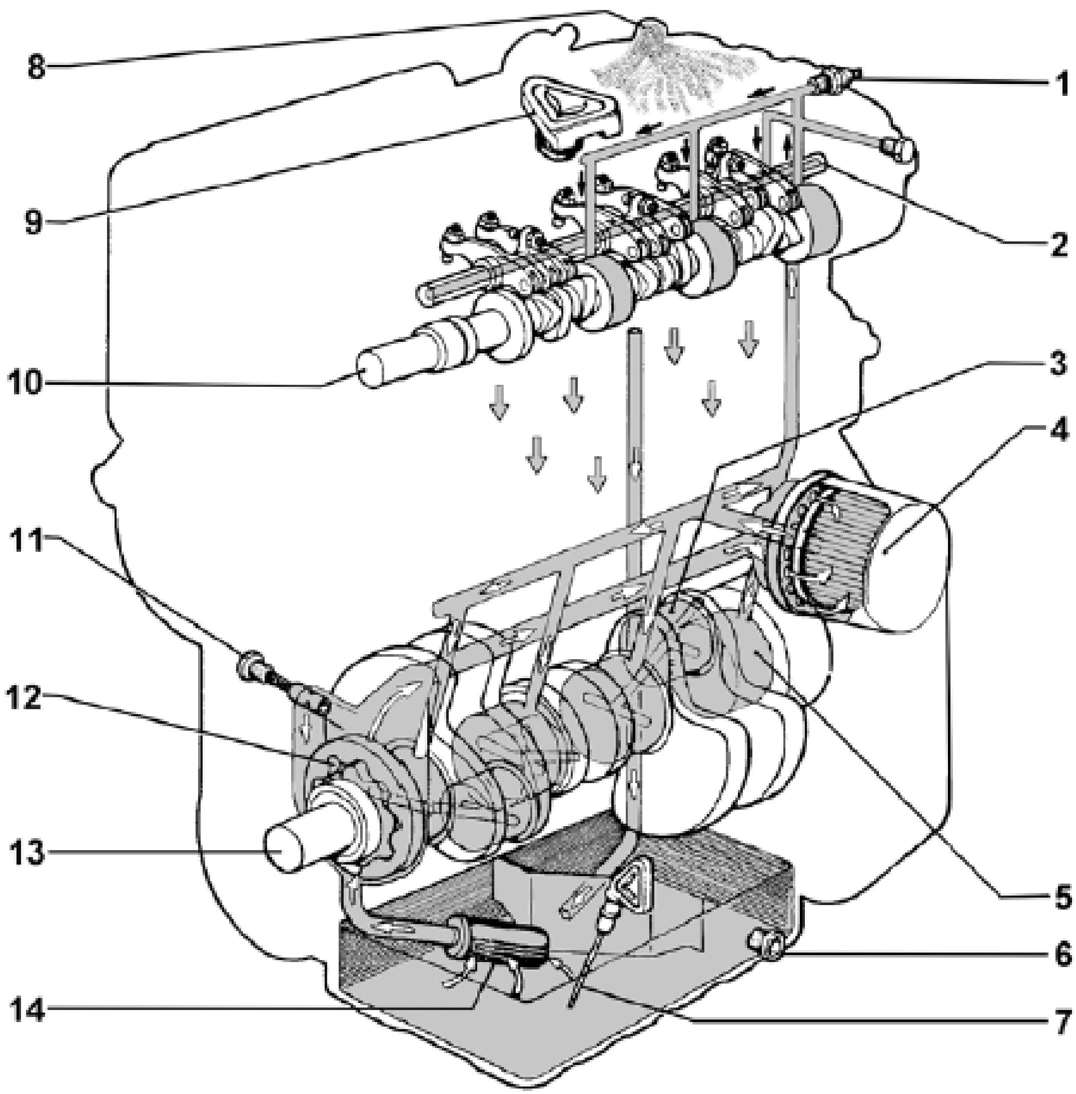
10) Camshaft
Albero a Camme
Arbre à Cames
Nockenwelle
Eje de Levas
Eixo Excêntrico

11) Pressure Regulator
Valvola Regolazione Pressione
Soupape Réglage Pression
Druckkontrollventil
Valvula Regulacion Presion
Vàlvula Regulação Pressão

12) Oil Pump
Pompa Olio
Pompa Huile
Schmierölpumpe
Bomba Aceite
Bomba Oleo

13) Crankshaft
Albero Motore
Vilebrequin
Kurbelwelle
Cigüeñal
Eixo Motor

14) Suction Strainer
Filtro Interno Aspirazione
Crépine Aspiration
Ansaugsieb
Filtro interno de Aspiración
Filtro interno de Aspiração



