TITLE PAGE

Report Title: LOW-ENGINE-FRICTION TECHNOLOGY FOR ADVANCED NATURAL-GAS RECIPROCATING ENGINES

Annual Technical Progress Report

Reporting Period: April 1, 2002 – May 31, 2003

Submitted by:
Victor W. Wong, Tian Tian, Grant Smedley
August 28, 2003

DoE Cooperative Agreement No. DE-FC26-02NT41339

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DISCLAIMER

ABSTRACT

This program aims at improving the efficiency of advanced natural-gas reciprocating engines (ANGRE) by reducing piston/ring assembly friction without major adverse effects on engine performance, such as increased oil consumption and emissions. A detailed set of piston/ring dynamic and friction models have been developed and applied that illustrated the fundamental relationships between design parameters and friction losses. Various low-friction strategies and concepts have been explored, and engine experiments will validate these concepts. An iterative process of experimentation, simulation and analysis, will be followed with the goal of demonstrating a complete optimized low-friction engine system. As planned, MIT has developed guidelines for an initial set of low-friction piston-ring-pack designs. Current recommendations focus on subtle top-piston-ring and oil-control-ring characteristics. A full-scale Waukesha F18 engine has been installed at Colorado State University and testing of the baseline configuration is in progress. Components for the first design iteration are being procured. Subsequent work includes examining the friction and engine performance data and extending the analyses to other areas to evaluate opportunities for further friction improvement and the impact on oil consumption/emission and wear, towards demonstrating an optimized reduced-friction engine system.

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Massachusetts Institute of Technology

EXECUTIVE SUMMARY

This program aims to improve the efficiency of advanced natural-gas reciprocating engines (ANGRE) by reducing piston/ring assembly friction without major adverse effects on engine performance, such as increased oil consumption and emissions. The approach is to apply or adapt existing computer models to evaluate the friction reduction potential of various power-cylinder component design concepts. The promising low-friction candidate design concepts will be validated experimentally on an actual full-size large-bore natural-gas engine at Colorado State University (CSU). Waukesha Engine Dresser, Inc., will provide an engine, parts, and engineering support for the program.

The tasks for this reporting period included the following: (1) Organize the work plan and project team and define the overall strategy and approaches; (2) Assess opportunities for friction reduction by performing preliminary analyses and evaluating existing empirical data; (3) Modify or adapt existing engine friction and lubrication models to ANGRE engine types; (4) Conduct a parametric study evaluating the friction reduction potential of various low-friction designs using the computer models; (5) Make pre-assembly parts measurements to establish baseline engine design data; (6) Complete engine installation and instrumentation at Colorado State University (CSU), and (7) Recommend the first generation design of low-friction components and procure the parts for initial testing at CSU.

Despite the approximate one-month late start in the program, all of the above tasks have been accomplished in the period. Existing friction, ring dynamics, and lubrication models have been adapted to the large-engine configurations. We applied our analyses first to the standard baseline configuration of the Waukesha F18 VGF engine, in-line 6-cylinder [152 mm bore, 165 mm stroke], 18-liter natural gas SI engine, rated at 1800 rpm, at 13.6 bars brake mean effective pressure (370 kW), with the standard reference piston and ring parameters. We then performed detailed studies that illustrated the fundamental relationships between design parameters and friction losses. Results indicate that the most significant contributors to friction are the oil control ring throughout the engine cycle and the top ring around top dead center of compression/expansion. As planned, we have developed strategies and guidelines for an initial set of low-friction piston-ring-pack designs.

Current recommendations focus on subtle top-piston-ring profiles and oil-control-ring characteristics. Results illustrate how the barrel shape of the piston rings, ring groove tilt,

piston land heights, piston and bore surface characteristics, and oil control ring tension can affect friction. For changes in design parameter values of about 50% of baseline values, up to 30% friction reduction from individual parameter variations can be achieved. If the individual effects are additive, total ring pack friction reduction of 50% or more can be realized. Assuming the ring-pack and piston contributes 1/3 to total mechanical friction, and that piston and ring-pack effects are comparable, the total mechanical friction can thus be reduced by about 17% (1/6). Total reduction in mechanical friction of this magnitude in an engine translates to substantial fuel savings.

A full-scale Waukesha F18GL engine has been installed at Colorado State University and testing of the baseline configuration is in progress. In the mean time, components for the first design iteration are being procured. We are extending our analyses to other areas to examine opportunities for further friction improvement and its impact on oil consumption/emission and wear. We will follow an iterative process of experimentation, simulation and analysis, as further test data become available.

We followed our initial project Milestone Plan very closely. However, at a major project team meeting among MIT, Colorado State University, and Waukesha on March 24, 2003, it became clear that the plan needed to be updated. Essentially the experimental schedule needed to be extended for three month, which also allowed additional time for more detailed analyses for the large number of analytical options uncovered. All team members were committed to accelerate subsequent work to meet the original overall program schedule. Accordingly, this annual report covers a longer period than administratively indicated in the program. Despite the schedule shift, first year objectives have largely been met.

Monthly telephone conferences were held among all team members (MIT, CSU, and Waukesha), in addition to two on-site team meetings: one each at MIT and CSU. A semi-annual informational report was submitted in January 2003. Student researchers have been an integral part of the team. This arrangement provided a good learning experience to students to become effective project engineers in the future, in both scientific research and in project management.

During the second year, we aim at (1) Analyzing the data taken from the Waukesha F18 VGF engine incorporating the initial low-friction design recommendations, (2) Performing further analyses and design iterations, (3) Investigating the tradeoffs among friction, component wear, and oil consumption (emissions), (4) Extending the analyses to low-friction piston design parameters, (5) Developing an optimized low-friction ring pack, piston, and engine system to be demonstrated. In addition, (6) we will continue to pursue our training, educational, and technology-transfer missions for our students, the industry, DoE, and the public at large.

This annual report presents progress in the order of the tasks as described in the Statement of Work. Task 1 is Program Planning. Task 2 “Make Engine Comparisons” involves the standard methodology of surveying existing knowledge that could potentially narrow the investigation to specific areas. Task 3, “Model Concepts” in combination with Task 4, the Experimental part of the program, and Task 5, “Analyze Test Results” form the primary part of the program, and it involves an iterative process that will continue throughout the program. The Project Management, Educational, and Training aspects of the program will be summarized in Task 6

LOW-ENGINE-FRICTION TECHNOLOGY FOR ADVANCED NATURAL-GAS RECIPROCATING ENGINES
Annual Technical Progress Report
(April 1, 2002 – May 31, 2003)

DoE Cooperative Agreement No. DE-FC26-02NT41339

INTRODUCTION

By reducing piston/ring assembly friction, parasitic losses of advanced natural gas reciprocating engines (ANGRE) will be lowered. Computer models have been developed to assess the opportunities of piston/ring-pack design strategies aimed at friction loss minimization. Fundamental design parameters and performance relationships have been evaluated. Effects of friction reduction strategies on wear, durability, and oil consumption (emissions) will be examined.

