Methods to Measure, Predict, and Relate Engine Friction, Wear, and Fuel Economy

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FT061

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Overview

Timeline

- Start date: 15 December 2014
- End date: 14 December 2017
- Completion: 70%

Budget

- Total funding (80/20): $1.32M
  - Cost share: $280K (> 20%)
  - DOE share: $1,040K
  - $390K to ANL over 3 yrs
- BY1: 12/2014 – 12/2015
  - $67K to Ricardo
- BY2: 12/2015 – 12/2016
  - $281K to Ricardo
- BY3: 12/2016 – 12/2017
  - $302K to Ricardo

Barriers

- Barriers to Friction Reduction Technology Adoption
  - **Risk aversion** → New technologies are not very well understood in regards to their durability and long-term benefits
  - **Cost** → The time and financial investment to screen technologies is prohibitive
  - **Computational models, design and simulation methodologies** → Analytical methods lack sufficient validation

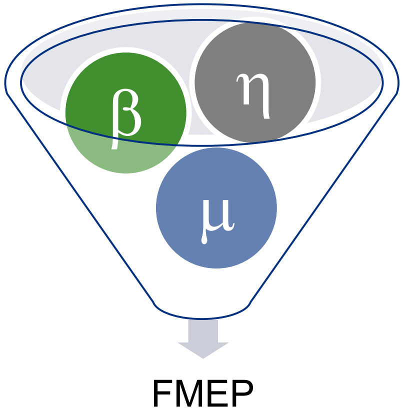
Partners

- Ricardo, Inc. (Lead)
- Argonne National Lab
- Isuzu
- ZYNP
- Infineum

Relevance

- To overcome the barriers to adoption of advanced vehicle technologies that improve fuel economy, in particular friction reduction technologies, this research effort has been designed with the following objective:
  - To develop methods capable of predicting the impact of friction reduction technologies on engine fuel economy and wear. The methods of prediction will be both empirically and analytically based.
- Empirical correlations will be established that allow for estimating changes in engine FMEP or fuel consumption based only on the engine speed, power and tribological parameters such as oil viscosity (η, β) and coefficient of friction (μ) which can be determined *a priori* in a lab-scale test.

Key Idea: If one knows how a particular friction reduction technology changes η, β and μ then the methods developed during this project can be used to predict the impact on fuel consumption and wear. It is more cost effective to measure η, β and μ in a lab-scale test than conduct motored or fired engine tests.



Funnel = empirical correlation or advanced simulation methods

Milestones (2015)

Description	Type	Date	Status
Delivery of base components from Isuzu	Milestone	6 May 15	Complete
Preliminary RINGPAK Model of AART	Milestone	27 May 15	Complete
Final determination of FM	**GO/NO GO**	**14 Oct 15**	**Complete**
Engine first fire and de-green	Milestone	30 Oct 15	Complete
Delivery of final oils from Infineum for testing	Milestone	16 Nov 15	Complete

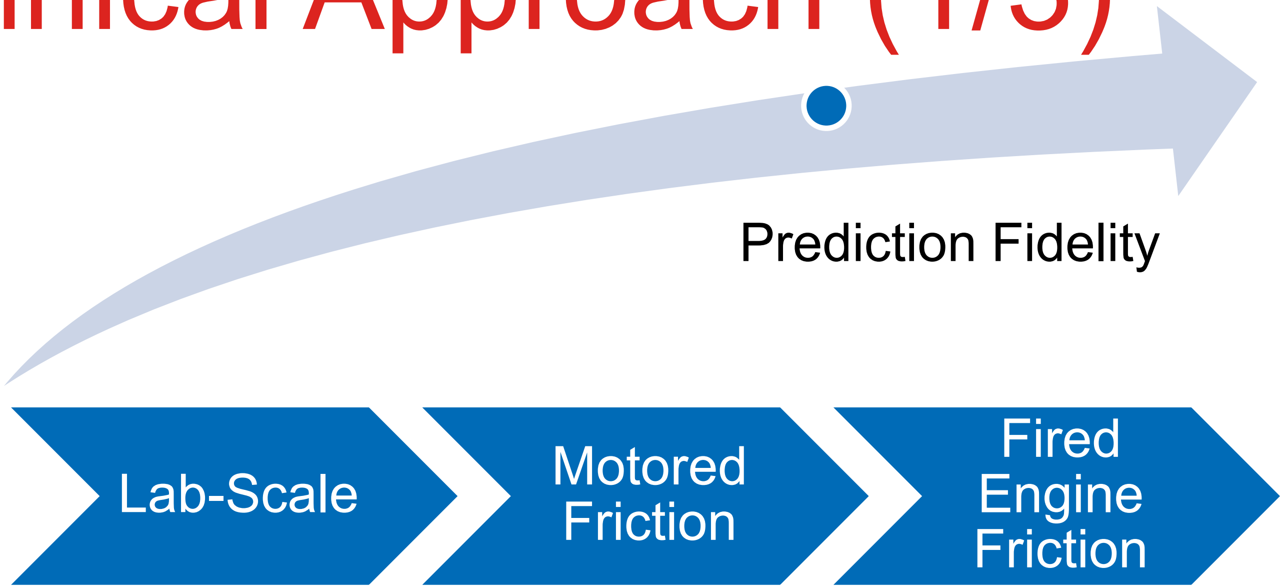
Milestones (2016)