1) Oil Pressure Gauge
Indicatore Pressione Olio
Indicateur Pression Huile
Öldruck-Anzeiger
Indicador Presion Aceite
Indicador Pressão Oleo

2) Rocker Arm Shafts
Perno Bilancieri
Axes Culbuteurs
Kipphebelwelle
Ejes de Balancines
Perno Bilancins

3) Conn-Rod Big End Bearings
Bronzine Testa Biella
Coussinets Têtes de Bielle
Pleuellager
Cojinetes Cabeza Biela
Pernos Testa Biela

4) Cartridge Filter
Filtro a Cartuccia
Filtre à Cartouche
Patronenfilter
Cartucho Filtrante
Filtro à Cartucha

5) Krankshaft Support
Supporti di Banco
Support de Banc
Kurbelwellelager
Soportes de Banco
Pernos de Banco

6) Oil Drain Plug
Tappo Scarico
Bouchon Vidange
Olablass-Schraube
Tapon Vaciado Aceite
Tampa Descarregamento

7) Dipstick
Asta Livello
Jauge Niveau
Olmess-Stab
Varilla de Nivel
Hasta Nivel

Kohler KDW 702 twin-cylinder diesel engine specifications

Model	*Diesel KDW702*
Max Power @3600 RPM hp (kW)	16.8 (12.5)
Displacement cu in (cc)	41.9 (686)
Bore in (mm)	3 (75)
Stroke in (mm)	3.1 (77.6)
Peak Torque @ Maximum lbs ft (Nm)	29.9 (40.5)
Compression Ratio	22.8:1
Dry Weight lbs (kg)	145.4 (66)
Oil Capacity U.S. quarts (L)	1.7 (1.6)
Lubrication	Full-pressure with full-flow filter
Dimensions L x W x H in	16.6 x 16.2 x 20.3

Task 4.0: Lubricant and friction measurements

Separation of lubrication loops for individual subsystems also allows lubricant formulation changes with ease

1. Friction changes due to lubricant formulations for individual subsystems
2. Degradation and lubricant property changes versus time against friction changes
3. System allows for determination of the sensitivity of individual subsystem contributions (overhead valvetrain, crank, piston/ring /liner) to friction using different lubricant formulations
4. System allows for closed loop or open loop lubricant flow to study effects of lubricant property degradation or contamination on friction

Task descriptions (continue): [Phase 1]

Task 5.0 Data analysis, interpretation, and iteration between modeling and testing

- Results from the extensive modeling effort and the large number of tests involving the matrices of test and measured parameters will be analyzed and correlated

- Guidelines for formulation changes to realize further friction improvements will be developed, new formulations proposed and tested, in an iterative process

Task descriptions (continue): [Phase 2]

<u>Phase 2:</u>

Identify the tradeoffs and compromises necessary for an optimal composite lubricant formulation for the overall engine with the combined subsystems

Task 2b: <u>Additional Modeling</u> the effects of lubricant parameters on friction and wear for subsystems

Task 4b: <u>Additional parametric experiments</u> to determine lubricant & additive effects on subsystems

Task 5b: <u>Additional data analysis, interpretation</u>, and iteration between modeling and subsystems

Task 6: Modeling the effects of lubricant formulations with local variations in chemistry in overall engine with combined subsystems

- The models developed in Task 2.0 can be applied to study the overall engine with all the subsystems combined. Analytically, via the modeling, various concepts of controlling lubricant properties can be explored

- Frictional benefits using an optimized lubricant formulation will be compared to the best formulations for the subsystems individually.

Task descriptions (continue): [Phase 2]

Phase 2 (continued):

Task 7: **Engine experiments to determine lubricant and additive effects for the entire engine system**

Task 7 deals with the pragmatic issue of actually implementing the "laboratory" optimal lubricant formulation strategy. The best lubricant formulation will probably depend on how the lubrication system will be designed.

There are four major configurations:

(a) One fluid with best compromised formulation: Fully segregated, no mixing. Non-optimal, but pragmatic. There will be differing degradation rates in each subsystem

(b) One fluid: Full mixing – conventional configuration, which is the prevalent lubricant formulation strategy. Non-optimal

(c) Two fluids, but only one needs to be changed during routine engine operation. The other lubricant formulated to last until major engine overhaul.