During the first year, analyses included development and application of the basic models that resulted in initial recommendations of friction piston ring designs. These designs are in the process of being validated. The engine facilities have been set up (Task 4.0). Further iterations of design/analysis and experimentation will continue during the second year.

This program focuses on current large-bore natural gas engine and power cylinder components. The modeling and analyses have demonstrated their great utility in efforts to understand and to optimize friction reduction concepts. Concept validation will be conducted experimentally on a Waukesha VGF engine, and concurrent computer parametric studies will continue to be performed and tested. Testing has just started at Colorado State University. System demonstration of an optimized engine system (Waukesha VGF) awaits further test results, data analyses, and continued design iterations.

REPORT OUTLINE

This report will present progress in the order of the tasks as described in the Technical Proposal and the Statement of Work. Task 1 is Program Planning, and will first be presented. Task 2 “Make Engine Comparisons” involves the standard methodology of surveying existing knowledge that could potentially narrow the investigation to specific areas. Task 3, “Model Concepts” in combination with Task 4, the Experimental part of the program, and Task 5, “Analyze Test Results” form the primary part of the program, and it involves an iterative process that will continue throughout the program. The Project Management, Educational, and Training aspects of the program will be summarized in Task 6

RESULTS AND DISCUSSION

Task 1.0 Prepare Milestone Plan

Using DoE Form 4600.3 as a guide, an initial project Milestone Plan was developed and submitted, as show in Figure 1. Specific tasks shown therein correspond directly to those described in the original work plan. The shaded bars correspond to the projected time horizon in which the tasks would be performed. A semi-annual technical progress report was submitted to the Technical Monitor, Tom George, in January 2003, as well as to the NETL AAD Document Center (but was returned, as it was not required).

At a major internal team review meeting among MIT, Colorado State University, and Waukesha on March 24, 2003, it became clear that the plan needed to be updated. A revised DoE Form 4600.3 containing the updated Milestone Plan was later submitted (and subsequently approved), as shown in Figure 2. The essential elements of the proposed changes were three-month extensions of Tasks 3 (Model Concepts) and Task 4 (Demonstrate Optimal Designs). Task 3 change was necessitated due to the large number of analytical options uncovered for further evaluation, and Task 4 was delayed by a late start. All team members were committed at the time to accelerate subsequent work to meet the original overall program schedule.

Task 2.0 Make Engine Comparison/Assess Opportunities

We targeted using the Waukesha F18 VGF engine as a baseline, and planned to select a comparable heavy-duty diesel engine that has similar operating range (speed and mean effective pressure) for reference. We aimed at a comparison to gain understanding of the ANGRE engine and to establish areas of potential further gains.

We compared the motoring friction of the Waukesha natural gas VGF engine to four other heavy-duty diesel engines from two manufacturers for a range of engine speeds. The results are shown in Figure 3. At 1800 rpm, motoring friction is higher in the Waukesha VGF18. Even higher friction is expected in firing conditions. This shows that there is significant potential for improvement for ANGRE engines.

Attempts to evaluate the detailed designs of comparable engine and component configurations, including wear patterns, engine performance, blow-by, and oil consumption have been hampered by the lack of data. In fact, direct engine friction measurements in general are scare for all engines, published or unpublished, especially for natural gas engines. However, based on review of available literature and discussion among team members, the preponderance of general engine data pointed to opportunities in ring and piston designs. All team members accepted this conclusion at this stage, which supports the original conjecture that piston and ring components offer opportunities of immediate friction reduction.

Task 3.0 Model Concepts: Design and Performance Analysis

<u>Summary:</u>

The following are our accomplishments in brief versus our plans:

1. We set out to modify and apply existing computer models to evaluate selected baseline ANGRE engine performance. This sub-task has been completed.
2. We aimed at using the models to investigate the fundamental behavior of piston rings, piston, lubricant behavior, lubricant and solid-solid contact conditions. We have made substantial progress in analyzing the piston rings for both hydrodynamic and boundary lubrication, as well as illustrating the fundamental effects of piston-ring design and dynamics on friction.

Project Milestone Plan

Program Project Identification: DE-FC26-02NT41339
Project Title: Low-Engine-Friction Technology for Advanced Natural Gas Reciprocating Engines
Organization: Massachusetts Institute of Technology Principal Investigator: Victor W. Wong
Program/Project Start Date: April 1, 2002
Program/Project Completion: March 31, 2004

Task ID #	TASK/SubTask Description	DURATION: CY 2002 (A M J J A S O N D)	CY 2003 (J F M A M J J A S O N D)	CY 2004 (J F M)	Comments
0	**Develop Program Plan**				
0.1	Develop Project Milestone Plan				
0.2	Deliver Program Fact Sheet				
0.3	Prepare Powerpoint Project Presentation				
1	**Assess Opportunities: Compare Engines**				
	- Preliminary Analyses. Empirical observations.				
2	**Model Concept: Design and Perf. Analyses**				
2.1	(a) Modify and adapt lubrication models				
2.2	(b) Apply models to study fundamental friction behavior. Develop and explore low friction concepts. Parametric studies.				
2.3	(c) Recommend low friction design options. Request for protoptype components				
3	**Demonstrate Optimal Design Concepts**				
3.1	Establish baseline test engine measurements				
3.1.1	- Install engine and make standard measurements				
3.1.2	- Instrument & test engine for special diagnostics				
3.2	Test components in controlled engine expt's to validate design concepts				
3.3	Demonstrate complete low-friction engine system				
4	**Analyze Performance and Iterate Designs**				
4.1	- Analyze more in-depth various design options				
4.2	- Refine models and iterate tests as necessary				
5	**Conduct/prepare periodic reviews & reports**				
5.1	- Deliver semi-annual reports				
5.2	- Deliver Final Report				

Figure 1: Initial Project Milestone Plan

DOE Form 4600.3

PROJECT MILESTONE PLAN

Updated: March 28, 2003

1. Program/Project Identification No. **DE-FC26-02NT41339**

2. Program/Project Title: **Low Engine Friction Technology for Advanced Natural Gas Reciprocating Engines**

3. Performer (Name, Address) **Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139**
Technical: Dr. Victor W. Wong, Room 31-155, MIT Business: Mr. Jeffrey Friedland, Room E19-750, MIT. Tel: 617-253-4734
Tel: 617-253-5231 Fax: 617-253-9453 vwong@mit.edu

4. Program/Project Start Date **4/1/02**

5. Program/Project Completion Date **3/31/04**

8. Program/Project Duration **(4/1/02 – 3/31/04)**

Calendar Year 2002: A M J J A S O N D | Calendar Year 2003: J F M A M J J A S O N D | CY 2004: J F M

Charting Information:
Major Milestones △ Milestone Reached ▲
Task/subtask planned completion point ▽
Task/subtask actual completion point ▼
Schedule Deviation (early or slippage) ◇