Description	Type	Date	Status
Completion of testing at ANL with base Isuzu components	Milestone	14 Feb 16	Complete
Completion of testing at EMA with Isuzu base components	Milestone	20 July 16	Complete
Final RINGPAK model of AART including validation	Milestone	3 June 16	Complete
Delivery of coated Isuzu components	Milestone	1 July 16	Complete
Testing of coated Isuzu components	Milestone	11 July 16	Complete
Completion of engine thermal survey	Milestone	7 Sep 16	Complete
Lab-scale correlation (ANL vs. EMA)	Milestone	9 Dec 16	Complete
Determination of hardware for long-term wear testing	**GO/NO GO**	**15 Dec 16**	**Complete**

Milestones (2017)

Description	Type	Date	Status
Methodology for optical wear characterization	Milestone	23 March 17	Complete
Completion of motored engine friction tests	Milestone	May 17	On Track
Completion of long-term wear testing	Milestone	May 17	On Track
Completion of fired engine friction tests	Milestone	June 17	On Track
Thermal/FEA Analysis	Milestone	July 17	On Track
Completion of RINGPAK/PISDYN model of motored & fired engine including validation	Milestone	Sep 17	On Track
Model-of-a-Model for Fuel Economy Predictions	Milestone	Nov 17	On Track

Technical Approach (1/3)

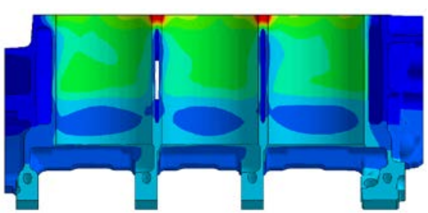


- Friction reduction technologies will be chosen for evaluation not necessarily because they are commercial viable but because of their usefulness in developing and validating prediction methodologies.
- These technologies will be tested in a progression of controlled test methods each with its own pros and cons for quantifying friction and wear.
- Data obtained from these experiments will be used to develop and validate empirical models and CAE methods.

Key Deliverables:
- An empirical model-of-a-model which relates tribological parameters to engine friction, wear and fuel economy
- CAE best practices for predicting friction and wear

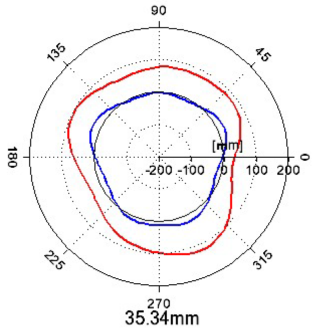
Technical Approach (2/3)

- RINGPAK and PISDYN models of the Isuzu engine will be created and validated against lab-scale and motored fired engine friction tests.
  - The physical test and models measure and predict FMEP respectively.
- Motored engine RINGPAK and PISDYN models will be updated with fired engine boundary conditions and validated against fired engine dyno data (FMEP from cylinder pressure measurements).
  - Thermal-FEA will be used to provide boundary conditions for bore distortion and local surface temperatures of components.
- Fired engine RINGPAK and PISDYN models will be used to compute changes in FMEP at a few selected operating conditions (engine speed, engine load) due to particular friction reduction technologies.

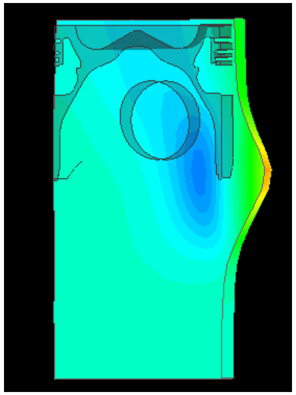


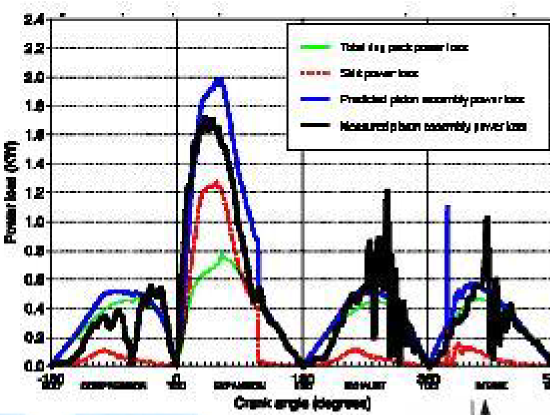
SIMULIA

ABAQUS



FEARCE

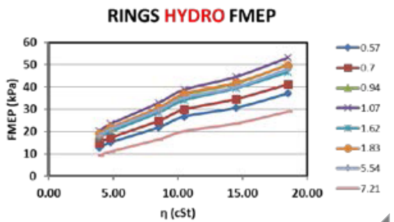


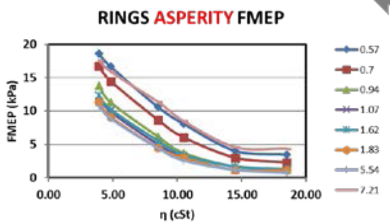


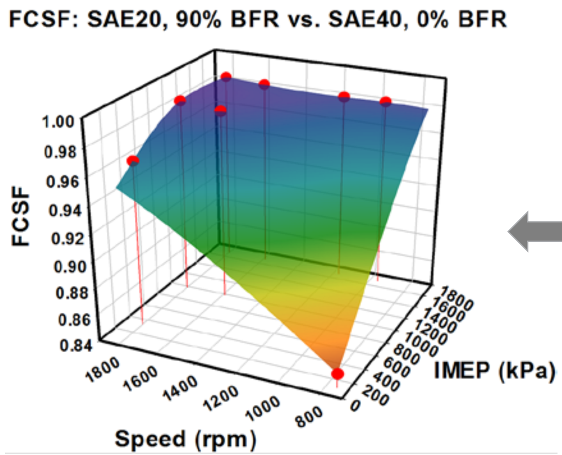
RINGPAK

PISDYN

Technical Approach (3/3)







