“Improvement to Pipeline Compressor Engine Reliability through Retrofit Micro-Pilot Ignition System”

FINAL TECHNICAL REPORT

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ABSTRACT

This report documents a 3-year research program conducted by the Engines & Energy Conversion Laboratory (EECL) at Colorado State University (CSU) to develop micropilot ignition systems for existing pipeline compressor engines.

Research activities for the overall program were conducted with the understanding that the efforts are to result in a commercial product to capture and disseminate the efficiency and environmental benefits of this new technology. An extensive state-of-art review was conducted to leverage the existing body of knowledge of micropilot ignition with respect to retrofit applications. Additionally, commercially-available fuel injection products were identified and applied to the program where appropriate. This approach will minimize the overall time-to-market requirements, while meeting performance and cost criteria.

The objective for Phase I was to demonstrate the feasibility of micropilot ignition for large bore, slow speed engines operating at low compression ratios under laboratory conditions at the EECL. The primary elements of Micropilot Phase I were to develop a single-cylinder test chamber to study the injection of pilot fuel into a combustion cylinder and to develop, install and test a multi-cylinder micropilot ignition system for a 4-cylinder, natural gas test engine. In all, there were twelve (12) tasks defined and executed to support these two (2) primarily elements in a stepwise fashion. Task-specific approaches and results are documented in this report. The four-cylinder prototype data was encouraging for the micro-pilot ignition technology when compared to spark ignition.

The objective for Phase II was to further develop and optimize the micropilot ignition system at the EECL for large bore, slow speed engines operating at low compression ratios. The primary elements of Micropilot Phase II were to evaluate the results for the 4-cylinder system prototype developed for Phase I, then optimize this system and prepare the technology for the field demonstration phase in Year 3. In all, there were twelve (12) tasks defined and executed to support objectives in a stepwise fashion. The optimized four-cylinder system data demonstrated significant progress compared to Phase I results, as well as traditional spark ignition systems.

These laboratory results were enhanced, then verified via a field demonstration project during Phase III of the Micropilot Ignition program. An Implementation Team of qualified engine retrofit service providers was assembled to install the retrofit micropilot ignition system on an engine operated by El Paso Pipeline Group at a compressor station near Window Rock, Arizona. Testing of this demonstration unit showed that the same benefits identified by laboratory testing at CSU, i.e., reduced fuel consumption and exhaust emissions (NOx, THC, CO, and CH2O).

Commercialization of the retrofit micropilot ignition technology is awaiting a “market pull”, which is expected to materialize as the results of the field demonstration become known and accepted. The Implementation Team, comprised of Woodward Governor Company, Enginuity LLC, Hoerbiger Corporation of America, and DigiCon Inc., has direct experience with the technology development and implementation, and stands ready to promote and commercialize the retrofit micropilot ignition system.

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INTRODUCTION

This report documents a 3-year research program conducted by the Engines & Energy Conversion Laboratory (EECL) at Colorado State University (CSU) to develop micropilot ignition systems for existing pipeline compressor engines. This research was in support of DOE's Natural Gas Infrastructure Reliability program.

The objective of this project is to increase the operational integrity, to increase fuel efficiency, and to reduce the environmental impact of two-stroke, natural gas, compressor engines. In total, the U. S. pipeline industry has approximately 8,000 reciprocating engines installed for natural gas compression with a capacity of 7 gigawatts (9.4 million horsepower). The overwhelming majority of these engines are low compression ratio, slow speed, large bore, low brake-mean-effective-pressure (bmep), 2-stroke, gas engines. Almost all of these engines are between 20 and 50 years old, and they represent a critical part of the natural gas pipeline infrastructure. To replace any significant fraction of this asset base would cost billions of dollars.

BACKGROUND and TECHNICAL ISSUES

The most advanced new natural gas engines use "micropilot ignition", in which a small quantity of diesel fuel is injected into the cylinder to ignite the air/fuel mixture. This eliminates the spark plug and corresponding maintenance problems with spark plug life. Economics and gas compressor utilization requirements dictate that the 8,000 large integral compressors currently in use will remain in use for the next 20+ years, but no effort has been made to apply the emerging micropilot technology to these existing pipeline engines. The application is challenging, since existing engines were not designed with the higher compression ratios normally used for pilot-ignited engines.

In order to increase the throughput of the U.S. natural gas pipeline system, the reliability of the gas compression system must be sustained. The reliability and efficiency of the pipeline system is compromised by the ignition systems used in the reciprocating engines used in natural gas compressors. In spite of research by ignition system manufacturers, spark plug erosion constitutes the largest maintenance problem on natural gas engines. The problem is increasing due to the increasing use of precombustion chambers for NOx controls. Spark plugs used in precombustion chambers only last 25%-35% as long as spark plugs in normal "open chamber" operation. Since current NOx regulations can only be met through the use of precombustion chambers, the effect of these regulations has been to reduce the potential availability and reliability of the pipeline system. NOx regulations are expected to become more stringent in the future, so efforts to eliminate the "availability penalty" from the use of retrofit NOx controls are needed.

Maintenance

Spark plug replacement and ignition system maintenance (prechamber check valves, o-rings, ignition leads, and coil replacements) comprises the most frequent source of scheduled and unscheduled maintenance on gas compressor engines. Properly designed pilot ignition systems require very little maintenance and would represent a significant maintenance cost savings over spark ignition systems. The high temperatures seen by the spark plugs in modern prechamber engines have dramatically reduced spark plug life compared to older open-chamber engines. Due to the high cost of compressor downtime, extended maintenance intervals are highly desirable. This suggests that the most appropriate solution for high reliability in compressor engines is to eliminate the spark plug entirely and switch to the use of micro-pilot injection for ignition.

Emissions Formation and Misfire

The difficulty of propagating a flame reliably through lean gas mixtures has been identified as a major source of engine misfire and a potential major source of formaldehyde formation. A more robust source of ignition could reduce combustion variability and reduce fuel consumption and emissions of NOx and hazardous air pollutants (HAPs). It is estimated that a micropilot ignition system using 0.1% pilot fuel would deliver 1500 times as much energy to the natural gas fuel as would a typical spark ignition system. The associated effect on ignition performance and misfire reduction is substantial. Up to now efforts to reduce NOx have been limited by the ability of spark ignition systems to ignite very lean fuel mixtures (high air/fuel ratios).

Operating Costs

The fuel gas for reciprocating engines used in pipeline transmission of natural gas costs the pipeline industry almost $5 billion per year.[1] Prior to the commencement of this research, an initial review of the literature on pilot ignition performed by EECL personnel suggested additional potential fuel savings of 3%-5%[2] through the use of pilot ignition, resulting in potential annual U.S. energy savings of approximately $150 million annually.

Solution Proposed by This Research

Pilot ignition of a high cetane liquid, such as diesel fuel, engine oil or dimethyl ether, has been identified as an effective solution for igniting very lean mixtures of natural gas. A diesel pilot, dispersed throughout the cylinder, was shown to eliminate the misfires created by spark-initiated natural gas flame propagation as a source of misfire and improving overall combustion stability. The intent of this research is to demonstrate that micropilot ignition can be used to simultaneously reduce NOx, formaldehyde (CH20) and fuel consumption while avoiding the requirement of catalyst-based, exhaust after-treatment. The operating costs for micro-pilot ignition are expected to be less that those associated with operating a catalyst unit.

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[1] $8,000\ engines \times \frac{2,500\ hp}{engine} \times \frac{8,000\ btu}{bhp \times hr} \times \frac{8,760\ hrs}{year} \times 75\%usage \times \frac{\$4.50}{1,000,000\ btu} = \$4.7\ billion$

[2]Fuel savings range from negative (indicating poor implementation) to ≈5%. 3% savings used for the economic projection. Most published work has focused on ultra-low NOx, with the result that fuel consumption is often not compared to a reliable baseline. SAE #972664 indicates 2.4% decrease in BSFC on a 1996 Caterpillar 3176B engine; ASME Journal of Gas Turbines and Power, "Natural Gas Fueling of a Caterpillar 3406 . . .", 1992, indicates a 5% efficiency improvement on a turbocharged Cat 3405 engine; SAE 2000-01-1805 indicates a 5% efficiency improvement on a Detroit Diesel 1-71; SAE 1999-01-3522 indicates a 1.4% increase in efficiency of a Navistar T444E on natural gas; SAE 841001 indicates a 10% improvement of BSFC; ASME 90-ICE-30 indicates that optimized pilot ignition reduces of 3.3%-7% over standard pilot delivery.

EXPERIMENTAL

Numerous experiments were conducted for each of the 3 phases of the research program. A summary of these experiments is listed below, with additional details and results provided in the following report section.

1. Single-Cylinder Prototype (Phase I): this step included the design and fabrication of a combustion test chamber (CTC) to quantify the spray patterns for pilot fuels and was also used to evaluate injection parameters such as timing and fuel pressure. Visual imaging, pressure, and temperature data were obtained using commercially-available instrumentation.
2. 4-Cylinder Prototype (Phase I and II): the pilot ignition system developed for the CTC experiments was expanded and adapted to the EECL's Cooper-Bessemer GMV-4TF research engine. Combustion data was recorded using a Redline combustion analysis system. Emissions data was captured using a Rosemount Analytical 5-gas bench for criteria pollutants and a Nicolet FTIR (Fourier Transform Infra-Red) analyzer for hazardous air pollutants.
3. Optical Engine Experiments (Phase II): the EECL's optical engine was adapted for this research program to evaluate the pilot injection spray characteristics with respect to moving piston conditions. The data was primarily visual in nature, with imaging provided by a PLIF (planar laser-induced fluorescence) and high-speed digital camera.
4. Field Demonstration Testing (Phase III): the engine selected was a Worthington SUTC-10 operated by El Paso Pipeline Group near Window Rock, Arizona. Emissions data was recorded using the EECL's mobile emissions laboratory equipped with dedicated analyzers for criteria pollutants and a FTIR analyzer for hazardous air pollutants.

RESULTS AND DISCUSSION

PHASE I – Laboratory Demonstration

The overall, 3-year program was segmented into manageable, step-wise activities. These individual tasks and original timeline are shown below, followed by a description of the results and deliverable produced for each task.

Task 1.1: Research Management Plan

This document, specified by the DOE's National Energy Technology Laboratory (NETL), described each task with corresponding deliverables and schedule and was submitted at the project's start and was updated for each quarterly progress report.

Task 1.2: Review Prior Research

This report detailed the existing body of knowledge regarding micropilot ignition systems for reciprocating engines. In all, thirty-nine (39) technical papers were reviewed in the areas of dual-fuel, pilot ignition, and micro-pilot ignition for reciprocating engines. Areas of interest included: combustion characteristics, knock phenomena, ignition delay, emissions, light load operation, pilot fuel quantity, and implementation experiences by others.

It was concluded that retrofit micro-pilot ignition technology, defined as pilot fuel consuming less than 1.0% of total energy content, is nonexistent for large, stationary engines and virtually undeveloped for most other applications. Micro-pilot ignition systems are, however, commercially available for some new engines as a purchased option and the benefits associated with the technology have been demonstrated. The literature review also served as a starting point for modeling and other analytical efforts.

Task 1.3: Develop System Specifications

This task served as a starting point for further system enhancements as experimental information was obtained. The system specification was developed using information from the literature review and input from EECL, Delphi and Woodward personnel.

Cold-flow models were used to predict non-evaporating penetration. The available models, such as Dent (Figure 1) and Hiroyasu, were developed for much higher mass flow. Delphi has performed evaporative modeling, predicting liquid spray lengths of 20-30 mm.