6. Task New #	7. Planning Category (Task/Subtask Description)	9. Comments (Notes, Name of Performer)
1	**Develop Program Plan**	**Completed**
1.1	Develop Project Milestone Plan	**Completed**
1.2	Deliver Program Fact Sheet	**Completed**
1.3	Prepare Powerpoint Project Presentation	**Completed**
2	**Make Engine Comparison: Assess Opportunities**	**Completed**
	Preliminary analyses & empirical observations	
3	**Model Concepts: Design & Perf. Analyses**	**Extend 1 month**
3.1	(a) Modify and adapt lubrication models	**Completed Early**
3.2	(b) Apply models to study fundamental friction	**Extend 3 months**
	behavior. Develop and explore low friction	Extensive analyses
	concepts. Perform parametric studies.	Multiple designs
3.3	(c) Recommend low friction design options.	to propose thru Jun
	Request prototype components for tests	**Extend 1 month**
4	**Demonstrate Optimal Design Concepts**	Colorado State U.
4.1	Establish baseline test engine measurements	**Extend 3 months**
4.1.1	- install engine and make standard measurements	**Extend 3 months**
4.1.2	- instrument and test engine with special diagnostics	**Extend 3 months**
4.2	Test components in controlled engine	Accelerate to stay
	experiments to validate design concepts	on schedule
4.3	Demonstrate complete low-friction engine system	To be performed
5	**Analyze Test Results and Iterate Designs**	To be Performed
5.1	- Analyze more in-depth various design options	To be Performed
5.2	- Refine models and iterate tests as necessary	To be Performed
6	**Project Management, Reporting & Education**	**Continuous**
6.1	Conduct/prepare periodic reviews and reports	Two team reviews
6.1.1	- Monthly team conferences (involving students)	Monthly teleConfs
6.1.2	- Deliver semi-annual/annual reports	1 semi-annual report
6.1.3	- Deliver Final Report	

10. Remarks: This updated project milestone plan is hereby submitted for review and approval. The plan was agreed to by the project team at a team review meeting on 3/24/03,. The essential elements of the proposed changes are three-month extensions of Tasks 3 (Model Concepts) and Task 4 (Demonstrate Optimal Designs). Task 3 change was necessitated due to the large amount of analytical options, and Task 4 was delayed by a late start. We will attempt to accelerate subsequent work to meet original overall program schedule at this point.

11. Signature of Recipient and Date: Victor W. Wong Victor W. Wong 3/28/03, MIT

12. Signature of U.S. Department of Energy (DoE) Reviewing Representative and Date

Figure 2: Updated Project Milestone Plan

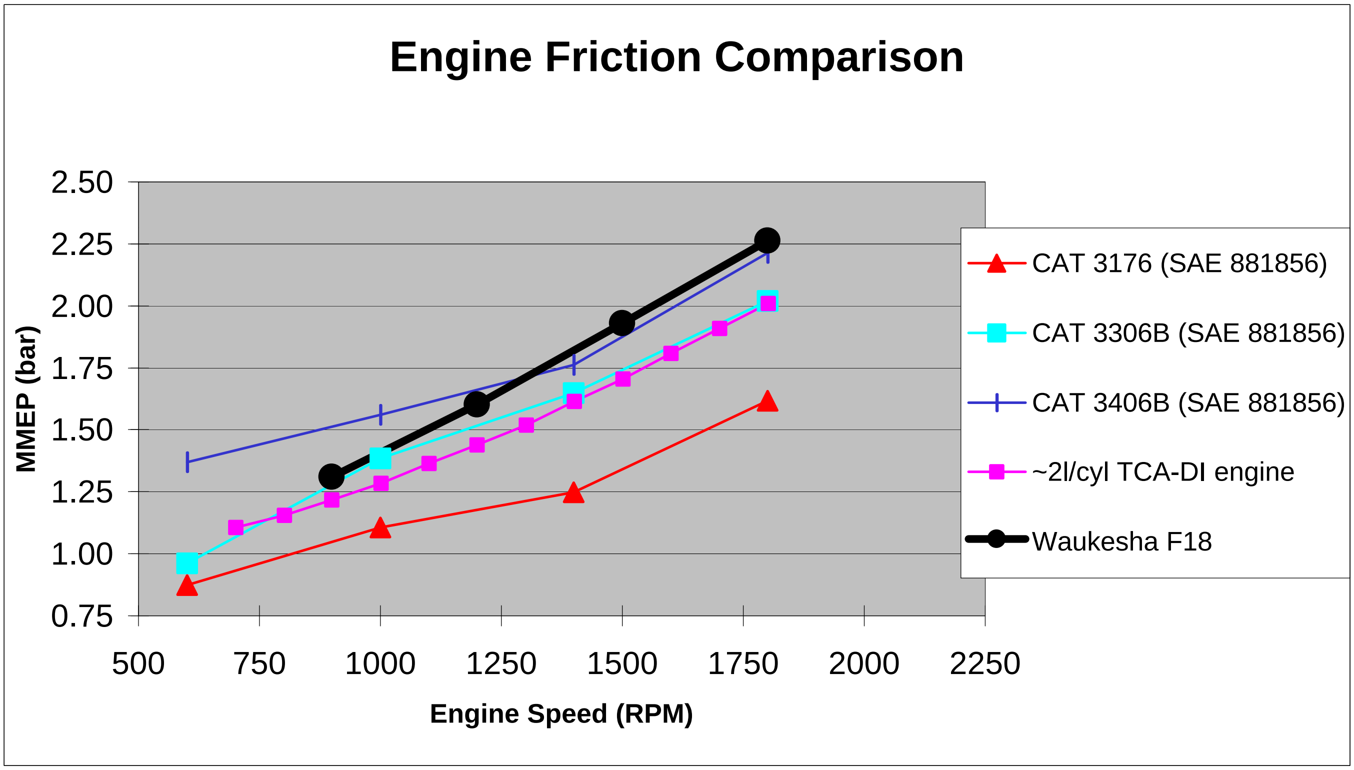

Figure 3: Engine Comparisons: Motoring Friction Versus Engine Speed

3. We developed initial recommendations of proposed piston-ring designs for low friction. The design guidelines focus on top piston ring profile and oil-control ring tension.
4. We requested prototype designs to be fabricated or furnished by component or engine manufacturer. These components are being procured.

<u>Modeling and Analysis</u>

<u>1. Overview</u>

MIT's computer models [1-5] have been applied to target the most important contributors to friction in the piston-cylinder assembly of the engine. Specifically, three models were applied to analyze the behavior of the piston rings and these are described in some detail in the section that follows. Preliminary results from the models indicate that the most significant contributors to friction in the piston-cylinder assembly are from the oil control ring throughout the engine cycle and from the top ring around TDC (top dead center) of compression/expansion. Strategies for design changes to reduce these contributions are suggested in the sections that follow. A detailed parametric study was conducted to explore the effect of these proposed design changes on friction using the computer models. In the months ahead, the limits of these design changes will need to be established in order to translate the results of the parametric study into low-friction design guidelines.