- Linear regression models of predicted FMEP from RINGPAK/PISDYN simulations will be made (i.e., model-of-a model to expand rage of applicability).
  - FMEP predictions will be validated against motored and fired engine dyno testing*.
- Possible model forms used to calculate ΔFMEP could be:

$FMEP_{hydro} = y_{h0} + a_h \eta$
$FMEP_{asp} = y_{a0} + a_a e^{(-b\eta)}$
$FMEP = FMEP_{hydro} + FMEP_{asp}$
$(y_{a,h0}, a_a, a_h, b) = A_0 + A_1 N + A_2 N^2 + A_3 IMEP + A_4 IMEP^2$
η = viscosity
N = Speed (rpm)
MEP = Mean Effective Pressure (kPa); F → Friction I → Indicated

- Through fuel consumption scaling factors (FCSF), fuel economy improvements relative to a baseline fuel economy map from friction reduction technologies will be calculated and validated against actual fuel economy improvements from fired engine dyno tests*.

$$FCSF = \frac{(IMEP + \Delta FMEP)}{IMEP}$$

- Interrogate FCSF over drive cycle to obtain real world fuel economy improvements.

*Corrected to account for lubricant effects on non power cylinder components contributing to FMEP or fuel consumption

Updated Test Matrix (1/2)

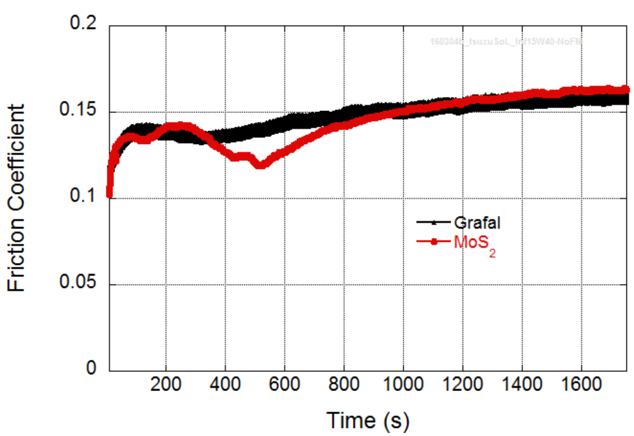
- Set backs have forced a mid-course correction for the project.
- Original plan assumed motored and fired friction tests according to the following build schedule:

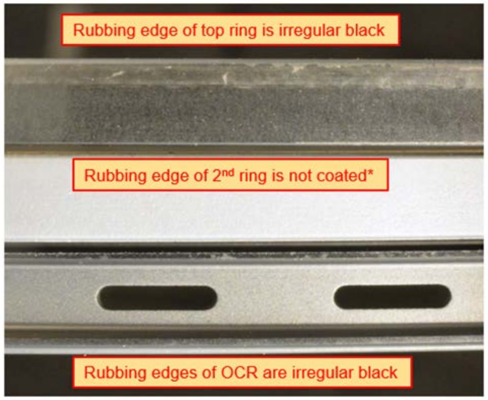
Build	Ring	Piston	Oil
1	Base	Base	A
2	New	Base	A
3	Base	New	A
4	New	New	A
5	Build 1		B
6	Build 2, 3, or 4		B

A = High Viscosity Oil

B = Low Viscosity Oil w/ FM

- However, rings and piston skirts coated with friction reducing material proved to be either under performing or not very robust due to poor adhesion.





Updated Test Matrix (2/2)

- Development of coatings was outside the scope of the project.
- A third oil blend was added to build matrix.
  - A special blend of oil using PAO coupled with ZDDP and MoDTC is known for significantly lowering the boundary fiction coefficient.
- Lab-scale tests confirmed this:

Blend	COF	
Infineum/Ricardo 15W/40 NO FM	0.13	← A
Infineum/Ricardo 5W/20 High FM	0.10	← B
ANL In-house PAO4 – ZDDP/MolyVan855	0.05 to 0.07	
Proprietary Blend	0.03	
Infineum E01208-028-002 (ZDDP1 + Moly Trimer)	0.06	← C
Infineum E01208-028-003 (ZDDP1 + high rate Moly Trimer)	0.06	

- The modified test matrix for motored and fired friction is as follows:

Build	Ring	Piston	Oil
1	Base	Base	A
5	Build 1		B
7	Build 1		C

Lab-Scale Correlation

- Data obtained from lab-scale tests are considered very critical to the success of the methodology being developed.
- Therefore, the team considered it very beneficial to validate lab-scale measurements done at ANL against measurements obtained using an alternative methodology.
  - These alternative measurements were performed by ElectroMechanical Associates (EMA).
  - ANL uses test coupons for both the ring-on-liner and skirt-on-liner tests cut from full components.
  - EMA uses full rings and pistons rubbed against liner test coupons for its tests.
  - Comparisons were based on measurements obtained with baseline Isuzu components and alternative hardware provided by ZYNP (ring w/ 3 liner combinations).
- Tests indicate fairly good correlation except for skirt on liner. Sensitivity to this input will be studied in the simulation phase of the project.