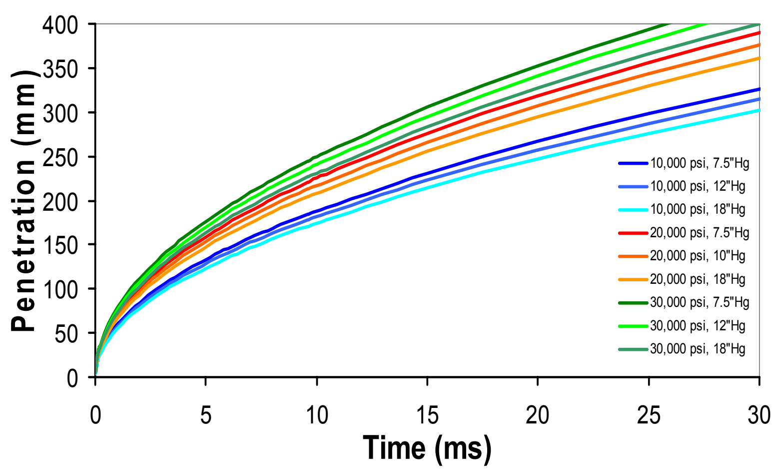

Figure 1 - Dent Model results

Figure 2 suggests that penetration at a given time is a function only of volume of fuel delivered

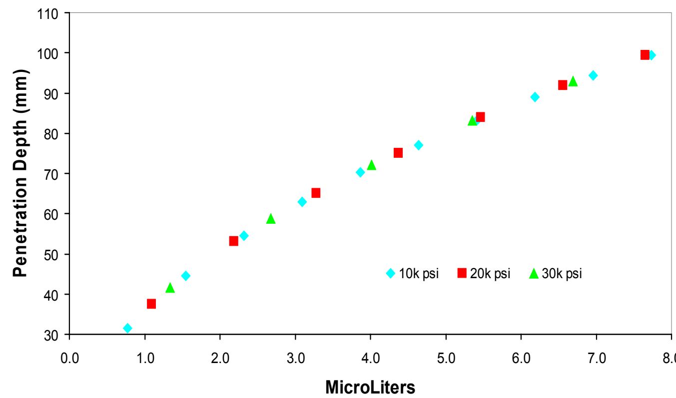

Figure 2 - Modeling results for various injection pressures

A comparison of the modeling and analytical results with the system components from Delphi and Woodward yielded the following, basic system specifications:

- *Pulse Width* – Injector should be capable of delivering 5-10 mm^3 of fuel in a minimum of 0.5 milliseconds. Nominal operation will be between 0.5 and 4 msec. 10 msec will be the maximum pulse width.
- *Rail Pressure* – A rail pressure of up to 20,000 psi
- *Orifice Diameter* – The injector orifice hole will be produced by a specialty nozzle manufacture if possible. This will allow the lab to evaluate identical injectors with different orifice diameters. Orifice holes will be between 0.1mm and 0.2 mm.
- *Injector Size* – The fuel injector must be small enough to allow installation through an existing 18mm spark plug hole.
- *Pulse Width* –Nominal operation will be between 0.5 and 4 milliseconds. Ten milliseconds will be the maximum pulse width.
- *Manual Controls on the ECU* – The ECU (electronic control unit) must be able to manually adjust rail pressure between ~10-20k psi, operate in a "single shot" mode, and have the ability to accurately adjust injection volume.
- – Electronics must be able to support the slow speed of the engine (300rpm), and large number of teeth on the flywheel (411).
- *Current Signal* – Achieve 18-20 amps in 0.2 milliseconds.
- *Low Pressure Stage* – Pre-supply pump with pre-filter, and primary Fuel Filter
- *High Pressure Stage* – Injectors, High Pressure Pump with Pressure Control Valve, Pressure Limiter Valve, Flow Limiter

Task 1.4: Design/ Build 1-Cylinder Prototype

The objective of this task was to create an experimental apparatus in order to evaluate RMI injection pressure, quantity, and spray patterns. The final deliverable for this task was a Combustion Test Chamber (CTC) which was designed (Figure 3) and assembled (Figure 4) by EECL personnel.

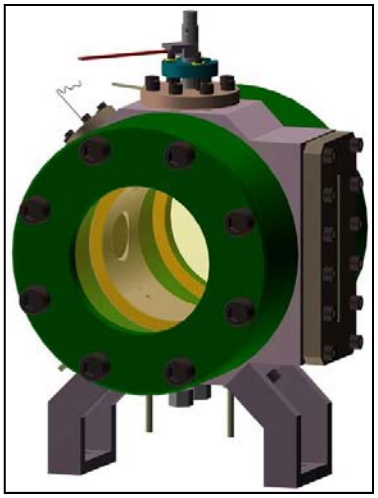

Figure 3 - Solid model of CTC

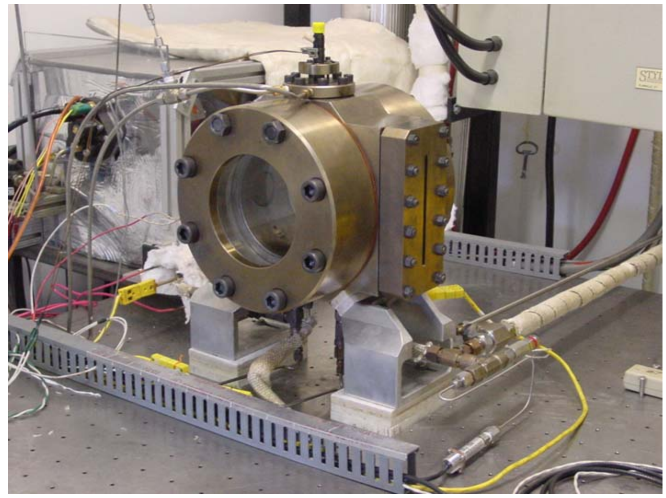

Figure 4 – CTC fabricated and assembled

Task 1.5: Test 1-Cylinder Prototype

The data from CTC experiments were primarily visual in nature, consisting of various image types, such as digital still photos, high-speed digital video images, and laser techniques. These images were analyzed per the next task to quantify spray angle and penetration for the pilot fuel.

Task 1.6: Analyze Results from 1-Cylinder Prototype

CTC studies (Figure 5) verified that the capability of the prototype performed well against the specification set in Task 1.3.

Figure 5 - Imaging software to quantify spray pattern

A comparison of the spray characteristics, as determined by the CTC experiments, with the modeling results show excellent agreement with the Hiroyasu model (Figure 6).

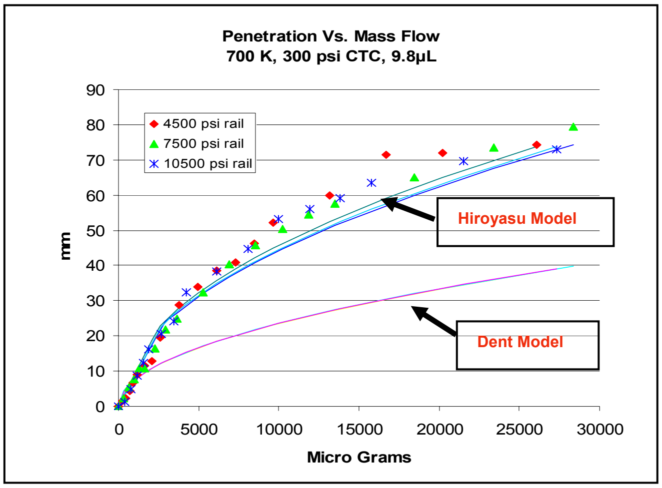

Figure 6 - comparison of measured and modeled sprays

Task 1.7: Develop 4-Cylinder Prototype

Prototype hardware for the GMV-4 test engine (Figure 7) was developed using a commercially available pilot fuel injection system manufactured by Delphi Corporation. Identification and procurement of an appropriate, "off-the-shelf" system was critical to meeting the cost objectives of the program.

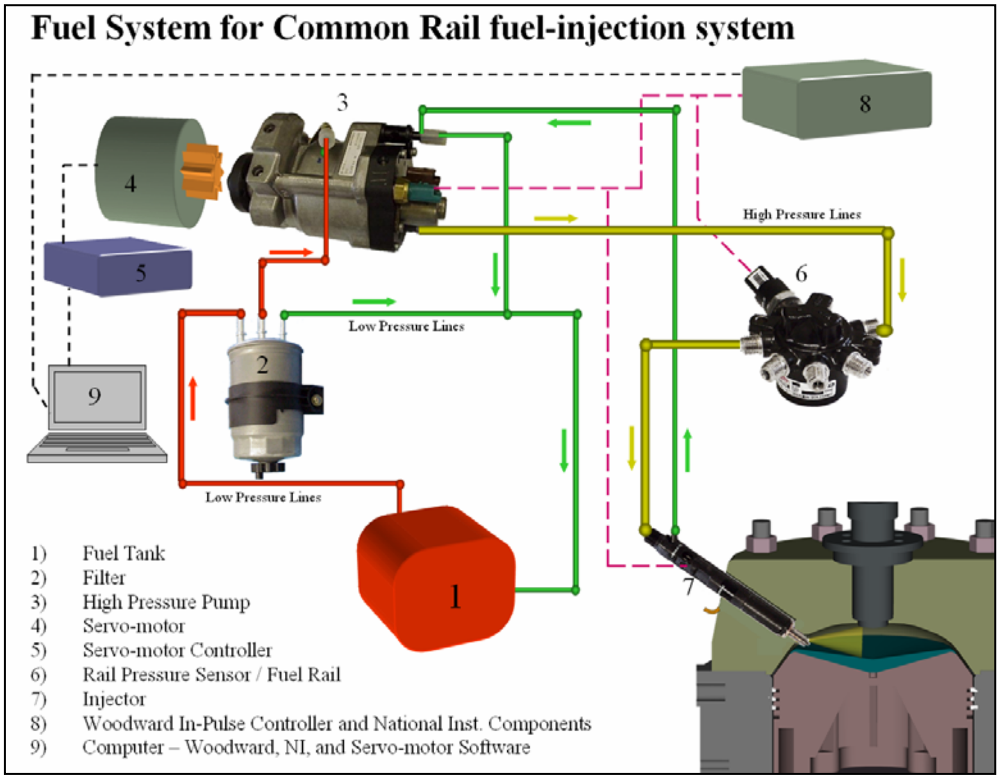

Figure 7 - 4-Cylinder system components

Task 1.8: Design/ Build the 4-Cylinder Prototype

Certain modifications were necessary to adapt the Delphi system to the GMV-4 test engine (Figure 8), the most notable being the electronic valve controller. An "InPulse" electronic valve driver (Figure 11) manufactured, by the Woodward Governor Company (commercialization partner), was programmed to properly control the Delphi components. Also, custom fuel storage tank and delivery tubing was fabricated (Figure 10).

Figure 8 – GMV Research Engine

Minor modifications to the engine were also implemented. Since the Delphi fuel injectors were designed for an automotive engine, an adapter was designed by EECL personnel and fabricated accordingly (Figure 9). The GMV engine model typically uses 2 spark plugs per cylinder and one spark plug port per cylinder head was used for the injector/ adapter. Another modification involved the design and fabrication of bolt-on "pancakes", or contoured plates (Figure 7, lower right) that were used to increase the height of the pistons and thereby increase the compression ratio in the combustion cylinders.

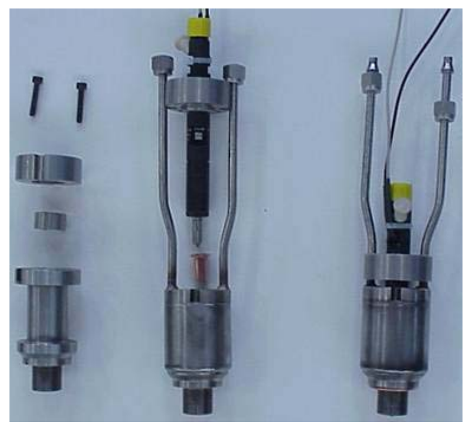

Figure 9 – Injector & adapter components

Task 1.9: Install the 4-Cylinder Prototype

The system was relatively simple to install, since most of the control system components were integrated previously for the 1-Cylinder prototype (CTC) studies. Engine modifications were limited to machining of the spark plug ports to accept the pilot fuel injector (Figures 12, 13) and installing the piston "pancakes" described above.