(d) Other means of controlling lubricant properties and their effects: (i) lubricant species removal stations: chemical or particle sequestration, (ii) chemical or active species periodic release, (iii) oil conditioning of lubricant flow between subsystems

Task descriptions (continue): [Phase 2]

Task 8.0

Develop and design the enabling lubricant-handling technology and configuration in the engine, so that the best formulations can be implemented

- Addresses the pragmatic issue of how to implement the best formulation tested in a “laboratory” configuration
- Investigate and develop practical means to enable implementation of the best formulation in an engine
- Demonstrate potential feasible means for use in the field

Task descriptions (continue): [Phase 3]

<u>Phase 3:</u> To demonstrate the mechanical efficiency improvement for the best optimized lubricant formulation in an actual full-size engine over a range of operating conditions that both reflect those in standardized industry protocols and other driving conditions

Task 9: Demonstrate in an actual engine the quantitative improvements in the mechanical efficiency the best formulations from this study, in a production engine

- The demonstration will last a sufficiently long duration to illustrate the satisfactory deterioration rates, if any, of the lubricant formulation within major oil drain intervals, and durable engine performance with acceptable wear

Task descriptions (continue): [Phase 3]

Task 10: Evaluate the impact of the best friction-reduction lubricant formulations on emission-control systems

- Focus on Diesel particulate filters (DPF)
- Use accelerated ash accumulation test rig at MIT using the best candidate low-friction oil formulations
- Evaluate back pressure build-up, by passive or active regenerations, and DPF performance, of the candidate formulation

Task 11: Technology transfer and interfacing with users & researchers

- Throughout program
- With DOE-NETL
- With public at large via conferences, theses, publications
- With working team supporters in industry – oil, additive, engine co.

Deliverables

- Summary of accomplishments and project work report will be prepared for inclusion in the annual Vehicle Technologies programmatic progress report. Report will be due by October 31 of each year
- Upon completion of a milestone, a brief milestone report will be provided to verify and document the completion of the milestone
- The Project Management Plan will be updated periodically as needed. Updated plans will be submitted to NETL

Project Timeline

Lubricant Formulations to Enhance Engine Efficiency in Modern Internal Combustion Engines

DOE-NETL Cooperative Agreement #DE-EE0005445

Massachusetts Institute of Technology

Project Start Date: Oct 1, 2011

Proposed Project Completion: Sep 30, 2014

Milestones M1, M2, M3.... on Chart indicate time schedule of completion of accomplishment

Phase	Task No. #	MAJOR TASKS/ MILESTONES	SCHEDULE (CY 2011: O N D; CY 2012: J F M A M J J A S O N D; CY 2013: J F M A M J J A S O N D; CY 2014: J B M A M J J A S)
Phase 1: Best Lube Formulations for Subsystem			
PHASE ONE	1.0	Develop Project Management and Planning	
	2.0	Model Lubricant Effects on Individual Sub-Systems	
	2.1	- For piston, ring, liner sub-system	
	2.2	- For valvetrain sub-system	
	3.0	Develop Lube Test Parameters w/ Industry Partners	
	4.0	Perform Parametric Experiments on Lube Effects	
	5.0	Data Analysis, Interpretation and Design Iterations	
		MILESTONE 1 (M1) : Modeling Power Cylinder	M1
		MILESTONE 2 (M2): Modelig Valvetrain	M2
		MILESTONE 3 (M3): Develop Candidate Matrix	M3
		MILESTONE 4 (M4): Modify/Prepare Test Engine	M4
		MILESTONE 5 (M5): Instrument Diagnostics	M5 M6
		MILESTONE 6 (M6): Parametric Lube Effect Tests	
		MILESTONE 7 (M7): Tests with Floating Liner Engine	M7
Phase 2: Best Composite Formulations for Combined System			
PHASE TWO	6.0	Model Lube Formulations with Regional Variations	
	7.0	Test, Optimize Composite Oil Formulations	
	7.1	For Segregated Power-cylinder, Valvetrain Subsystems	
	7.2	For One-Oil Fully Mixed Combined System (Baseline)	
	7.3	For Regional (Local) Modulation of Lubricant Properties	
	8.0	Develop Practical Means to Implement New Formulations	
		MILESTONE 8 (M8): Model Variable Lube Formulations	M8
		MILESTONE 9 (M9): Parametric Lube Tests, one oil, full mixing	M9
		MILESTONE 10 (M10): Parametric Lube Tests, one oil, segregated	M10
		MILESTONE 11 (M11): Parametric Lube Tests, with local modulation	M11
Phase 3: Proof of Concept, Final Demonstration			
PH. THREE	9	Demonstrate Final Lube Formulation in Full System	
	10	Evaluate & Test Impact on Aftertreatment Systems	
		MILESTONE 12 (M12): Full Demonstration, Optimized Oil	M12
		MILESTONE 13 (M13): Aftertreatment Impact Assessment	M13 M13 M13
All Phases: Throughout project			
	11	Review lube formulation iterations with industry	
	12	Periodic formal reviews & reports	
		- Deliver annual reports	
		- Deliver Final Report	