Ring-on-Liner Tests w/ ZYNP Components

	Nominal Honing	Z-fine Honing	DLC
ANL	0.11	0.11	0.12
EMA	0.11	0.10	0.11
% Diff	0%	10%	9%

Ring-on-Liner Tests w/ Isuzu Components

	EMA	ANL	% Diff
15W40	0.12	0.13	8%
5W20	0.11	0.1	9%

Skirt-on-Liner Tests w/ Isuzu Components

	EMA	ANL	% Diff
15W40	0.14	0.17	21%
5W20	0.1	0.09	10%

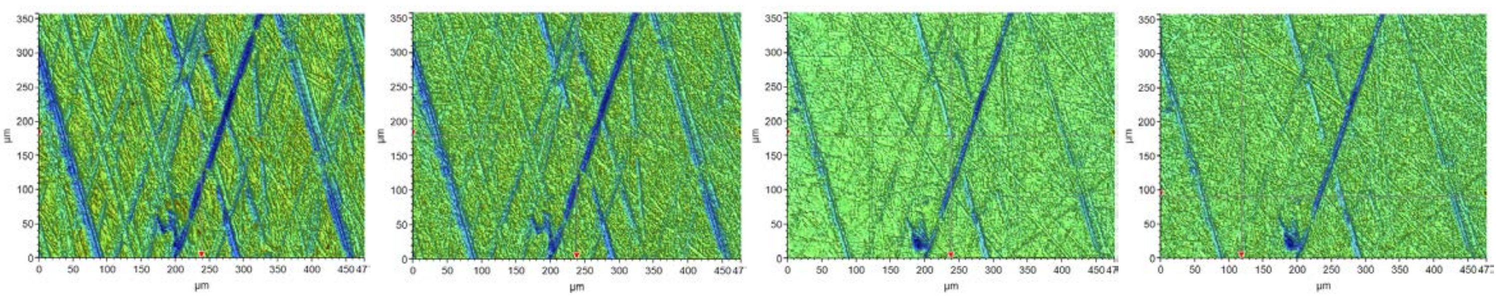
Wear Characterization (1/4)

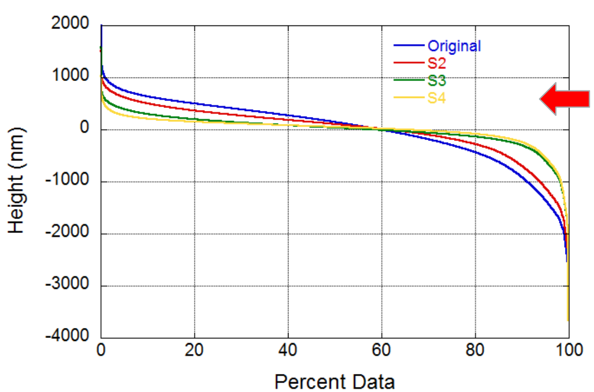
- Quantifying wear is difficult; many methods exist but none are considered very accurate.
- A paper* by Mike Stewart published in 1990 indicated that bearing area curves (BAC) aka Abbott-Firestone curves could be used for this purpose.
- The team embarked on developing an optical method for quantifying wear which uses white light interferometry (WLI) measurements as the basis for generating BAC curves.
- The methodology assumes the following:
  - If an accurate BAC can be measured for an unworn and worn part of surface then the volume of material removed can be exactly calculated.
  - This is accomplished by matching the lower 20% of the BAC curve which should remain unaltered because the wear mechanism tends to remove the peaks of surface leaving valleys untouched.
  - If this is correct, then the area between the two curves represents the volume material removed.

*Stewart, M., **A New Approach to the Bearing Area Curve**, FC90-229, Society of Manufacturing Engineers, 1990.

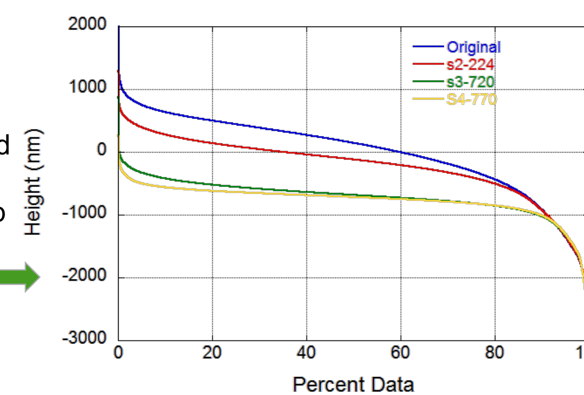
Wear Characterization (2/4)

- The methodology was validated as follows:
  - A single liner segment was imaged using the Bruker GTK white light interferometer.
  - The surface of the liner segment was progressively polished with different sandpapers to produce wear and the exact same area was imaged each time.
- The WLI images from the progressively sanded sample and the corresponding BAC curves are shown below:



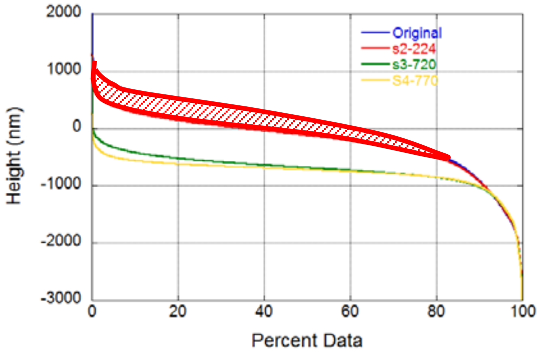


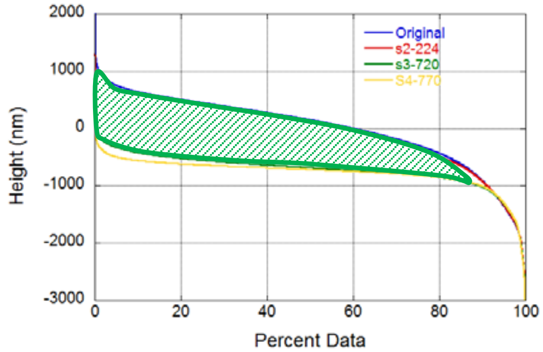
1. The Bearing area curves cannot be compared directly because the Y-axis of the BAC is determined by Bruker with respect to the mean line.
2. In order to make a comparison, an intermediate step is needed: the vertical registration is adjusted in order to match the lower part of the curves.

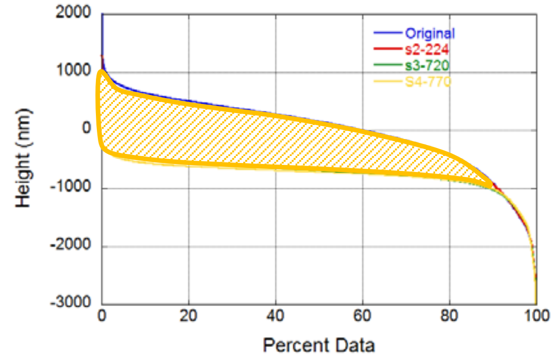


Wear Characterization (3/4)

- The area between curves is equal to the material volume lost during each of the sanding steps:







= Volume lost by S2 (μm^3)

= Volume lost by S3 (μm^3)

= Volume lost by S4 (μm^3)

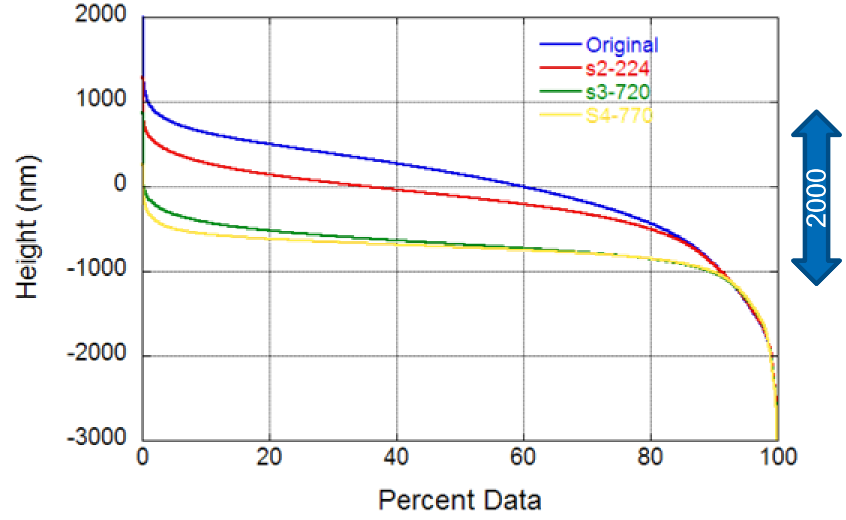
= Area under the curve (original) - Area under the curve (S2)= 399,633-377,207=22,426

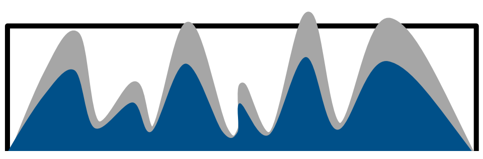
= Area under the curve (original) - Area under the curve (S3)= 399,633-327,676 = **71,957**

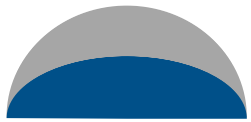
= Area under the curve (original) - Area under the curve (S4) = 399,633-322,636 = **76,997**

Wear Characterization (4/4)

- A simple back of the envelop calculation can verify the calculated values:
  - The XY size of the scanned image is 477 μm x 355 μm = 169,000 μm^2 so the volume of a block 1000 nm tall would be 169,000 μm^3
  - The histogram shows that the peaks were worn from about 2000 nm to about 1100 nm (where the lines diverge).
  - The rough topography is not a rectangular block, it is more like a series of hemispheres – a hemisphere has a volume that fills 52% of the block that it is inside
  - The volume lost of a hemisphere that is compressed from 2000 nm tall to 1100 nm tall would be about 79,000 μm^3.
  - This matches well with the value obtained from integrating the BAC curves.