Figure 10 - Pilot fuel pump, storage, filter

Figure 11 - Control System for RMI

Figure 12 – GMV head with injector adapter (non-cooled)

Figure 13 – injector adapter (cooled)

Task 1.10: Test the 4-Cylinder Prototype

Preliminary testing was performed in December, 2002. A description of the experimental data, data reduction methods, and conclusions is included described in the following. The four-cylinder prototype data was encouraging for the RMI technology when compared to spark ignition. Initial testing results showed:

- Brake specific fuel consumption of natural gas was improved from standard spark ignition across the map, 1% at full load and 5% at 70% load (Figure 14).
- 0% misfires for all points on RMI . Fuel savings were most likely due to this percent misfire improvement.
- THC (Total Hydrocarbon) emissions were improved significantly at light load, 38% at 70% load.

- VOC (Volatile Organic Compounds) emissions were improved above 80% load.
- Coefficient of Variance for the IMEP (Indicated Mean Effective Pressure) was significantly less at lower loads, 76% less at 70% (Figure 15).

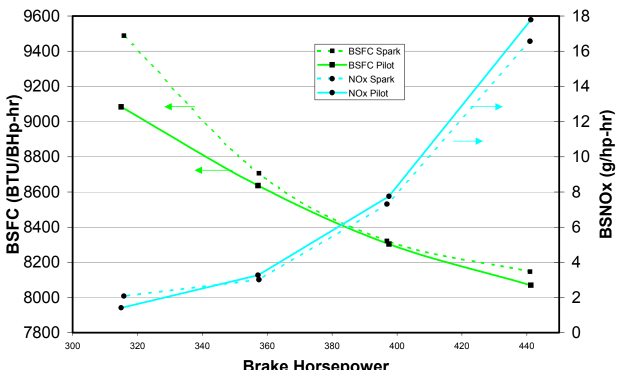

Figure 14 – Phase I BSFC and NOx data @ 70% load

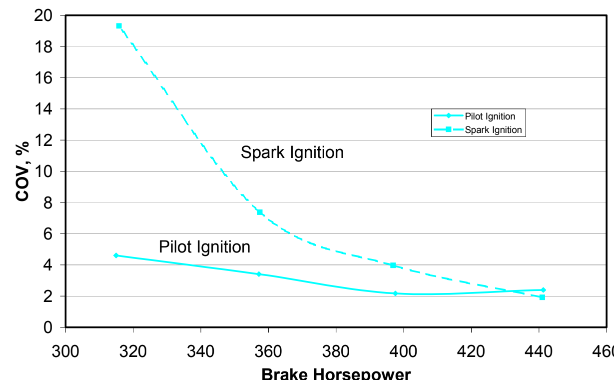

Figure 15 - Phase I Combustion data @ 70% load

These preliminary results are consistent with the program objectives as originally proposed and were substantiated and enhanced during Phase II of the RMI program.

Phase I - Significant Accomplishments

1. Design of CTC
2. Complete assembly of CTC
3. Procedure for injector quantity mapping
4. Advances is heating techniques allowing greater test temperatures in CTC
5. Producing high resolution spray images with Laser illuminated mie scattering
6. Running 1 cylinder of the Cooper Bessemer GMV-4 on RMI
7. Running all four cylinders of the Cooper Bessemer GMV-4 on micro pilot

PHASE II – Laboratory Optimization

Task 2.1: Research Management Plan

A work breakdown structure and supporting narrative that concisely addressed the overall project as set forth in the agreement was developed and submitted to NETL. This plan was updated following the completion of Phase I to reflect the status of the project and the understanding that was gained.

Task 2.2: Evaluation of Compression Ratio

The effects of compression ratio on the implementation of RMI were evaluated, although the desirability of implementing pilot without changing the compression ratio is acknowledged. The efficiency benefits of increasing compression ratio are well documented in the open literature. It is generally accepted that an increase of 8.5:1 to 10.5:1 increases indicated efficiency by over 7%, and should reduce fuel consumption by an even greater amount. In the past, higher compression ratios have been precluded due to potential detonation in a cylinder's end gas. Decreased flame propagation times have been shown to reduce problems associated with end gas detonation; similar results may be possible with pilot ignition.

Evaluation of this at the EECL using the GMV-4 test engine was initially performed by using an insert to reduce the "bowl" volume in the piston, to decrease the clearance volume at top-dead-center (TDC). The nominal compression ratio (CR) for the standard GMV is 8.5:1. These modifications were be made to raise the compression ratio and the performance was monitored to determine the impact of increased compression ratio on fuel consumption and emissions. Originally, two higher CR values were to be evaluated, 10:1 and 12:1 using inserts. Although the performance of the RMI system improved for both CR conditions, the operational window of the engine was reduced to an unacceptable margin. Also, the bolt-on inserts caused overheating problems. Final CR evaluations were performed by shimming the piston to create a CR of 9.5:1.

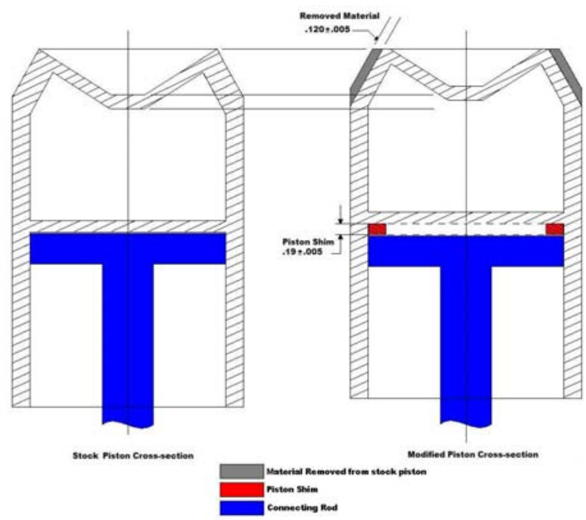

Figure 16 - Comparison of stock & modified pistons

Following completion of optimization testing at the stock compression ratio, the GMV4 test engine was modified to obtain the medium compression ratio of 9.48/8.75:1. In order to achieve the increase in compression ratio, a piston shim .190 in. thick was machined to fit between the connecting rod and piston. Additionally, the piston crown was machined to maintain the squish volume between the piston and cylinder head as in the stock compression ratio. A comparison of the stock and modified pistons is displayed in Figure 16.

Several modifications were made to the optimization testing (refer to Task 2.6) at the medium compression ratio. Modifications were made to the response variable due to previous results skewed toward higher brake-specific NO_x and lower Total Modified Fuel Consumption (TMFC).

The response variable at the medium compression ratio was modified by accessing a penalty of 10 to the diesel fuel along with an additional penalty of 2 to the BSFC term. In addition to the response variable, several modifications were made to the testing procedure used in the stock compression ratio testing, as described in later sections.

When compared to Phase I test results, we were able to sustain reliable operation with a wider air/fuel ratio window, lower NOx emissions, and less pilot fuel.

A baseline with spark ignition was taken for each compression ratio prior to any experimental points at each compression ratio. The baseline included: a nominal point of rated load at 13.5" Hg boost, a maximum lean point for low load, and a maximum lean point at max boost.

Also before the experimental points began, the timing of the RMI system was adjusted to place the peak pressures as close to 18° ATDC as possible. This timing point was the first center point for testing.

All experimental points were taken with the engine at a rated load and 13" Hg boost. For each compression ratio, the procedure was performed twice: the first run minimized Total Modified Fuel Consumption and the second maximized combustion stability. Two compression ratios were investigated resulting in a total of four tests. With reference to cylinders 1 and 3, the first compression ratio studied was 9.5:1 and the second, 8.7:1. After the first set of 11 test points, calculations were performed to determine the next set of points to optimize the variable being studied, i.e. fuel consumption or combustion stability. In this manner, we continually searched to optimize the dependent variable.

After a point of minimum fuel consumption and an optimum combustion stability were found, the combustion stability point was tested for a maximum lean limit.

Task 2.3: Evaluation of Pilot Fuels

The choice of pilot fuel can have a large impact on ignition delay and therefore on system performance. We examined the effect of different pilot fuels as reported in open literature, focusing on diesel fuel, engine oil and dimethyl ether. Diesel fuel is an obvious choice as it is inexpensive and readily available. Engine oil has a higher cetane index and is already available on-site, so it is an attractive candidate. Finally, dimethyl ether is a particularly promising fuel and could be manufactured on-site with a small fuel reformer. It is likely that different nozzle hole patterns and pressure would be required for each pilot fuel.

Various fuels were evaluated for performance in a RMI fuel system based upon their respective chemical compositions, emission characteristics, and on-site availability. The traditional pilot fuel used for pilot ignition is diesel fuel and has the additional advantage of being immediately compatible with injection equipment. Researchers have also demonstrated the use of dimethyl ether, Fisher-Tropsh fuels, engine oil, and other fuels. These fuels were evaluated based upon the previously stated criteria for use in the RMI system, yielding the following observations.

Diesel: Currently used. Cetane number 40-45 (CSU EECL diesel supply is 42.8)

> Advantages: Known properties. Current fuel delivery system designed for diesel. Easily available with current infrastructure.

Disadvantages: Poor emissions (when compared to other possible fuels). Delivery to the compressor engine site.

Biodiesel: An artificial diesel made from vegetable oils or animal fatty acids.

Advantages: High cetane numbers (ranging from 40-77 averaging in the 50's). High lubricity. Contains no sulfur. Tests indicate lower emissions in the following categories: overall smog, carbon monoxide, particulate matter (soluble organic fraction and overall PM), sulfur compounds, total hydrocarbons, and aromatic compounds. Renewable energy source. Should work well with current fuel delivery system.

Disadvantages: Unavailability. Poor fuel property repeatability in manufacturing. Tests indicate higher NOx and particulate matter (volatile organic fraction) emissions. Higher fuel costs.

Fischer-Tropsh Fuel: A synthetic diesel fuel made from coal or natural gas.

Advantages: High cetane number (72). Can be made from natural gas. Would work with current fuel delivery system. Contain low/no sulfur (<0.3% by weight) and aromatic chemical compounds (<5-10 ppm). Tests indicate lower NOx and PM emissions. Slightly less energy dense than diesel. Production plants being built by Conoco (OK), Syntroleum (OK), and British Petroleum (AK). Mass production and usage would make F-T fuels similar or cheaper in price than diesel. Nearly odorless.

Disadvantages: Limited availability currently in the US. Higher fuel costs compared to conventional diesel. Low lubricity. Properties can vary substantially depending on catalyst and reactor technologies used for the production.

Dimethyl Ether: A simple compound that can be made from natural gas.

Advantages: Can be made from a natural gas reformer onsite. High cetane number (55-60). No carbon-carbon bonds and high oxygen content resulting in low amounts of soot and hydrocarbons in the exhaust. Vaporizes easily. Decomposes quickly in the atmosphere. Much lower energy density than diesel. Faster flame propagation and shorter combustion time.

Disadvantages: Poor Lubricity. Physical properties present fuel delivery difficulties. High testing costs. Unknown cost of reformers.

Engine Oil: Unable to find specific data for using engine oil as a fuel, from the internet, stored SAE papers, Shell Inc., Chevron Phillips Specialty Fuels Division, Southern Petroleum Labs, or Southwest Research Institute. Because of the nature of engine oil, a cetane number (ASTM D 613) test can not be performed, but a cetane index (ASTM D976) test could be performed if desired. The complex hydrocarbon make-up of lubricating oil (and any additives contained) may cause undesired emissions.

The results of the literature review confirm that diesel, engine lube oil, and dimethyl ether are candidate pilot fuels. Diesel fuel was used extensively for testing at the EECL for both the prototype and optimized RMI systems. Based on limited on-engine testing, lube oil is also a promising pilot fuel, as shown in later sections.

Task 2.4: Analysis of Product Prototype Results

The data collected in Phase I testing and Task 1.10 was analyzed by CSU and Woodward representatives to document the performance of the prototype RMI system. One important observation made during testing was the impingement of the pilot fuel spray on the GMV head and piston when using the standard, 6-hole Delphi injector. Particular emphasis was paid to comparisons of combustion stability, fuel consumption, NO_x production, and Hazardous Air Pollutant (HAPs) production. These results were used to determine fuel selection, compression ratio, and other overall system parameters. The primary decisions made at this juncture included: selection of diesel fuel for further engine testing, increasing the compression ratio to 9.5:1, and selection of a 3-hole nozzle to inject the pilot fuel in a spray pattern that was matched to the combustion cylinder geometry (Figure 17).