2. Description of Computer Models

The following models were developed at MIT and were applied to analyze the behavior of the piston ring pack throughout the engine cycle.

a) *RINGPACK-OC*

This model provides information about piston ring dynamics throughout the engine cycle. In particular, outputs include ring lift and twist, ring-groove clearance, ring-liner clearance and forces and moments acting on the piston rings. The model also provides land pressures and mass flow rates of gases between various locations on the piston.

b) *FRICTION-OFT*

This model predicts instantaneous friction forces acting on the rings, and also provides oil film thickness under the rings and on the liner at various locations.

c) *TLOCR*

This model provides a combination of the outputs provided by *RINGPACK-OC* and *FRICTION-OFT*, but specifically for the geometry of the twin-land oil control ring, which is modeled in a very simplified manner in the other models.

3. Preliminary Results

We applied our analyses first to the standard baseline configuration of the Waukesha F18 VGF engine, in-line 6-cylinder [152 mm bore, 165 mm stroke], 18-liter natural gas SI engine, rated at 1800 rpm, at 13.6 bars brake mean effective pressure (370 kW), with the standard reference piston and ring parameters.

Figure 4 shows the friction power loss of the ring pack at the rated condition for ring and liner roughness (rms) values of 0.30 micron and 0.21 microns respectively, and a friction coefficient = 0.1 during boundary contact. For these conditions, the results indicate that the most significant contributions to the ring pack friction come from the top ring around top dead center (TDC) of compression/expansion and from the oil-control ring (OCR) throughout the engine cycle.

Figure 5 shows the FMEP (Friction Mean Effective Pressure) contributions from each of the piston rings to the overall friction in the piston-cylinder assembly, for the same conditions. The top ring and OCR are clearly the most important contributors to friction. Also, it is also important to note that the most significant contribution to oil control ring friction is from hydrodynamic lubrication, while for the top ring the most significant contribution is from boundary lubrication.

The high contribution of the top ring boundary friction is due to the low amount of oil that exists on the liner in the top dead center region. This low oil film thickness is a result of the lack of direct oil supply to this region, owing to the fact that the oil control ring never reaches this part of the liner. The oil supply is thus determined by whatever was left by the top two rings in the previous stroke. This “dry region” is illustrated in Figure 6. The effect of the poor oil supply to this region is shown in Figure 7, which shows the wetting extent under the top ring throughout the cycle. The minimum point is defined as the point on the ring face profile that is closest to the liner. When the three lines in the figure converge into one, there is no longer any oil between the piston ring and the liner. This occurs around TDC as shown.

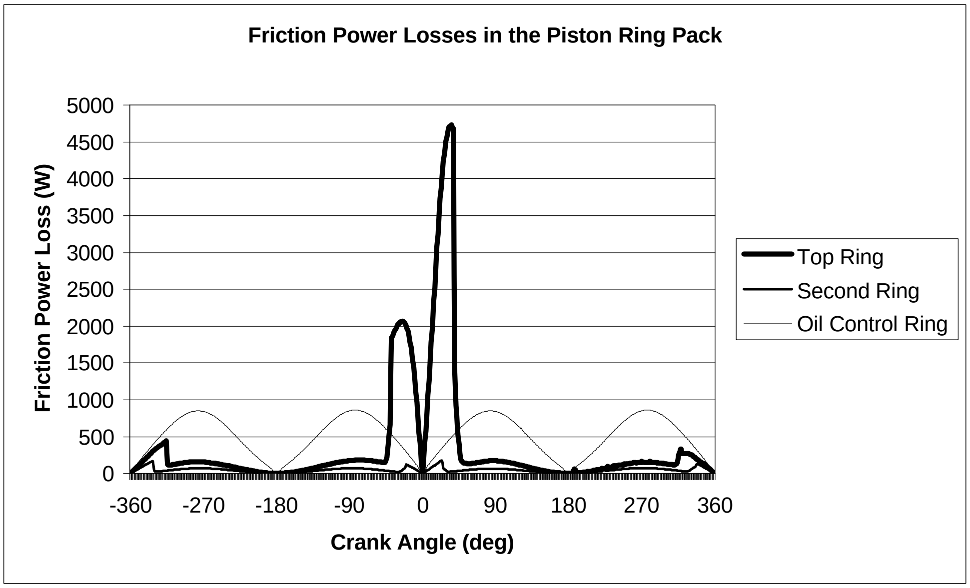

Figure 4: Friction Power Loss of the Ring Pack (Per Cylinder).

(Top Curve is top ring. Second Ring is the bottom curve, and OCR Ring Curve in the middle)