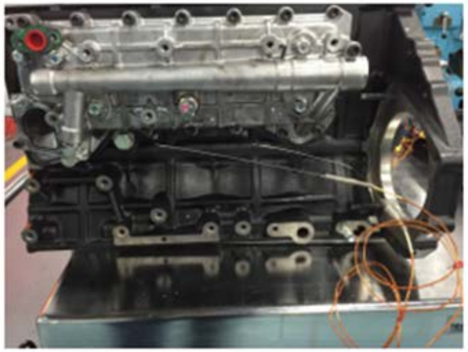


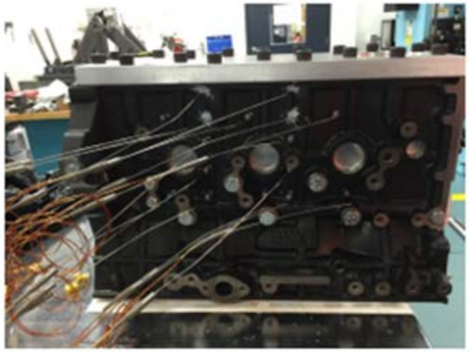
Long-Term Wear Test

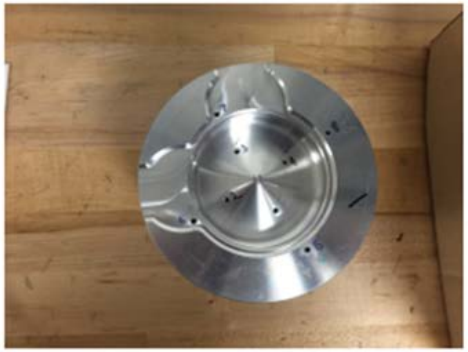
- With the wear methodology development complete, long-term wear testing can proceed.
- One of the difficulties associated with measuring material wear rates arises when a tribofilm covers the fine honing marks of a surface leading to net material gain instead of material loss.
- If this tribofilm cannot be removed, then measurements of wear may not account for the true wear rate of the material; they may either under account for the wear or actually show a net material gain.
- It is well known that fully formulated oils create tribofilms that are difficult to remove, whereas the tribofilm formed from simpler formulations can be easily removed using ethylenediaminetetraacetic acid (EDTA) and observations of the surface underneath the tribofilm can be made.
- It is for this reason, the project team has decided that the long term wear test will be conducted using the specially blended oil (PAO/ZDDP/MoDTC) that was formulated to achieve an ultra-low boundary friction value (oil C discussed earlier) and the baseline Isuzu ring-on-liner hardware set. This combination provides the best hardware match (i.e., a hard ring on a relatively soft liner) with an oil whose tribofilm can be easily removed.
- This fulfills the requirements of the 2nd GO/NO GO technical criteria.

Thermal Survey (1/2)

- A key input into the CAE modeling of the power cylinder is the thermal distortion of the engine bore and piston.
- In-situ measurements of bore and piston distortion in a firing engine are impossible; the next best way to validate predictions of thermal distortion is to validate metal temperature predictions against actual measurements made in the piston or the engine block.
- The Isuzu block and piston was instrumented with thermocouples and templugs to provide basis for model validation.