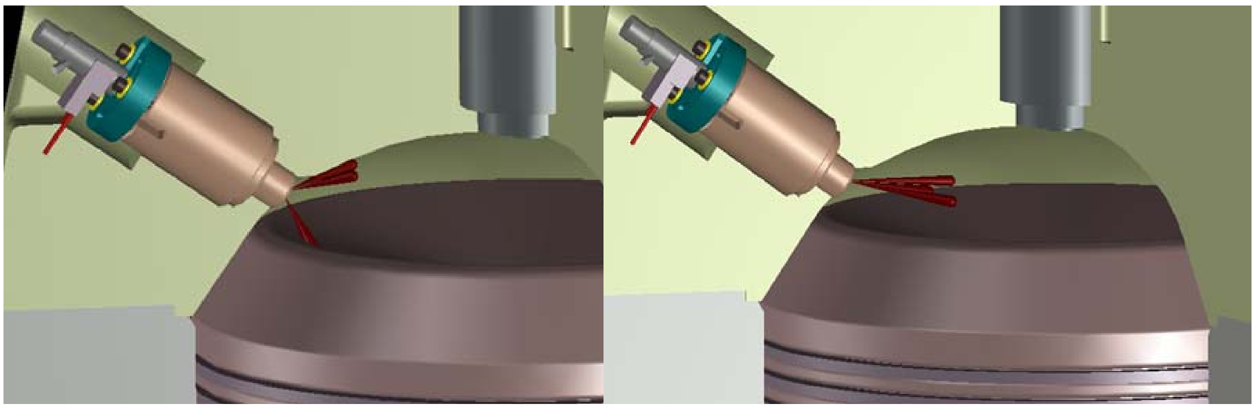

Figure 17 - Injector spray patterns for standard 6-hole (left) and optimized 3-hole injectors

Task 2.5: Revision of Product Specifications

The product specifications were updated by Woodward based on the results of Task 2.4. In addition to operational issues that were experienced at the EECL, the matrix of injection quantity, fuel pressure, and nozzle designs from the test program was used to guide the development of the revised product specifications. The revised specifications were submitted to a cooperative of three (3) field implementation contractors (the "Vendor Team") for deployment at two (2) field demonstration sites completed during Phase III of this program.

Task 2.6: Design Revisions to Optimize Performance

Design changes and revisions were made by Woodward and CSU to correspond to the new specifications developed in Task 2.5. The Vendor Team mentioned above will be responsible for further enhancements and engine-specific modifications.

A pre-determined method of verifying optimized performance via on-engine testing was developed in conjunction with this task, described in the following.

Optimization Method Description

The Design of Experiments technique appeared promising as a method to provide an effective and efficient experimentation path to RMI optimization by considering the factors and their interaction that influence exhaust emissions and engine performance.

Optimizing the RMI system involved studying three factors:

1. Fuel Rail Pressure
2. Pilot Injection Quantity
3. Pilot Injection Timing

And a number of observed responses:

1. Efficiency
2. Fuel Consumption
3. Hydrocarbon production
4. Carbon Monoxide production
5. NOx production
6. Combustion Stability

The initial screening experiments determined which factors or combination of factors contributed in a significant way towards performance responses. Once the empirical models were established and the objective function formulated, the search for the optimum values of the responses along the path of steepest ascent was carried out.

Optimization Method as Implemented

All experimental points were taken with the engine at a rated load and 13” Hg boost. The procedure was performed twice. The first time through, the NOx response were minimized and the second time, the total modified fuel cost response was minimized. The total modified fuel cost (TMFC) was calculated by adding the NG (natural gas) cost to ten times the pilot fuel cost per cylinder per day.

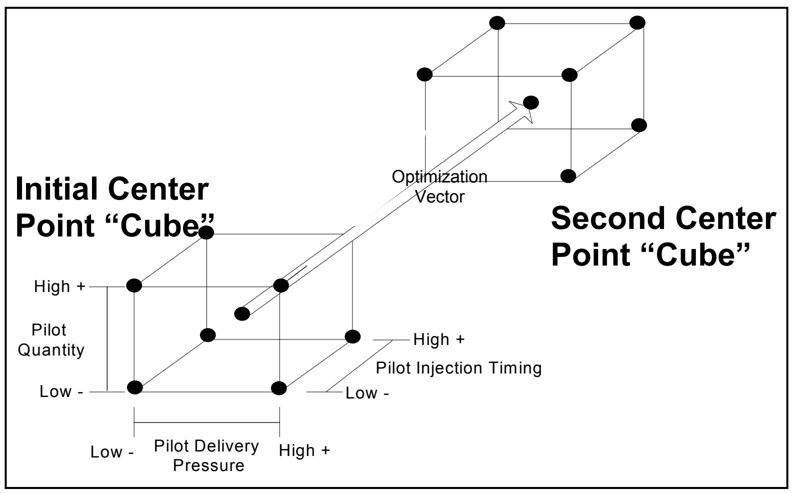

Figure 18 - "Golden Section Search" technique

A summary of the optimization steps used:

1. Calculate the expression for the gradient.
2. Select an end point for the search by performing a preliminary set of experiments.
3. Using the center of the experimentation region and the end point established in Step 2, use “golden section search” technique to narrow the interval along the path of steepest ascent until the interval containing the optimum has been reduced to an acceptably small length (Figure 18).
4. The midpoint of this optimum becomes the center point for a new 11-point matrix

These steps were iterated until an overall optimum was found.

Task 2.7 Evaluation of Optimized System in Optical Engine

Experimental Apparatus

The RMI system hardware developed for the prototype tests was evaluated in the EECL's Optical Engine (Figure 19) in order to identify enhancements. These tests were useful in studying the effects of cylinder scavenging, impingement of fuel on the piston and cylinder walls, and penetration of the pilot fuel as a function of fuel pressure, timing and duration.

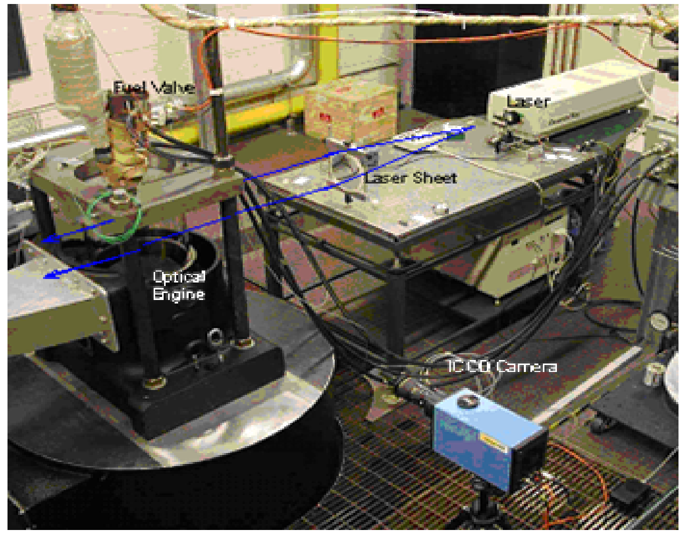

Figure 19 - Optical Engine arrangement

Evaluating the RMI system with the optical engine setup illustrated the effects of other engine characteristics with respect to injection. These characteristics include residual scavenging flow, turbulent flow from the fuel injection, and flow induced by the compression stroke of the piston. Taking pictures during injection at multiple pressures and durations allowed an accurate determination of the effect of these flow-inducing engine characteristics.

The optical engine used was designed to imitate one of the cylinders on the Cooper Bessemer GMV-4TF. However, due to physical restrictions of the materials used and the imaging techniques employed, there are some differences. First, the piston is motored (i.e. no combustion), so the cylinder gasses are not as hot as they would be in a firing engine. In an operating engine, the pilot fuel spray would probably vaporize more quickly. Also, a flat cylinder head is used rather than a curved one. This difference had little impact on fuel mixing, due to the location of the pilot injector and limited travel of the pilot plume. The engine motion was at a reduced speed of 3.33 Hz (about 200 rpm) verses 5 Hz (300 rpm). The optical engine was operated at an 11" stroke versus 14" on the GMV. The speed and stroke differences are not significant for this evaluation.

Results from Evaluating the Optimized System in the Optical Engine

This system was used successfully and a series of images were taken (Figure 20 is a representative image). Multiple sets were taken at many different times throughout the injection. The images were processed removing reflections from the quartz cylinder, and Teflon residue by subtracting a background picture with an image processing program. Images were then

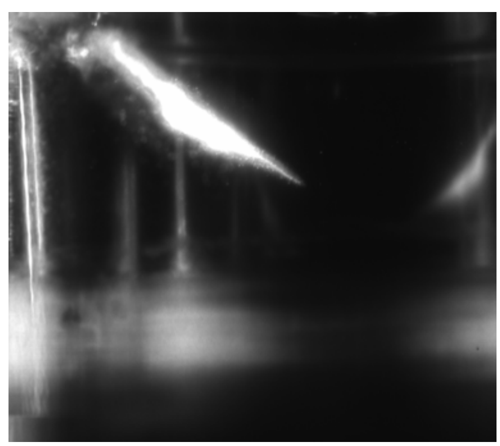

Figure 20 - jet proximity to piston crown at TDC

compiled into a movie showing the entire injection in the cylinder. This allowed for an easier analysis of the injection:

1. Residual scavenging flow does not significantly deflect the trajectory of the diesel jet.
2. Turbulent flow from fuel injection does not significantly deflect the trajectory of the jet.
3. Upward flow/compression induced by piston motion does not significantly deflect trajectory of the diesel jet.
4. For the conditions in the optical engine, the diesel droplets impinge on the piston and are deflected upward; in an operating engine, the droplets would likely evaporate/combust before being deflected.

Task 2.8: Laboratory Test to Verify Performance

The performance of the revised product was evaluated at CSU, per the Design of Experiments method described for Task 2.6, using the GMV-4 test engine discussed in the following.

Experimental Equipment and Conditions

Variations in engine operating parameters and changes to engine hardware configuration were performed relative to the nominal operating conditions and hardware configuration. Injection of the RMI fuel was performed by a combination of Delphi, Woodward, and custom hardware and software as described previously. A Delphi diesel common rail injection pump and injectors deliver the pilot fuel. The system was capable of creating 1,000 to 24,000 psig of fuel pressure to inject through a 24 volt electronically controlled injector. This Delphi system was used to allow a large range in injection pressures to be studied. Custom software and hardware interfaces with the Delphi equipment to vary the fuel rail pressure and monitor the fuel temperature. The Delphi injectors were driven with a modified Woodward InPulse engine control unit. The InPulse created the specific current waveform needed to actuate each injector and timed each injection event with the engine's speed and crank angle. The timing and duration of the pilot event for each cylinder could be independently tuned using Woodward software.

Investigated RMI Variables

Ignition of a premixed air/fuel mixture using small volume pilot ignition ("micro-pilot") depends on many variables. Four of these variables are due to the engine characteristics:

- Compression ratio in the cylinder
- Temperature in the cylinder
- Pressure in the cylinder
- Air/Fuel ratio

Five others are inherent to the pilot injection system:

- Cetane number of the pilot fuel
- Injector nozzle design
- Pilot injection timing
- Pilot fuel quantity
- Pilot delivery pressure

This experiment held constant the compression ratio, in cylinder temperature and pressure, the configuration of open chamber combustion, the pilot fuel cetane rating and the injector nozzle design. By holding these variables constant, trends created by changes in the control characteristics of the pilot injection system were easily identified.

It is important to note that the design of the pilot injector nozzle, and therefore the spray pattern, were not designed for this engine. They were designed for a European marketed Ford Focus diesel engine, selected for the systems ability to deliver the correct range of pilot fuel for the GMV-4TF application. The spray pattern created by the current nozzle impinges both on the top of the piston and the surface of the head. To completely optimize this pilot system, we tested another nozzle design as described later in the report.

Pilot Injection Timing

The effect of pilot injection timing on engine performance is very similar to spark timing. The combustion event will commence sooner when the pilot fuel is injected earlier and visa versa. However, for RMI injection ignition delay varied with injection timing.