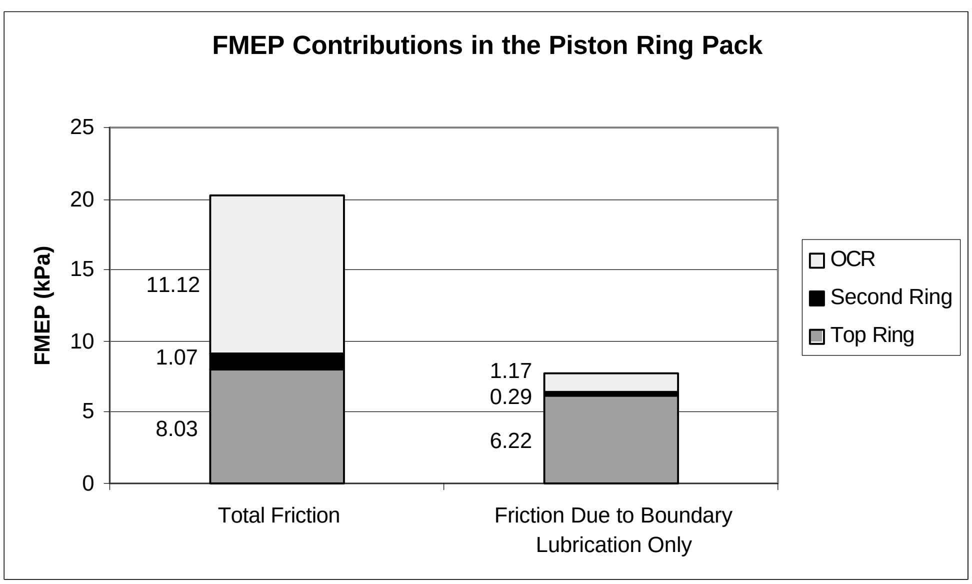

Figure 5: FMEP Contributions in the Piston Ring Pack

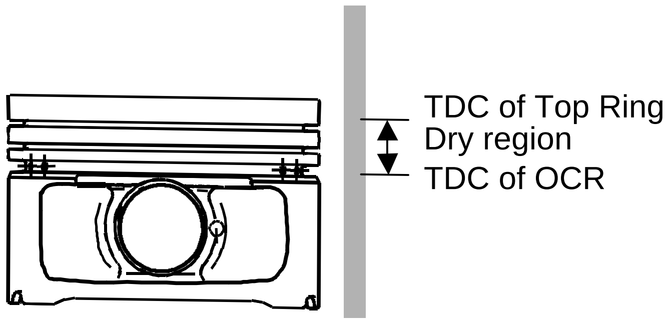

Figure 6: The Dry Region of Top Ring Travel

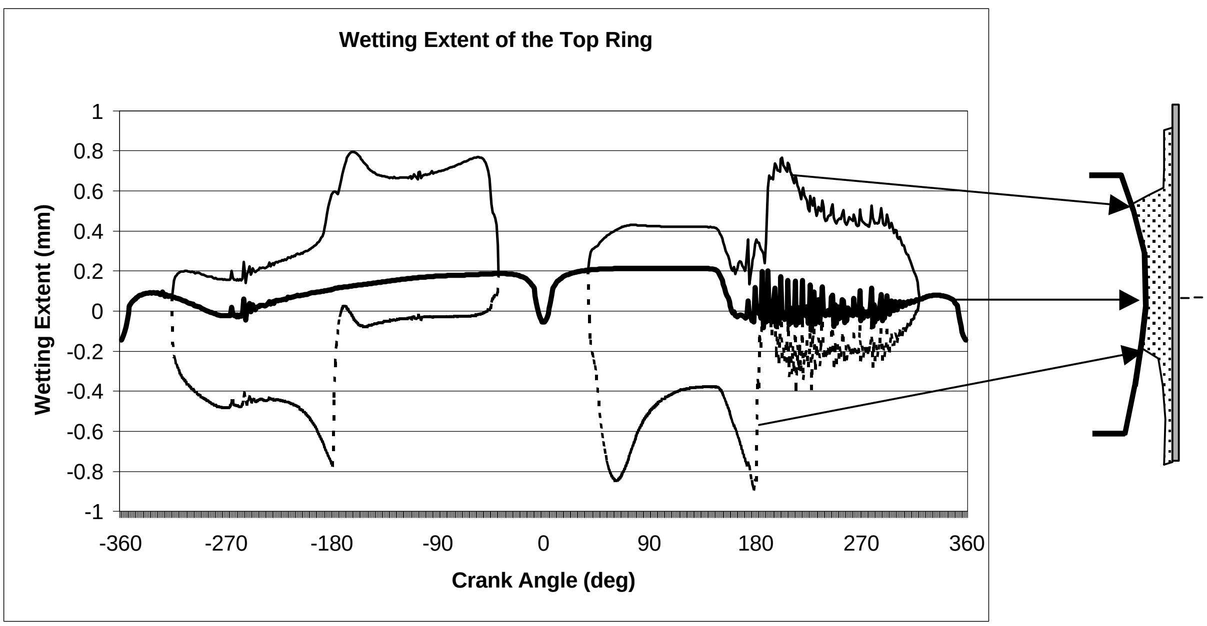

Figure 7: Wetting Extent of the Top Ring

The high contribution of the OCR to overall ring pack friction throughout the cycle is due to its high tension. High tension is required so that OCR can conform to the bore at all times throughout an engine cycle, especially when bore distortion becomes significant. The effect of the high-tension force of the OCR acting on its small land widths results in a very high unit pressure on the oil film. This results in low oil film thickness between the liner and the OCR, which leads to high friction.

4. Friction Reduction Strategies

In the following section, strategies for friction reduction in the oil control ring and the top ring are suggested. In addition to these, certain design changes reduce friction overall, but do not target specific rings. For example, lower ring pack friction can be achieved by reducing the lubricant viscosity by changing the oil type used. Also, reducing the liner roughness can result in significant friction reduction overall.

a) Oil-Control Ring Friction

The friction generated by the OCR throughout the cycle can be reduced by reducing the OCR tension. This reduction in tension should be accompanied by appropriate geometric changes to preserve conformability when bore expansion is significant. One such change would be to reduce the moment of inertia of the OCR. This can be done in various ways and thus investigation is needed to determine which parameters would best be changed to reduce moment of inertia.

b) Top Ring Friction

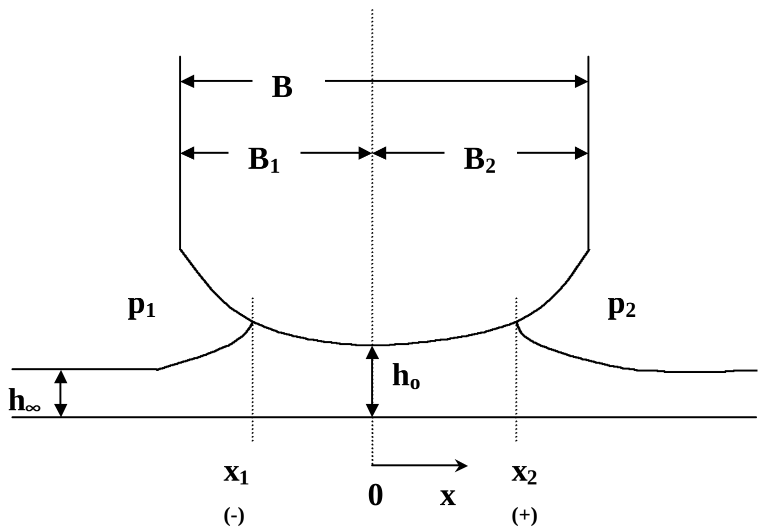

Figure 8: Top Ring/Liner System

Top ring friction can be reduced by several methods. Since most of the top ring friction is generated in the dry region where boundary lubrication conditions exist, the friction force is controlled by the normal load on the ring. For the configuration shown in Figure 8, this can be estimated as follows:

$$F_f = a_{asp}\left[\left(p_2 - p_1\right)B_1 + W\right]$$

where F_f is the friction force, a_{asp} is the asperity contact coefficient, p_2, p_1 are gas pressures, B_1 is the leading-edge ring width, referenced to the point of minimum proximity to the wall, and W is the load due to ring tension. When the top ring is near TDC of compression/expansion, the pressure difference term dominates as the cylinder pressure is very high compared to the second land pressure. Therefore, changes in the top ring tension have very little effect on top ring friction. Cylinder pressure is determined by the engine operating conditions, which are assumed to remain fixed for this power generation engine. The strategy for friction reduction is thus to reduce B_1, which is the area onto which the force generated by the large pressure difference acts. This can be accomplished in three ways that are described below.

(i) Reduce top ring axial height

Lower top ring axial height proportionally reduces the area over which the high-pressure difference acts, reducing the normal load on the top ring and thus also reducing top ring friction.

(ii) Manufacture the ring with a skewed barrel profile

The top ring can be manufactured such that the barrel profile is skewed, as shown in Figure 9 below. The minimum point is thus lower on the ring running surface, and this reduces the area over which the high-pressure difference acts, reducing friction.