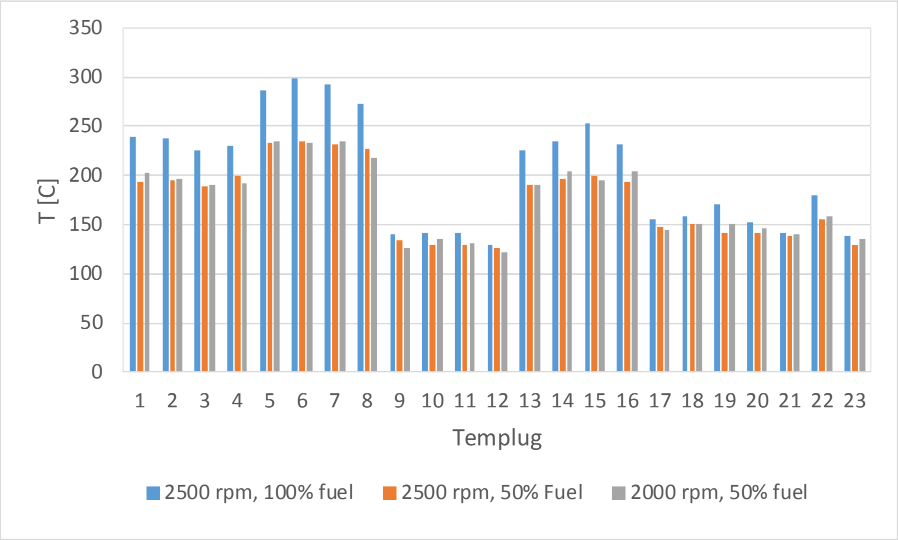




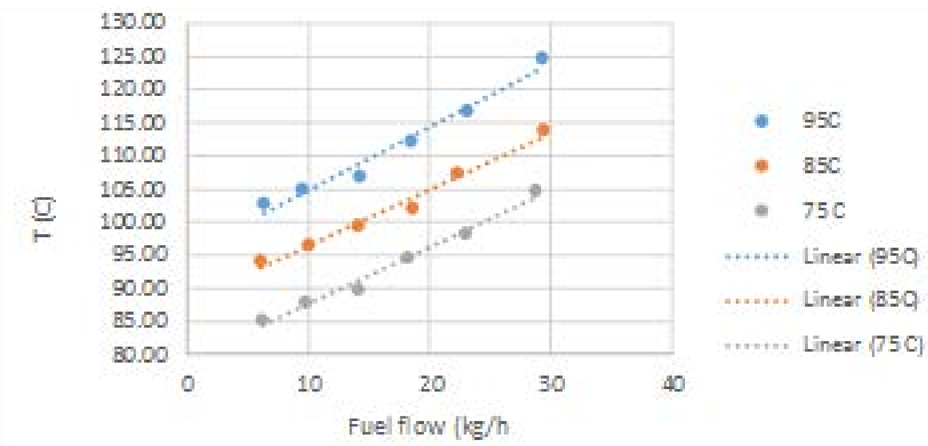


Thermal Survey (2/2)

- Templug data was obtained a only a few key operating conditions:
  - 2500 rpm, 100% fueling; 2500 rpm, 50% fueling; 2000 rpm, 50% fueling
- A more extensive data set was obtained for the block temperatures.
  - Cylinder block temperatures were recorded along the full load curve of the engine, at engine idle, and at the peak torque and full load speed for various fueling conditions. Measurements at these operating points were repeated for different coolant temperatures: 75, 85 and 95 °C.