The time measured from the beginning of pilot fuel injection to the point at which the fuel ignites is referred to as ignition delay. This delay will vary with the type of fuel as well as the temperature, pressure, and turbulence of the environment. Therefore, it will also change with the timing of the pilot fuel's injection.

If the pilot fuel is injected early enough in the cycle, the pressure and temperature will not be sufficient to initiate combustion and a misfire will occur. In this case the pilot fuel vaporized and mixed with surrounding gases before cylinder conditions were favorable for ignition. It was desirable to have liquid droplets present when ignition temperature is reached, whereby ignition occurred at the stoichiometric zone surrounding the droplet. Given that ignition occurred, ignition delay decreased when pilot fuel was injected later in the cycle because the reactant temperature increased as the cylinder gases were compressed by the piston.

In addition to ignition delay, there was a length of time from the injection signal to when the fuel began exiting the nozzle. On average, this delay was about 300 microseconds for the Delphi injectors used. If both of these the injection and ignition delays are considered, there was a total of 6.155 ms after the injector signal before ignition was predicted to begin. At 300 rpm, this is 11.08 deg.

Pilot Fuel Quantity

The quantity of fuel delivered represents the energy available for initiating combustion. To determine the amount of pilot fuel required, we looked at fuel volume measured as a percentage of the total energy content. We then calculated pilot fuel quantities corresponding to 1.0, 0.5, 0.25, and 0.1 percent of the energy content.

As indicated in Figure 21, 8 μL of pilot fuel will supply a 110 HP cylinder with 0.5% of its total energy. Therefore, this was the targeted fuel quantity.

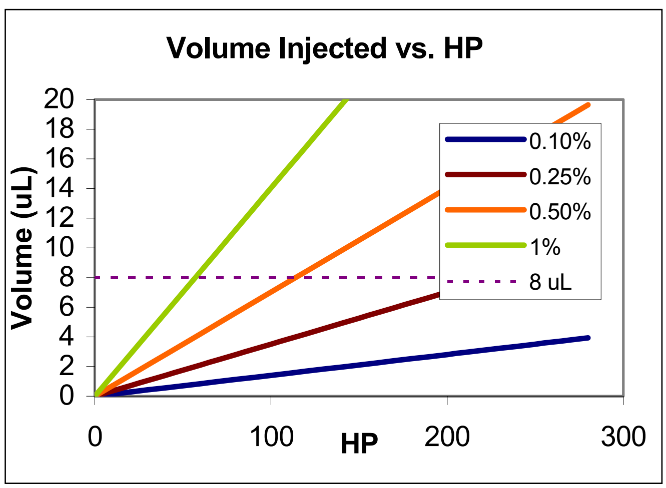

Figure 21 - Pilot Fuel injection measurements

Pilot Delivery Pressure

The pilot delivery pressure largely affects the droplet size. A higher rail pressure will decrease the mean droplet size. Larger droplets take longer to evaporate, allowing more time for ignition to occur. However, for the same injected quantity smaller droplets provide more potential ignition sites. Thus, there is a trade-off between droplet diameter and number of ignition sites. For a given set of cylinder conditions and nozzle design there will be an optimum injection pressure. The injection pressure also directly affects the speed with which the plume will reach its final penetration depth.

Testing Procedure

Testing was first performed first with the non-optimized nozzle (6-hole) to demonstrate RMI feasibility for this application. Many variables could have been used to track the optimization of the pilot system including different key emissions, engine performance characteristics, and fuel consumption rates. After careful consideration, it was determined that by minimizing fuel consumption we would likely improve other important variables. In this test, fuel consumption was minimized both for natural gas and the pilot fuel during steady state operation.

A variable titled Total Modified Fuel Consumption (TMFC) was created to track the use of both fuels. TMFC represents the combined fuel consumption of pilot and natural gas, on an energy basis, with a penalty of 20 on the pilot fuel. The penalty on the use of pilot fuel is associated with the additional cost of the diesel fuel as well as its delivery, storage, and handling. At today's current prices, natural gas costs about $4.5 per one million BTU of fuel energy. Diesel fuel is about $9 per one million BTU of fuel energy. To fairly add these two fuels together on purely an energy basis, a penalty of 2 must be applied to the use of diesel fuel based only on the cost of the fuel. In addition to the higher cost of diesel, the delivery, storage, and handling of the product must be considered as well. After discussion with individuals involved with the gas industry, it was determined that a total diesel pilot penalty of 20 would be appropriate.

All experimental points were taken with the engine at a rated load and 13.5" Hg boost. No transient studies were performed. Before any RMI data was taken, a baseline was run with single strike single plug spark ignition. The spark ignition system consisted of Altronic controls and Altronic Black coils rated at 12,000 volts.

Testing Results: 6-Hole Injector

The resulting Total Modified Fuel Consumption (TMFC) for the initial test points are shown in Figure 22. This cube shows that the system favored lower pilot quantities, lower pilot injection pressure, and more advanced timing.

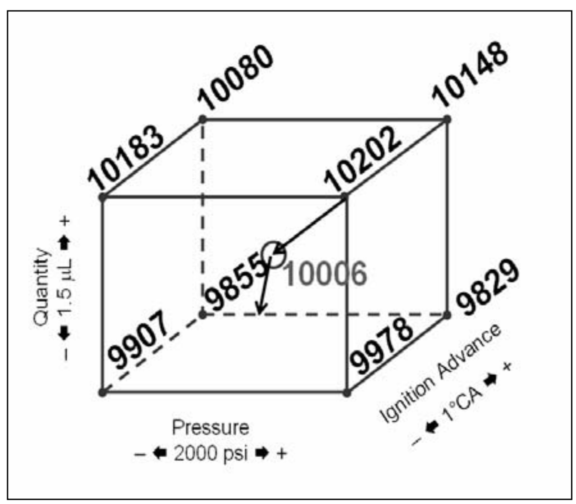

Figure 22 - Natural Gas Consumption for Spark, Center Point, and Optimizing Vector

The resulting empirical model produced an optimizing vector, which specified the direction and step size that pilot pressure, quantity, and timing should be moved to decrease TMFC. This linear vector predicted ever-decreasing values of TMFC so the actual measured value had to be tracked to find the real minimum. These new values were tested and TMFC was tracked at each point to observe when the value reached a minimum. The TMFC values are plotted in Figure 23.

Point 7 of the optimizing vector proved to be the local minimum determined by following the specified pilot settings. The 9^{th} point was a “best guess” setting based on experimenter observation.

During each test point for minimizing TMFC, data was recorded on all major emissions constituents as well as engine performance and combustion behavior. While minimizing the TMFC, the use of gas was following a similar path as shown in Figure 23. The optimum point for TMFC however, was found to be different than that for minimum natural gas usage.

As the amount of pilot fuel was reduced, natural gas consumption first trended down with TMFC, but reached a minimum at point 7 (Figure 24). With the 9^{th} optimization vector point, pilot quantity was reduced further, which resulted in lowering TMFC but raising natural gas consumption.

Other significant measurements made during this testing are shown in Figures 25 and 26. Each measurement is labeled with an abbreviation that indicates the high or low setting used for the pilot injection. For instance, “QH-TL-PH” would represent a data point taken with a high setting for pilot quantity, low setting for timing, and a high setting for pressure.

Brake specific oxides of nitrogen ($bsNO_x$) emissions, along with Total Hydrocarbon

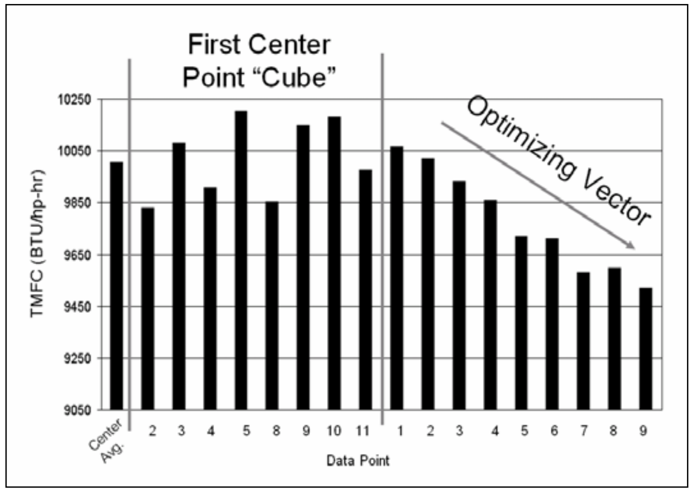

Figure 23 - TMFC (BTU/hp-hr) values for initial center point matrix

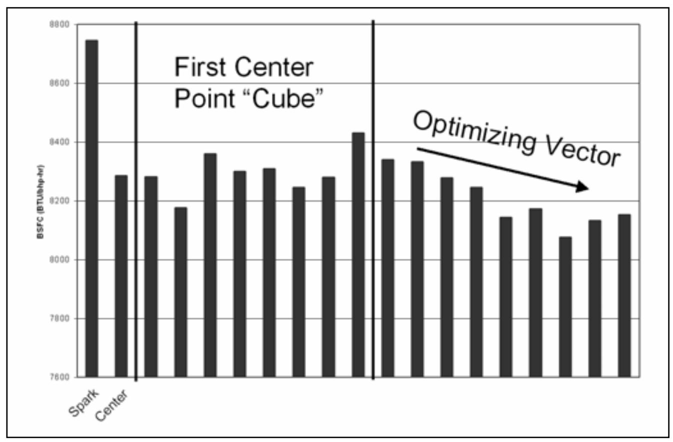

Figure 24 - TMFC values for Center Point and Optimizing Vector

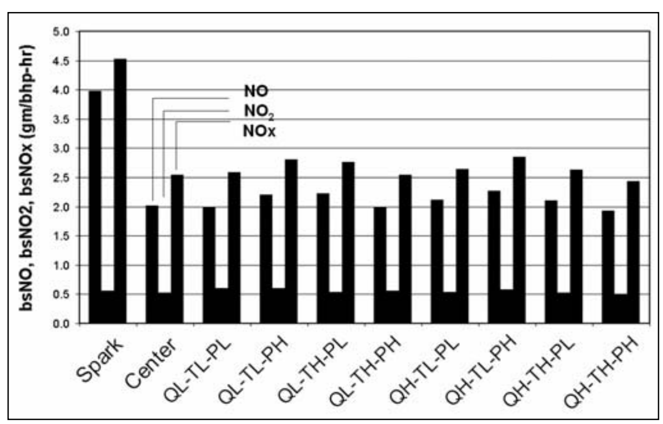

Figure 25 - bsNOx trends

(bsTHC) emissions were reduced across the board but did not seem to trend with changes in the RMI settings.

Brake specific Non-methane hydrocarbons (bsNMHC) and carbon-monoxide (bsCO) formation seemed unaffected by the use of RMI ignition. Brake specific formaldehyde ($bsCH_20$) formation was reduced slightly with the use of RMI but did not show a significant dependence on changes to the injection settings.

In addition to reducing the coefficient of variance of engine indicated mean effective pressure (COV of IMEP), the pilot ignition eliminated all misfires. The spark test point had an engine average of 0.925% misfire. The entirety of the pilot ignited data contained no misfires.

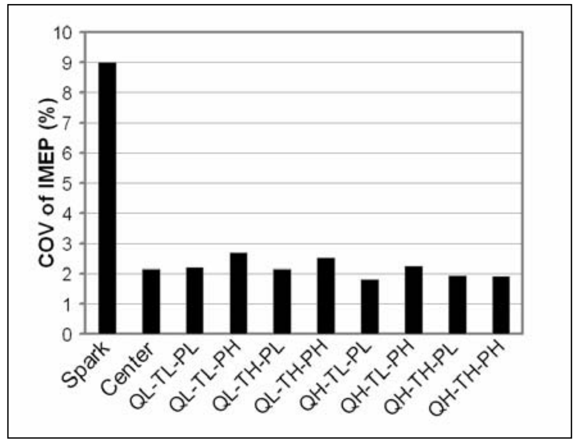

Figure 26 - Indicated Mean Effective Pressure coefficient of variance

Conclusions: 6-Hole Injector

The results were very promising and the likelihood an effective RMI injection system for large-bore, 2-stoke cycle natural gas engines was supported. At optimized pilot injection parameters the percent of fuel energy was lowered to 0.72% while still improving combustion stability and lowering key emissions with respect to spark ignition.