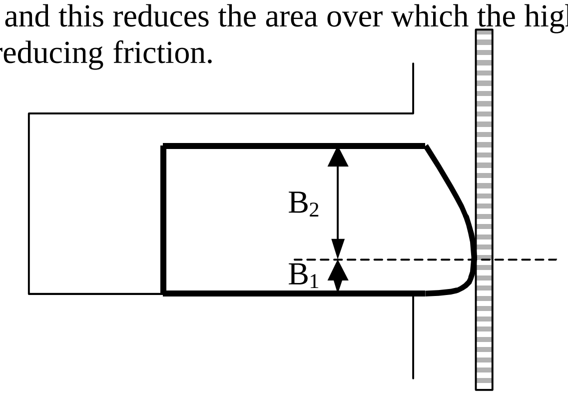

Figure 9: Top Ring with Skewed Barrel Profile

(iii) Introduce top ring groove tilt

Another way to reduce this area would be to take advantage of the fact that near TDC of compression/expansion, the top ring conforms well to the groove owing to the high-pressure differences involved. As a result, if the top ring groove were tilted in the upward direction as indicated in Figure 10, the minimum point on the top ring profile would move downward and the area over which the high-pressure difference acts would be reduced.

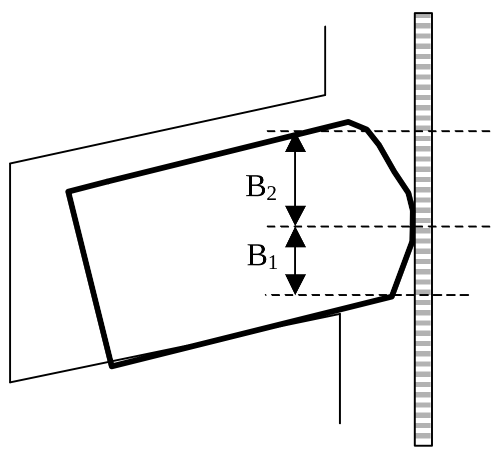

Figure 10: Effect of Top Ring Groove Tilt (B_2>B_1)

One final friction reduction strategy for the top ring involves reducing the physical length of the dry region itself. This can be accomplished by reducing the second and third land heights on the piston.

5. Parametric Study Results

The following figures compare the effects of the design changes discussed in the previous section. These results were obtained using the MIT computer models described in an earlier section. Figure 11 shows the OCR friction reduction achieved with different values of the OCR tension. Figure 12 shows the top ring friction reduction achieved with the different values of the parameters listed in the legend.

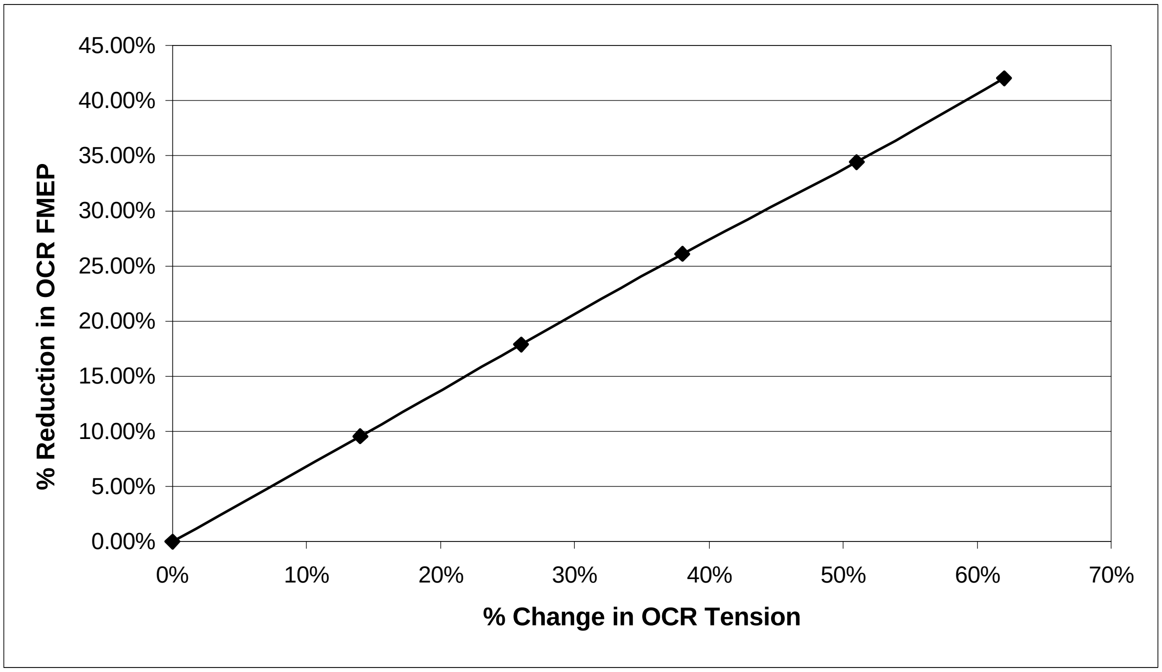

Figure 11: OCR Friction Reduction

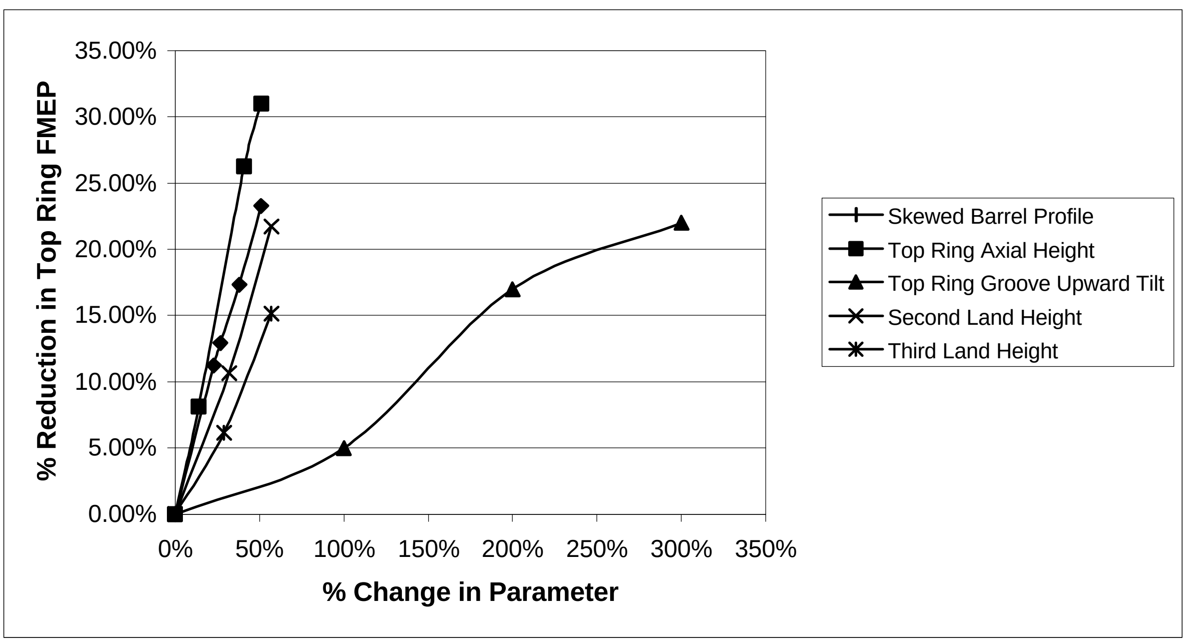

Figure 12: Top Ring Friction Reduction

As can seen from the figures, significant friction reduction can be achieved with sensible changes in the values of the parameters. Figure 13 compares the effect of each of the parameter changes on the overall piston ring pack friction, rather than on specifically the top ring friction or OCR friction. This provides a measure of the relative importance of the various changes. These results are for changes in the parameter values of 50% of their original values.