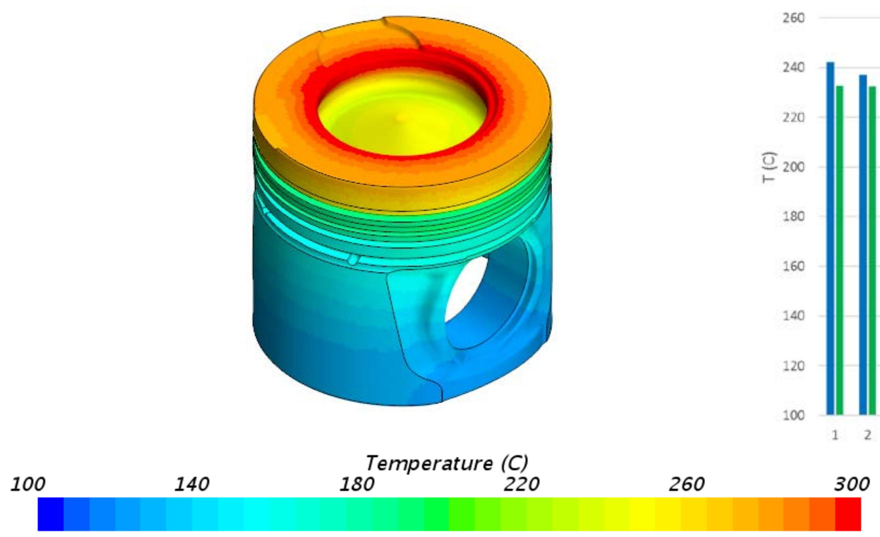


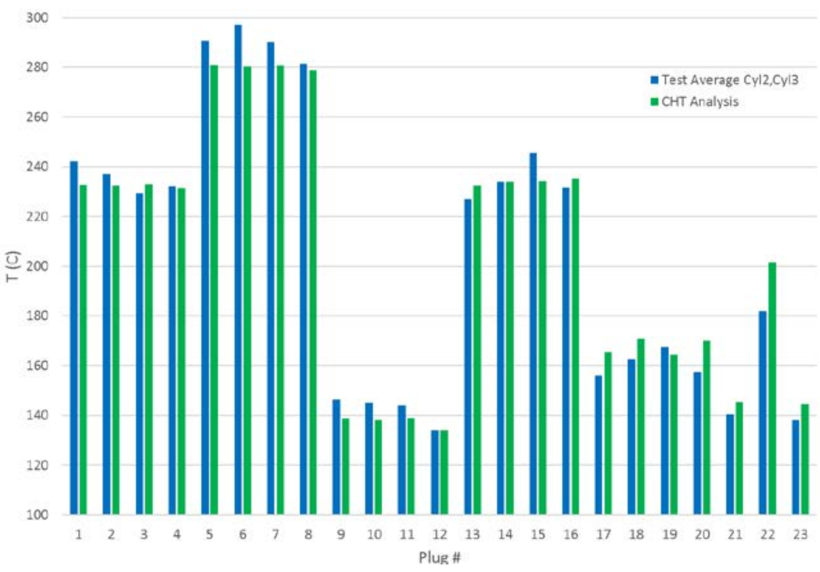
Interbore T between Cyls 1 & 2



CAE Modeling

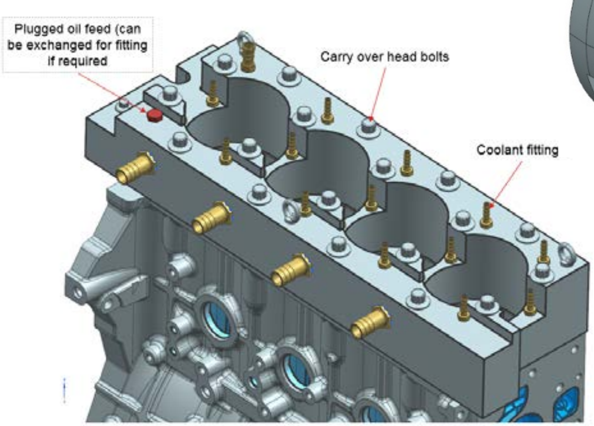
- The piston and block thermal data will be used to validate thermal simulations of the block and piston temperature.
- At this time, piston thermal simulations have been completed and validated against measurements
  - Comparisons indicated that the predicted temperatures are within 10% of measurements with the average error of approximately 3.5%.
- Block thermal simulations are pending the delivery of additional information from Isuzu.

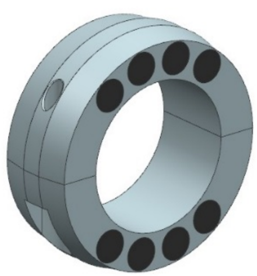


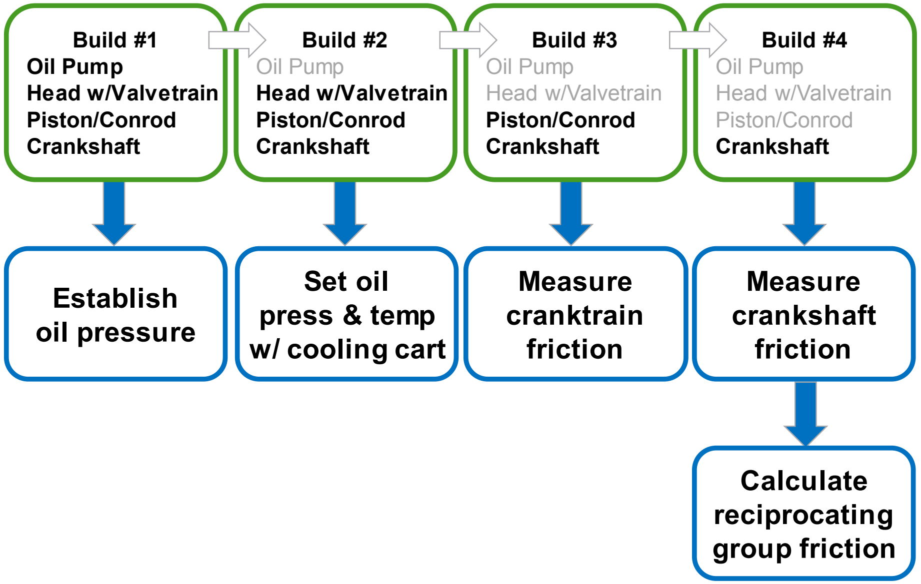


Motored Friction Testing

- Work is currently on-going to prepare the engine for the motored friction test.
- Test plan includes measuring FMEP across the engine speed range, using oils A, B, C at various oil temperatures.
  - At Build #3, the cylinder head and valvetrain need to come off and replaced by a deck plate.
  - At Build #4, the conrod, piston and rings come off and replaced by a bob weight to simulate inertia effects of the reciprocating components.







Challenges/Barriers

- The scope of the CAE modeling is confined to power cylinder components: ring and piston.
- However, lubricant changes affect the friction contributions from all components wetted by engine oil.
- Thus, FMEP measurements account for all contributors unless they are explicitly removed from the test.
  - Motored friction tests should be able to quantify the the friction contributions of the power cylinder.
  - However, this will not be possible for the fired friction tests.
  - This requires that an appropriate means to separate out the impact of lubricant changes on engine friction and fuel consumption realized through other components, e.g., main bearings, valve train, etc. be developed.
    - Other simulations tools will be leveraged to accomplish this.

Next Steps

- Receive required information from Isuzu to complete thermal analysis of the block, perform bore and piston distortion FEA, and conduct RINGPAK & PISDYN simulations.
- Perform motored and fired friction tests.
- Perform long-term wear measurements to obtain wear rate coefficients.
- Develop a model-of-a-model for fuel economy predictions; demonstrate that the model can be exercised over a real world usage profile to quantity fuel economy benefits for the different oils considered in this project.
  - Other theoretical case studies can/will be performed.
- Quantify wear over a reference usage profile; demonstrate that trade-offs between fuel economy and durability can be understood prior to any field or durability testing.

Any future work is subject to change based on funding levels.

Summary of Progress

- Build matrix finalized.
- Lab-scale correlation completed.
- Development of an optical method for wear characterization completed including the build specification for long-term wear testing completed.
- Thermal survey completed.
  – Piston thermal analysis completed.
  – Block thermal analysis pending.
- Motored friction tests initiated.

Partners/Collaborators

Ricardo: Technical lead responsible for project management and engine dyno testing, modeling and simulation.

Argonne National Laboratory: Responsible for lab-scale testing, data analysis and interpretation, modeling and simulation.

Isuzu: Partner providing in-kind contributions including the engine test platform, components for lab-scale and dyno testing, and consultation

Electro-Mechanical Associates: Sub-contractor providing additional lab-scale testing

ZYNP: Partner providing in-kind contributions of components for lab-scale testing