Custom, 3-hole nozzles were obtained and evaluated, as described in the next section.

Testing Results: 3-Hole Injectors

Figures 27 and 28 compare the results of the optimized 3-hole injectors to the previously tested 6-hole injectors by various exhaust constituents and engine parameters.

The newly optimized 3-hole injectors provided considerably improved combustion stability while also increasing the boost range of engine operation.

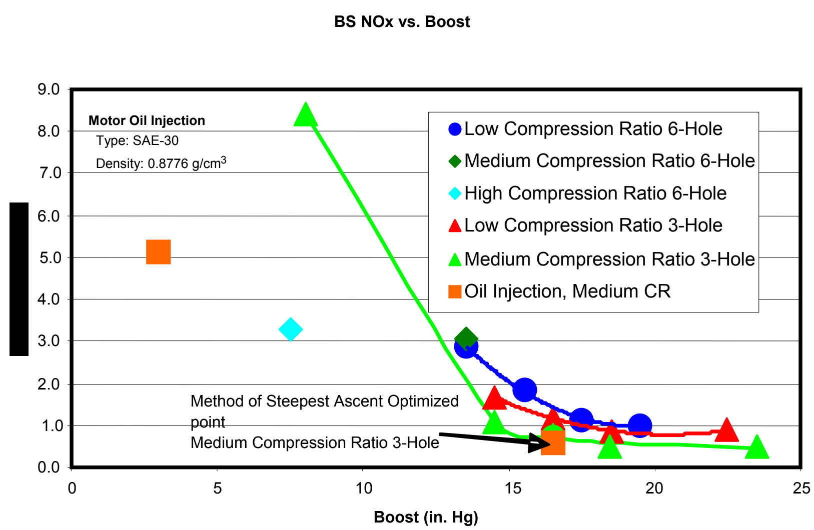

Figure 27 - NOx data for various injectors and CR

For the engine operating conditions used during testing, the optimized 3-hole nozzles displayed considerably higher TMFC and BSFC than the previously tested 6-hole injectors. In addition, NO_x emissions during 3-hole testing were lower than that of the 6-hole injector testing. Previously conducted 6-hole testing was performed at an ignition timing significantly more advanced than that of the 3-hole testing. This difference in injection timing was most likely the reason for the increased fuel consumption and lower NO_x emissions experienced during the 3-hole optimization testing.

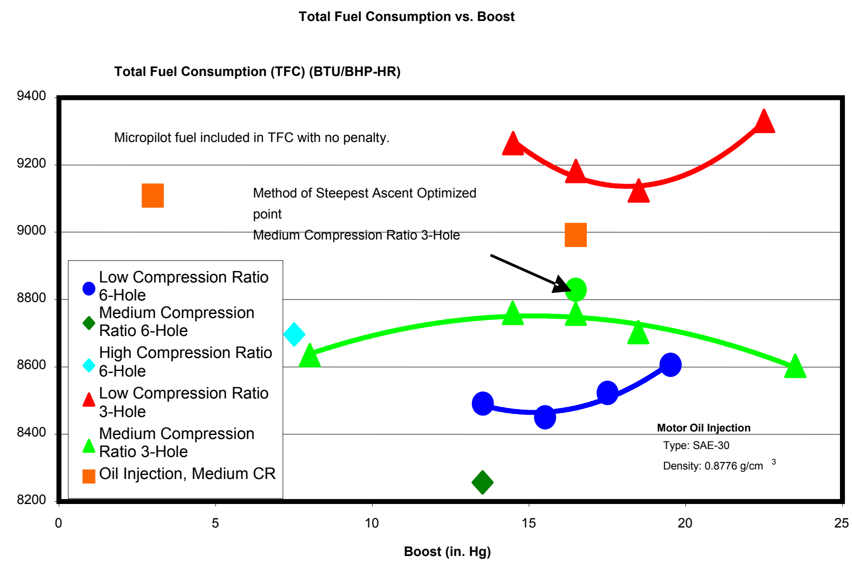

Figure 28 - BSFC Comparison for Various Injectors and CR

These observations can be combined and compared to the evaluation of various ignition systems in the next section. Both the 3-hole and 6-hole injectors provide lower fuel consumption than the standard spark-ignition and can operate at leaner air/fuel ratios. Since the 3-hole injectors provided the additional benefit of lower NOx production than the 6-hole injectors, they were considered to be optimal.

Limited testing was also conducted using SAE 30 engine oil as an alternative pilot fuel at the medium compression ratio. Preliminary results displayed a greatly improved range of engine operation over the boost map with a minimum boost level of engine operation occurring at 3.5" of Hg. While improving the boost range, the oil injection showed considerably higher fuel consumption (Figure 28) than that of the diesel pilot fuel. It is currently unclear as to why the engine fuel consumption was considerably higher for the oil injection, although this trend is expected to be improved through optimization efforts. Injector flow calibration curves and of the oil were not available. Consequently, parameters used in data reduction for the SAE 30 Data Points in the following figures were assumed to be the same as diesel fuel. A sample of the SAE 30 was analyzed and determined to have a Lower Heating Value of 45.74 MJ/kg, extremely close to that of the diesel pilot fuel (42.94 MJ/kg).

Following medium compression ratio testing, the modified medium compression ratio pistons were inspected for identifications of impingement by the pilot fuel on the piston dome. Upon inspection of the modified piston domes, it was determined that the optimized 3-hole injectors corrected the impingement experienced with previously tested 6-hole injectors.

Table 1: Injector Comparisons

Description	Minimum Boost Engine Could Run At (Corresponding Quantity)	Minimum Quantity Engine Could Run At (Corresponding Boost)	Ignition Temperature (Corresponding Engine Condition)
6-Hole Injector			
Stock Compression Ratio	N/A	16.25 µL (13.5" Hg)	751.9K (Min. Quantity)
Medium Compression Ratio	N/A	10.00 µL (13.5" Hg)	720.7K (Min. Quantity)
High Compression Ratio	N/A	8.36 µL (7.5" Hg)	738K (Min. Quantity)
3-Hole Injector			
Diesel			
Stock Compression Ratio	12.5"Hg	7.0 µL (16.5" Hg)	708.3K (Min. Quantity)
Medium Compression Ratio	8.0" Hg (13.0 µL)	4.0 µL (14.5" Hg)	765.4K (Min. Boost)
Oil			
Medium Compression Ratio	3.0" Hg (16.0 µL)	4.0 µL (16.5" Hg)	748.1K (Min. Boost)

Table 1 displays the minimum boost and injection quantities of the 3- and 6-hole injectors at various compression ratios. The optimized 3-hole injectors allowed for lower pilot fuel injection quantities than the previously tested 6-hole injectors. Bulk cylinder gas temperatures were determined at ignition for either the minimum boost or injection quantity evaluated during testing. These temperatures were evaluated from in-cylinder pressure data, the ideal gas law, and trapped mass evaluated from port closure volume, air manifold temperature, and exhaust manifold pressure. The minimum ignition temperature for the data analyzed was experienced with the 3-hole injectors at the stock compression ratio and a pilot quantity of 7.0 µL. In general the ignition temperature trend was to increase with compression ratio and boost. As mentioned above, calibration curves were not available for the oil injection so the injection quantity was assumed to be that of diesel at the tested RMI parameters, duration and pressure.

Comparison of Various Ignition Systems

Figures 29 through 31 displays various emissions constituents over a range of boost compared to various ignition systems.

Figure 29 displays the brake specific fuel consumption over a range of boost levels.

This figure includes the additional fuel consumption incurred with the diesel pilot fuel injection system. All RMI data in the following figures were taken from stock compression ratio testing.

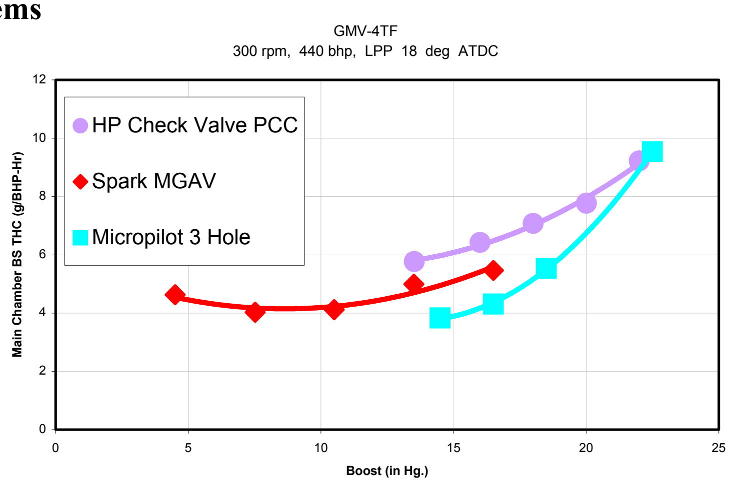

Figure 29 - BSFC comparison for various ignition systems

Conclusions: 3-Hole Injectors

The following conclusions were drawn following the completion of the optimized 3-hole RMI fuel injectors:

- In general the engine operated more stable with fewer misfires and partial combustion events when using the 3-hole injectors compared to the 6-hole injectors.
- The engine had, in general, a wider range of operation with the 3-hole injectors. Minimum operational boost levels were approximately 1-2"Hg lower and the minimum pilot quantity that the engine would operate on were reduced by more than 50%.
- A successful concept demonstration of oil pilot injection was performed where the minimum operational boost was reduced by another 5"Hg to a boost level of 3"Hg; this is, depending on altitude, in the range of boost levels of many blower and piston scavenged low BMEP engines
- RMI compares very favorably to other ignitions systems. The performance of RMI with mechanical gas admission valves is very similar to the performance of precombustion chamber ignition with high pressure fuel injection. Compared to spark ignition with mechanical gas admission valves the lean limit of operation is extended by about 5"Hg.

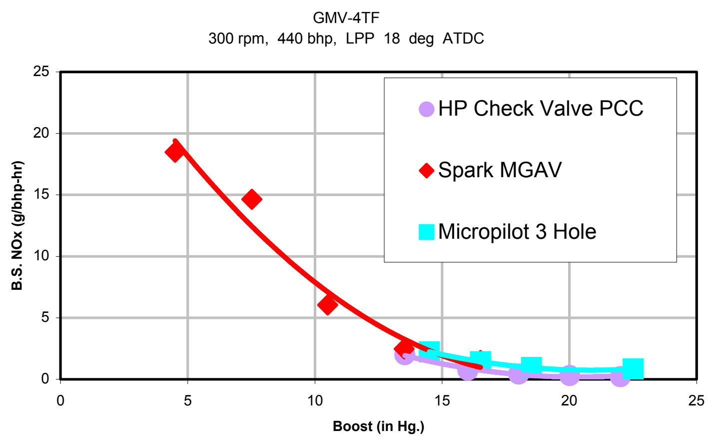

Figure 30 - NOx data for various ignition systems

- The RMI system performs similar to the pre combustion chambers by extending engine operation and reducing both emissions and fuel consumption in the higher boost ranges, as shown by Figures 30 and 31. Improvements in fuel consumption and emissions over traditional ignition systems are not incurred at the lower boost ranges with the 3-hole injector, however, these parameters may improve at lower boost levels if the injector hardware was modified and/or the system was optimized for that purpose.