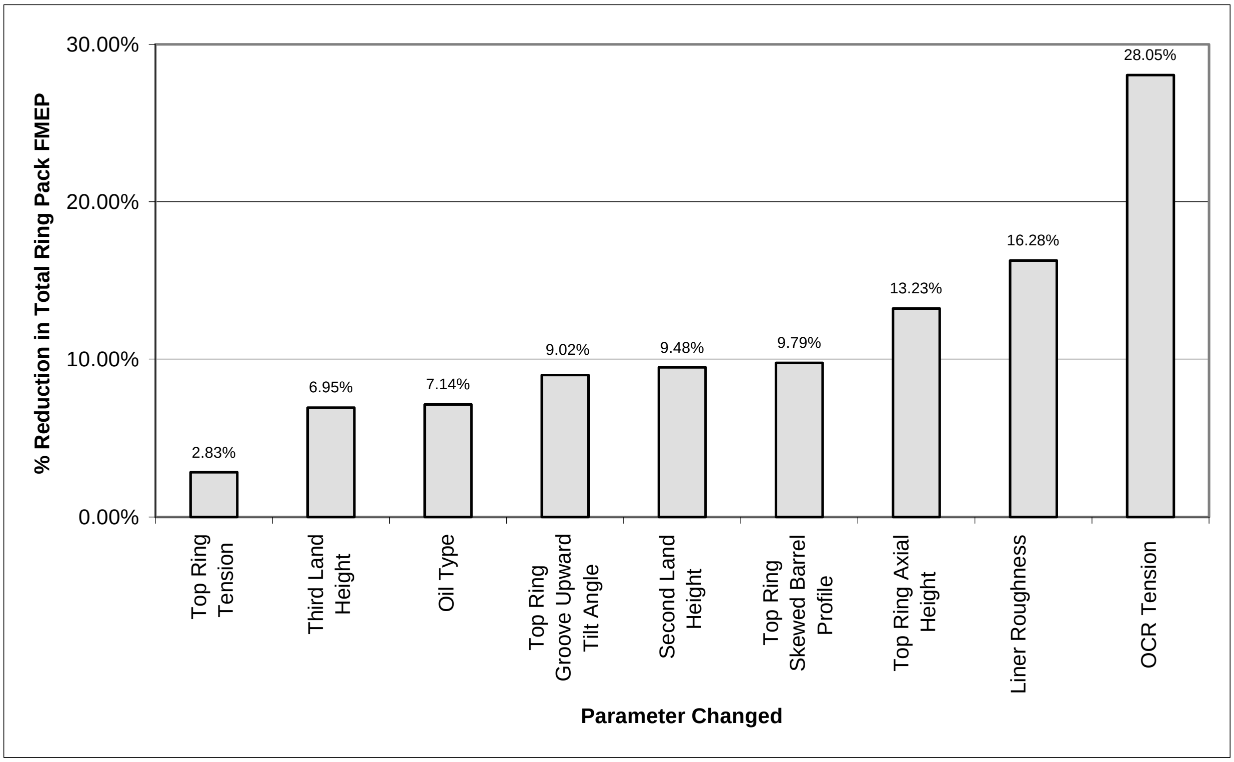

Figure 13: Comparison of Parameter Changes

6. Future Modeling and Analysis Work

In the months ahead, the results from the parametric study will be used to generate low-friction design guidelines for the piston rings. This will require an understanding of the factors that limit the design changes that can be made. Some of these factors include oil consumption, ring and piston groove wear, ring life and blow-by. Many of these factors will be left to experimental investigation. As such, a low-friction design will be chosen based on considerations discussed above, and testing at CSU will reveal the effect of the changes on the limiting factors. It has also been observed that some of the changes that reduce top ring friction around TDC, beyond a certain point, will actually begin to increase top ring friction in the mid-stroke region. Therefore, some investigation will be required in order to ensure that this effect does not compromise the friction reduction potential of the design changes. Once the low-friction guidelines are complete, the rings will be ordered and tested at CSU. The entire process will then be repeated for the piston.

EXPERIMENTAL

Task 4.0 Demonstrate Optimal Design Concepts

Pre-Assembly Measurement of Baseline Component Parameters and Engine Performance

Prior to the Waukesha engine being shipped to Colorado State University, component micro-geometries and surface characteristics were measured in order to correlate engine friction and performance with the appropriate design parameters. The measured design parameters included piston ring gaps, static twists, tensions, running-surface profile of the rings, ring groove tilt angles, free shape of the rings, and liner surface roughness. Piston parameters such as skirt profiles and surface finish were also made. Measurements were made at either Waukesha or at parts suppliers. Engine performance data collected at Waukesha included most essentially fuel and oil consumption and blow-by. It was decided to maintain standard lubricant properties (Mobil) for future comparison of test results.

Status of Engine and Instrumentation

An inline-6-cylinder, 18-liter, 152 mm x 165 mm (bore x stroke) Waukesha VGF natural-gas engine has been shipped to Colorado State University has been completely installed and instrumented. The engine is rated at brake mean effective pressure (bmep) of 13.6 bar (200 psi) and delivers 370 kW (497 hp) at 1800 rev/min. Pre-assembly measurements of component geometries and surface characteristics were made as described previously. Production testing on the engine has been done at Waukesha and included oil consumption and blow-by measurements.

Waukesha F18GL Installation Details at CSU

The installation of the Waukesha F18GL at the Engine's & Energy Conversion Lab (see Figure 14) at Colorado State University began with the creation of a CAD model of the engine. Using drawings provided by Waukesha representation of interface points were made in 3-D space to facilitate piping and instrumentation layouts. Using this CAD model installation and fabrication drawings were created. Based on the CAD model and the instruments layouts a detailed bill of materials was created and procurement of components began.

The engine arrived in mid October 2002 and new engine mounts were designed and fabricated to ensure proper alignment between the engine and the dynamometer. The engine was set in mid November 2002, and work on piping installation began. Once the major piping had been installed instrumentation and a control system were installed. The control system used for this installation is the National Instrument Field Point system. The system uses interchangeable modules to receive inputs, and to send output signals. All of the data is routed from the engine to the HMI via an Ethernet connection.