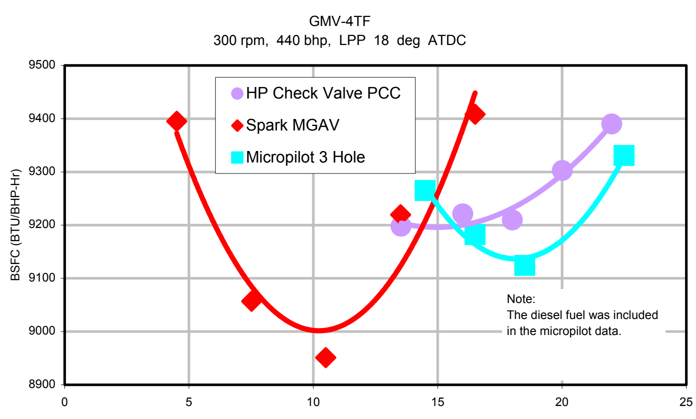

Figure 31 - BSFC data for various ignition systems

Task 2.9: Finalization of Design for Field Test

Field-testing was planned for two different engine models, similar to the laboratory engine, during Phase III of the program. As mentioned previously, a Vendor Team managed and supported by the EECL performed the design and installation of the field test units, as described in the next section. Considerable engineering documentation was transmitted to the Vendor Team and exchange of information continued during the field demonstration phase.

Phase II - Significant Accomplishments

1. Design, installation, and testing of a 4-cylinder system RMI prototype
2. Enhancement of the prototype system to affect a system optimized for reliability, emissions and fuel use.
3. 200+ hours of run time for the optimized system under laboratory conditions
4. Demonstrated a working relationship with Delphi capable of providing pilot fuel injectors that are optimized for various engine types.
5. Demonstrated that the GMV-4 test engine can operate using lube oil as a pilot fuel.
6. In conjunction with our commercialization partner, the Woodward Governor Company, established relationships with three (3) field installation contractors to migrate the RMI technology to field demonstration sites.

PHASE III: Field Testing and Production Engineering

Task 3.1: Research Management Plan/ NEPA

The EECL developed a work breakdown structure and supporting narrative, similar to the first two phases, which concisely addressed the overall project as set forth in the agreement. Following the completion of Phase II, the Research Management Plan was updated to reflect the status of the project and the understanding that was gained. A draft report that provided the environmental information necessary to satisfy requirements of the National Environmental Policy Act (NEPA) was also prepared and submitted to NETL.

Task 3.2: Identification of Field Test Sites

This was an effort to select field test sites that are most representative of frequent compressor operation and that can be well supported. Woodward and the PRCI/GRI Compressor & Pump Station Technical Committee (CAPSTC) have worked closely in the past on field tests for electronic fuel injection and high-pressure fuel injection so there was significant experience to guide the field test process. The CAPSTC worked with member companies to identify suitable field sites and to secure the required commitment of resources from the host company(s) in order to support the field tests. The roles in the field test were as follows:

<u>CAPSTC</u>- primary responsibility for leading industry efforts to identify the most appropriate field site(s), to secure the commitment and participation of the host companies, and to ensure that the field test is representative of normal field conditions.

Woodward - produced the hardware required for the field test and provided support for the hardware as needed during the field test. Woodward worked closely with the Vendor Team to ensure successful management of the field test.

CSU-The EECL continued to serve as project manager during the key field test phase. Technical efforts were scaled-back during the fabrication and installation of the field test hardware. The EECL assisted with the startup/shakedown of the RMI system at the field sites, and in analyzing the field data.

Host Company- provided an engine and operational support for the field test program. Two field test sites were anticipated at the beginning of the 3-year program. The host company provided operation personnel and obtained their support for the field test program. It was essential that the engine at the host site be in excellent operating condition during the baseline test and during subsequent testing of the new technology.

The above criteria were applied to secure two (2) host sites, both owned by El Paso Natural Gas as located on Figure 32. The first site involved the retrofit of a Worthington SUTC-10 (Unit 4A), 2500 HP, at Window Rock, Arizona. Blanco, New Mexico, was to serve as the second site, and the engine of interest was a Cooper-Bessemer GMV-10TF. For reasons discussed later, the demonstration project at Blanco was not performed.

Figure 32 - Field Demonstration Sites

Task 3.3: Manufacturing of Field Test Units

The fuel system hardware was provided by Woodward and the Vendor Team members for the field test at Window Rock. Woodward furnished the electronics, the fuel injector/nozzle/ adapter assemblies, and the fuel pump/ supply system. Hoerbiger Corporation of America (HCA) provided the wiring harness, fuel rail, and fuel supply/ return piping. Enginuity, LLC (ELLC) designed and fabricated the control system and injector driver systems. DigiCon, Inc. sized the fuel supply system and other system components per Figure 33. CSU

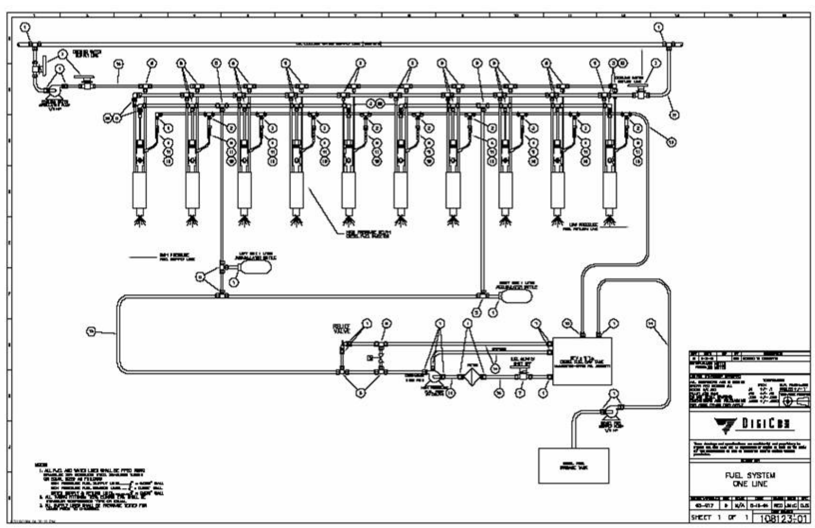

Figure 33 - Schematic of RMI Components

personnel fabricated the pump module at the EECL and shipped the unit to the site. A special tool for installing the injector adapter within the existing spark plug hole was designed by CSU personnel.

The system components can be described further using Figure 33 as a guide. Diesel fuel was delivered to the site via truck and stored in a 1,000 gallon storage tank located outside the compressor building within secondary containment. A fuel transfer pump located within the pump module (Figure 36) automatically filled the smaller "day" tank, which was also part of the pump module, in order to maintain a specified level in the day tank. The high-pressure fuel injection pump, manufactured by Delphi, drew filtered diesel from the day tank and discharged the pilot fuel to the injectors. These injectors, also made by Delphi, were mounted in the center of the cylinder head, which eliminated impingement issues and allowed the use of the 6-hole style. Since the system was designed as a "common-rail" injection scheme, any unused fuel was returned to the day tank. Hydraulic accumulators were installed on the ends of the common-rail header to absorb any pulsations developed by the high-pressure pump or injectors. A pressure relief valve was installed to limit the pilot fuel pressure within system design values. A closed-loop water cooling circuit, utilizing existing engine coolant, was included to maintain the pilot injectors at temperatures that would preclude varnishing as a result of overheating of the fuel.

The RMI system was a relatively straight-forward installation, as most issues were addressed during the laboratory demonstration phases (I and II) at the EECL. The RMI system components, shown in Figures 34 - 37, were installed in July and initially operated on August 26.

Figure 34 - SUTC power Cylinders before RMI

Figure 35 - SUTC power Cylinders after RMI

Figure 36 - Pump Cart & Diesel Tank

Figure 37 - Injector & Adapter

Hoerbiger Corporation of America was responsible for the field installation phase. Initial performance testing was conducted September 7-9, as described for Task 3.4.

It is generally accepted that pipeline engines will need to retain their spark ignition systems for startup, until sufficient engine heat is developed for compression ignition of the pilot fuel, at which time the spark ignition system can be deactivated. Automatic controls were provided for this function, as well as for the pilot fuel injection pressure, timing and duration. Enginuity, LLC was responsible for commissioning the control system. The first changeover to micro-pilot ignition was relatively problem free with all on-engine components functioning properly. Some necessary diesel transfer system enhancements were identified, which limited the time available for performance testing and system optimization. These enhancements, to allow automatic filling of the pump module from the 1,000 gallon diesel storage tank located outside the engine room, were implemented in early October and Unit 4A was restarted with micro-pilot ignition operational.

Unit 4A operated from October 5 until October 29 on the retrofit micro-pilot ignition system. By this time, some of the injectors experienced fouling from a varnish-like residue created by overheating of the diesel fuel. The RMI injectors were changed-out on November 02, 2004 and the emissions and performance tests were repeated (see Task 3.4). Several of the replacement injectors quickly fouled and the RMI system was deactivated pending a long-term solution of the fouling problem. A new injector adapter with enhanced water cooling has since been designed. Due to interface issues between the micro-pilot ignition system controls and the existing engine control system, the spark ignition system remained operational for one of the two ignition points, but had little effect on the combustion processes.

The RMI system for field demonstration at Blanco, NM was not fabricated, installed or tested due to operational limitations of the Cooper-Bessemer GMV engines at this site. The technology plan for the Blanco site included engine lube oil as the pilot fuel, instead of diesel, due to the low combustion air boost levels available. EECL personnel conducted a single-cylinder injection/ignition test at Blanco in August, 2004, but were unable to achieve auto-ignition of the lube oil fuel due to low compression pressures and temperatures. A high-compression ratio head was installed on one cylinder to mitigate these conditions, but mechanical interferences were encountered. It was concluded that all ten (10) power pistons would need to be removed and machined to reduce height in order to accommodate the high-compression ratio heads. Since the engine would need substantial modifications to be configured for the RMI system, an outcome that is not consistent with the objectives of this program, and further development efforts were discontinued for the Blanco, NM site.

Task 3.4: Field Test

Management of a successful field test is a significant and complex undertaking. There were multiple parties involved who must be coordinated, training which must be conducted for field personnel, monitoring of routine operation, setup/startup and system optimization, and gathering of high quality performance data. Significant components of the field test plan were prepared by CSU, Woodward and the host company. A comprehensive field test-planning document was produced to guide the field test. Preparation of the field test-planning document commenced at the beginning of Phase III and was in place to guide the field test efforts.

The pre-modification, or baseline, testing was performed by CSU personnel in June, 2004 using the EECL's mobile emissions laboratory. After installation of the field test hardware at Window Rock, Woodward and CSU assisted the Vendor Team through the startup and shakedown processes. The systems were then operated for a few days in order to "stabilize" and to gather operational experience. Once the field operations personnel were familiar with the equipment, a performance was scheduled. During the performance test, EECL personnel were on-site with a mobile emissions laboratory to monitor the performance of the engine with and without the pilot ignition system.

The data obtained during the September 7-9 testing at Window Rock validates the desired trends for RMI when compared to spark ignition, although system optimization and additional testing must be conducted. Figure 39 illustrates that combustion stability with RMI is about the same as with spark ignition. Improvements are expected after the injection system is optimized, and performance at leaner mixtures and part-load operating modes is expected to improve with RMI. Fuel consumption (Figure 40) was improved from 1-3%, which is significant for pipeline engines. NOx and CO emissions are slightly higher, as shown in Figures 41 and 42, but reductions in these emissions during lean mixture (high turbo boost levels) and part-load operating modes appear likely. Across-the-board emissions reductions may be achieved through optimization.

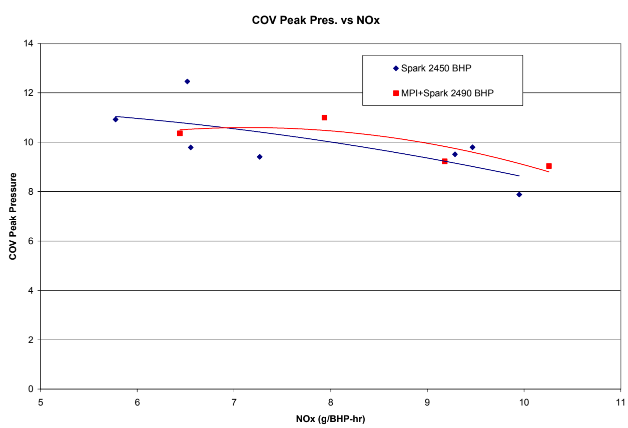

Figure 38 - Combustion Data: 1st Round

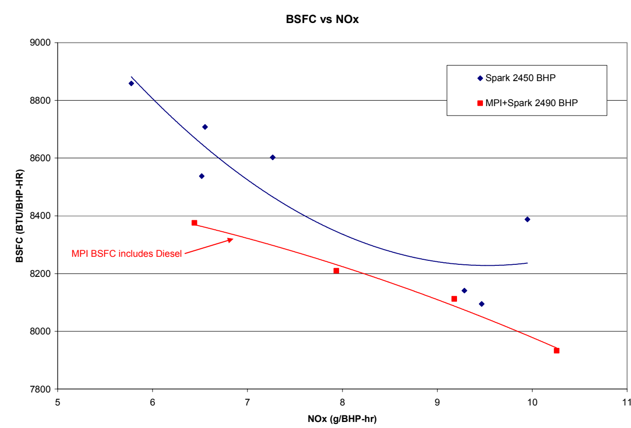

Figure 39 - BSFC Data: 1st Round

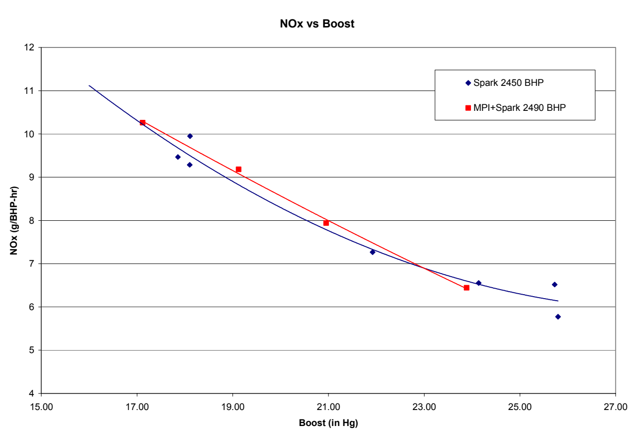

Figure 40 – NOx Data: 1st Round

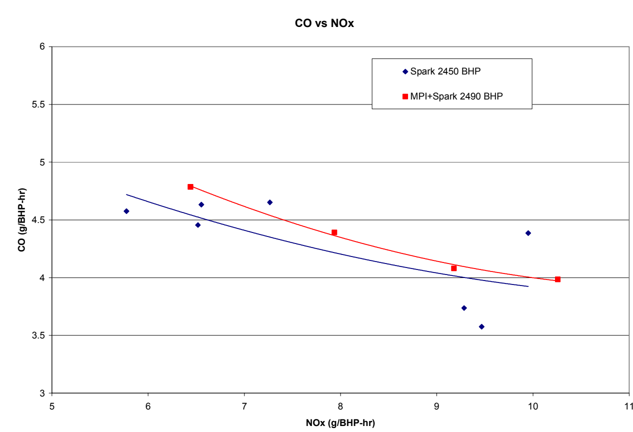

Figure 41 - CO Data: 1st Round

Figures 43-46 depict data obtained from the Window Rock site in early November, 2004. Compared to the spark-ignition baseline tests made before the RMI installation, combustion stability improved significantly (Figure 43), as did BSFC (Figure 44) and CO (Figure 46). NOx production (Figure 45) was slightly higher, although this can probably be reduced through optimization techniques that are scheduled during future durability test runs.

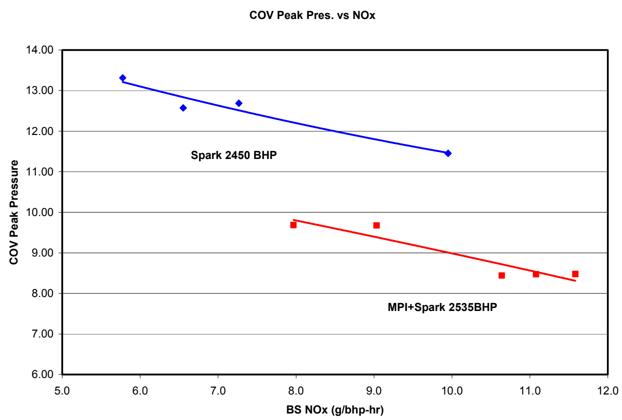

Figure 42 - Combustion Data: 2nd Round

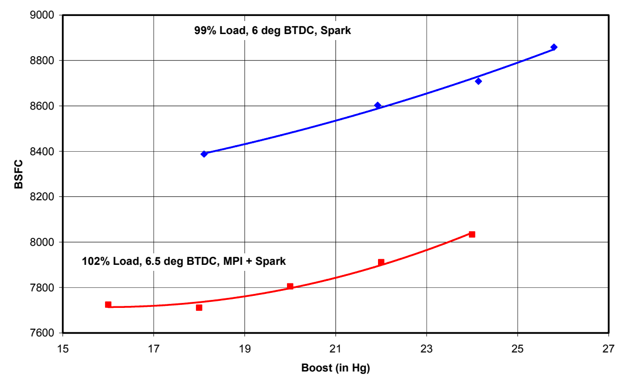

Figure 43 - BSFC data: 2nd Round

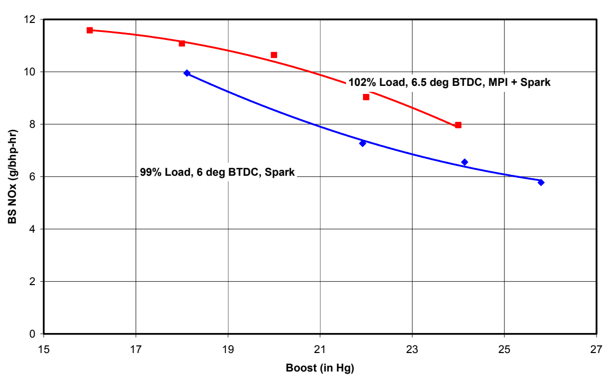

Figure 44 - NOx Data: 2nd Round

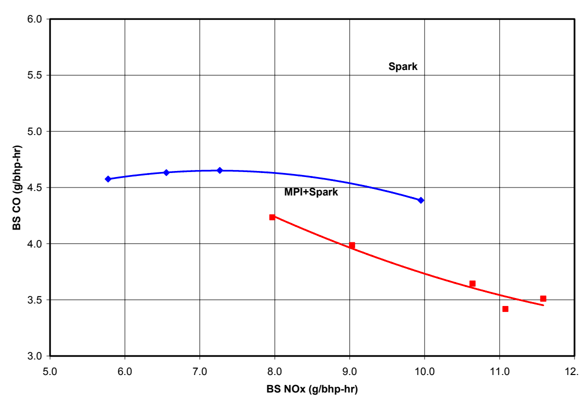

Figure 45 - CO Data: 2nd Round

Task 3.5: Durability Testing

The RMI injectors were changed-out on November 02, 2004 and the emissions and performance tests were repeated. It was originally anticipated that six months of operating history would be accumulated by the end of the Phase III project. Data that was monitored by CSU during the durability testing included overall fuel consumption, pilot fuel consumption, any history of mechanical problems, and weekly reports on engine stability. Typically, operators of large compressor engines monitor the engine operation periodically. For the durability testing we asked that this be performed on a weekly basis and that the pressure-time histories in each combustion cylinder be recorded and included as part of the data set during the durability test.

Installation efforts at Window Rock were completed towards the end of the budget period, which did not leave sufficient time to complete the nozzle cooling modifications and subsequent durability testing. These efforts are ongoing, with funding provided by El Paso Pipeline Group, and the results will be documented in a report to be issued at the conclusion of these efforts.

Task 3.6: Revision of Production Specifications

Based on the results of the performance analysis and durability testing, Woodward and the other Vendor Team members will make changes in the system design as needed.

Task 3.7: Finalize and Release Design for Production

Based on the revised specifications from the previous task Woodward will modify the design to produce a final design package that can be used in subsequent commercialization efforts. This will require appropriate attention to electromagnetic interference (EMI) and flammability classification of the injection equipment and electronic drivers.

Phase III - Significant Accomplishments

1. Design, installation, and testing of a 10-cylinder RMI prototype at an operating pipeline compressor station.
2. Initiation of a 6-month durability test.
3. 600+ hours of run time for the field demonstration unit at the time of this report.
4. In conjunction with our commercialization partner, the Woodward Governor Company, established relationships with three (3) field installation contractors to migrate the RMI technology to field demonstration sites.

CONCLUSIONS

Phase I – Conclusions

Phase I of the Retrofit Micropilot Ignition program was successful in demonstrating that:

1. Micropilot ignition systems are technically capable of delivering efficiency and emissions improvements when compared to spark ignition systems
2. Appropriate hardware and control system components are commercially available now, providing an expeditious path to market.
3. The technology can be applied to existing pipeline compressor engines on a retrofit basis.

Phase II – Conclusions

RMI system optimization and development efforts at the EECL demonstrated:

1. Commercialization partners were engaged to deploy this technology at two (2) field demonstration sites.
2. In general the engine operated more stable with fewer misfires and partial combustion events when using the 3-hole injectors compared to the 6-hole injectors.
3. The engine had, in general, a wider range of operation with the 3-hole injectors. Minimum operational boost levels were approximately 1-2”Hg lower and the minimum pilot quantity that the engine would operate on were reduced by more than 50%.
4. A successful concept demonstration of oil pilot injection was performed where the minimum operational boost was reduced by another 5”Hg to a boost level of 3”Hg; this is, depending on altitude, in the range of boost levels of many blower and piston scavenged low BMEP engines
5. RMI compares very favorably to other ignitions systems. The performance of RMI with mechanical gas admission valves is very similar to the performance of precombustion chamber ignition with high pressure fuel injection. Compared to spark ignition with mechanical gas admission valves the lean limit of operation is extended by about 5”Hg.

Phase III – Conclusions

1. A technology Implementation Team comprised of Woodward Governor, Hoerbiger Corporation of America, Enginuity LLC, and DigiCon Inc. was formed to design, install and commission the RMI system at a field demonstration site near Window Rock, AZ.
2. The RMI system, as designed and configured by the EECL and Implementation Team, was relatively straight-forward and amenable to field conditions. Other than the replacement of one spark plug with a pilot injector per cylinder, no existing engine components were machined or replaced.
3. The efficiency and emissions improvements observed during field testing at Window Rock were similar to those for laboratory testing at the EECL.
4. Efforts are ongoing at the EECL and Window Rock site to demonstrate the durability potential of the RMI system.

Overall Conclusions

At the outset of the 3-year research program, the following objectives were established: to increase the operational integrity, to increase fuel efficiency, and to reduce the environmental impact of two-stroke, natural gas, compressor engines. Listed below is a comparison of the results for the Retrofit Micropilot Ignition system to the stated objectives:

1. Fuel Efficiency: both the laboratory demonstrations and the field implementation tests for RMI showed an overall fuel reduction of 5%, as originally postulated.
2. Environmental Impact: RMI enables engine operation at near-zero misfire. In turn, fewer products of partial-combustion, such as hydrocarbons and formaldehyde are produced. Also, due to the much higher ignition energy provided by RMI, the lean limit of air/fuel ratio can be extended by 25%, which produces less NOx.
3. Operational Integrity:
    a. Range of operation: the additional ignition energy provided by RMI improved the part-load operation of the laboratory and field demonstration units by eliminating the misfires that were experienced before the modifications. In addition, the engine could be operated at higher turbocharger boost conditions. When coupled, these two effects extend the operating window for compressor engines, which enhances throughput by tolerating off-design system operation.
    b. Durability: insufficient operating experience had accumulated by the conclusion of the period of performance for this project, so this objective cannot be quantified at this time. The EECL is currently working with El Paso Pipeline Group to continue the durability testing of the RMI system at Window Rock, AZ, and this work is scheduled to resume in June, 2005.

The RMI system compares favorably to retrofit precombustion chambers with respect to combustion stability and fuel efficiency. Through continued research and development by the EECL and others, it is anticipated that Retrofit Micropilot Ignition systems will demonstrate the additional benefit of extended operating time, since precombustion chambers lead to unacceptable spark plug life. The research also indicates that low-bmep engines can be retrofitted for micropilot ignition without extensive modifications, such as turbochargers and air manifolds, to realize emissions and efficiency benefits at a lower installed cost.