A wide variety of instrumentation has been installed on the engine. Rosemount 3051 pressure transmitters are employed for most of the system pressure measurement. Temperatures are measured using type J thermocouples. For in cylinder pressure measurement Kistler 6067C water cooled pressure transducers were used due to the high level of accuracy needed in computing indicated mean effective pressure (IMEP).

Figure 14: Installation of Waukesha F18 Natural-Gas Engine at CSU

Several pieces of special instrumentation were needed in order to perform the friction reduction study. A blow by flow meter from J-Tec Associates has been installed to measure the difference in blow by from altered piston ring pack configurations. A highly accurate oil consumption meter has been procured and installed. This oil consumption meter has a refill accuracy of ±1gram and a refill level accuracy of ±2 ìm allowing for relatively short test points (3 hours). The final and most technically challenging instrumentation needed, was the inter-ring pressure transducers. These sensors were required to mount through the crankcase, through a jacket water cavity and attach to the cylinder liner. There location was set to measure piston land pressure at TDC and BDC. For this application, the Kistler 6052A pressure transducer was chosen due to its compact size and sleeve mounting capability. Installation of these sensors required precision machining to be done both on the engine and on the cylinder liner. This was completed in early July and the engine is currently being reassembled for baseline testing.

Decisions regarding appropriate instrumentation to be used for collecting test data were made during telephone conferences and semi-annual meetings between MIT, CSU and Waukesha. Waukesha has recommended the type of cylinder pressure transducer to be used in the engine as well as the method of installation, and provided spare parts for the installation. MIT has provided expertise on the installation of pressure transducers to be used to measure inter-ring (land) pressures. During the 1/14/03 telephone conference, axial locations for the pressure transducers were recommended. During the 3/24/03 semi-annual meeting, specific issues concerning the installation procedure for the pressure transducers were resolved. MIT has also provided recommendations concerning the equipment needed to measure oil consumption and blow-by. During the 2/25/03 telephone conference, it was decided to measure oil consumption using a load cell that detects oil level rather than with an S02 tracer method. Also during the 2/25/03 telephone conference, it was decided to measure blow-by using a standard blow-by flow meter. At this point in the program, the cylinders of the engine have been completely instrumented and baseline testing of the engine has begun.

Task 5.0 Analyze Test Results

According to the most recent Milestone Plan, neither test results were scheduled nor available during this reporting period. Analysis of results and iteration of further design modeling (Task 3) will continue as soon as data becomes available. Testing is scheduled to begin at the beginning of the second year.

Task 6.0 Project Management, Reporting and Education

6.1 Project Management

This program maintains a program plan, which has been developed jointly and reviewed with all team members. All team members main frequent and periodic communication regarding the progress of the program, mostly via regularly scheduled telephone conferences of usually one hour in duration.

Meeting and Reviews:

Victor Wong (MIT) and Bryan Willson (CSU) attended the Reciprocating Engines Peer Review Meeting from April 23-24, 2002 with a poster display describing the program. A project team "kick-off" telephone meeting was held among MIT, CSU, and Waukesha representatives on May 14, 2002 to review the program plan and discuss the efforts needed to move the program forward. Multiple telephone conferences (approximately monthly) were held thereafter: 6/6/02, 7/18/02, 8/22/02, 9/19/02, 10/16/02, 12/12/02, 1/14/03, 2/25/03, 6/4/03. On-site Team review meetings were held at MIT on 11/6/02, and at CSU on 3/24/03. These face-to-face meetings proved to be extremely helpful in keeping the program on track and team members mindful of the program stated goals and tasks at hand. Victor Wong (MIT) and Bryan Willson (CSU) attended the DOE/NETL AUREP Peer Review Meeting on 4/9/03.

6.2 Reporting

In addition to all required administrative reports, the following technical reports were submitted: A Semi-Annual Report was submitted to the Technical Monitor, for informational purposes, in January 2003 (due Feb1). In additional, a Powerpoint presentation of the project was submitted to the Technical Monitor. A Milestone plan was filed as required, and it was updated on 3/28/03. The approved revision to the Milestone plan included an approximately 3-month delay in the schedule, which all team members are committed to catch up during the second year to maintain the overall program schedule. Therefore, this Annual Technical Progress Report intended for the period from 4/1/2003-3/31/2003 actually covers the period from 4/1/2003 – 5/31/2003, due to the late start of the program and the revised Milestone Plan. Significant progress has been made in the program; therefore in the near future we intend to prepare topical reports and papers to professional journals (as well as to DoE) for review and publication.

6.3 Education

Student researchers have been involved in all stages of this program – program planning, implementation, and especially reporting. This arrangement provides a good learning experience to students to become effective project engineers and scientists in the future. The program management experience is in additional to the technical and scientific analyses and working together as a team in the project. Metrics to evaluate progress are (a) how well the students appreciate and be able to develop concrete research plans, (b) awareness of and sensitivities to the concept of goals, tasks, and schedules, and (c) the proper preparation of and maintaining high quality in the reports, (d) ability to communicate the results to others (sponsors and team members). Progress in these areas has so far been quite satisfactory.

CONCLUSIONS

This program aims at applying computer simulations to illustrate the lubrication characteristics in advanced natural gas reciprocating engines (ANGRE) and to explore low-friction design concepts with minimal adverse effects on engine performance or emissions. Engine experiments will validate these concepts and a complete optimized engine system will be demonstrated.

As planned, MIT has developed guidelines for an initial set of low-friction piston-ring-pack designs. These recommendations focus on subtle top-piston-ring profiles and oil-control-ring characteristics. Results illustrate how the barrel shape of the top ring, ring groove tilt, piston land height, and oil control ring tension can affect friction. For changes in design parameter values of about 50% of baseline values, up to 30% friction reduction from individual parameter variations can be achieved. If the individual effects are additive, total ring pack friction reduction of 50% or more can be realized. Assuming the ring-pack and piston contributes 1/3 to total mechanical friction, and that piston and ring-pack effects are comparable, the total mechanical friction can thus be reduced by about 17% (1/6). Total reduction in mechanical friction of this magnitude in an engine translates to substantial fuel savings.

A full-scale Waukesha F18GL engine has been installed at Colorado State University and testing of the baseline configuration is in progress. In the mean time, components for the first design iteration are being procured. We are extending our analyses to other areas to examine opportunities for further friction improvement and its impact on oil consumption/emission and wear. We will follow an iterative process of experimentation, simulation and analysis, as further test data become available.

PLANS FOR THE SECOND YEAR

During the second year, we aim at (1) Analyzing the data taken from the Waukesha F18 VGF engine incorporating the initial low-friction design recommendations, (2) Performing further analyses and design iterations, (3) Investigating the tradeoffs among friction, component wear, and oil consumption (emissions), (4) Extending the analyses to low-friction piston design parameters, (5) Developing an optimized low-friction ring pack, piston, and engine system to be demonstrated. In addition, (6) we will continue to pursue our training, educational, and technology-transfer missions for our students, the industry, DoE, and the public at large.

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