Improvement to Pipeline Compressor Engine Reliability through Retrofit Micro-Pilot Ignition System – PHASE II

ANNUAL TECHNICAL PROGRESS REPORT

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ABSTRACT

This report documents the second year's effort towards a 3-year program to develop micropilot ignition systems for existing pipeline compressor engines. In essence, all Phase II goals and objectives were met. We intend to proceed with the Phase III research plan, as set forth by the applicable Research Management Plan.

The objective for Phase II was to further develop and optimize the micropilot ignition system 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 to demonstrate the technology's readiness for the field demonstration phase. In all, there were twelve (12) tasks defined and executed to support objectives in a stepwise fashion. Task-specific approaches and results are documented in this report.

Research activities for Micropilot Phase II were conducted with the understanding that the efforts are expected to result in a commercial product to capture and disseminate the efficiency and environmental benefits of this new technology. Commercially-available fuel injection products were identified and applied to the program where appropriate. Modifications to existing engine components were kept to a minimum. This approach will minimize the overall time-to-market requirements, while meeting performance and cost criteria.

The optimized four-cylinder system data demonstrated significant progress compared to Phase I results, as well as traditional spark ignition systems. An extensive testing program at the EECL using the GMV-4 test engine demonstrated that:

- In general, the engine operated more stable fewer misfires and partial combustion events when using the 3-hole injectors compared to the 5-hole injectors used in Phase I.
- The engine had, in general, a wider range of operation with the 3-hole injectors. Minimum operational boost levels were approximately 5"Hg lower and the minimum pilot quantity that the engine would operate on was roughly cut in half.
- A successful concept demonstration of engine lube 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
- Micropilot ignition compares very favorably to other ignitions systems. The performance of micropilot ignition 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.

These laboratory results will be enhanced, demonstrated and commercialized by others, with management and support from CSU, during Phase III of the Micropilot Ignition program.

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EXPERIMENTAL

The objective for Micropilot Phase II was to optimize and enhance the micropilot ignition system for large bore, slow speed engines operating at low compression ratios. Four (4) experimental efforts were conducted to support this objective: 1) study the performance effects of compression ratio changes using the EECL's GMV-4 test engine, 2) evaluate the feasibility of using pilot fuels other than diesel fuel, 3) demonstrate the performance improvements provided by optimized pilot fuel injectors using the test engine, and 4) evaluate the spray properties of the pilot injectors using the EECL's optical engine.

Compression ratio was extensively studied for this phase of the research, as documented in Appendix 14. This appendix contains detailed documents, "Optimization of a Micropilot Ignition System using Design of Experiments Technique", "Procedure for Evaluating Compression Ratio", and "Cylinder Geometry – Compression Ratio Calculations". The data obtain from implementation of these analytical approaches and testing procedures verified that some modifications to most engines will be required to achieve the necessary compression ratios to enable auto-ignition of the pilot fuel.

Various pilot fuels were evaluated first using a literature review, as described in Appendix 15. Of the five (5) candidate fuels identified in the literature, only two (2) are readily available: diesel fuel and engine lube oil. Diesel fuel was used for the majority of the testing performed for Phases I and II. Engine lube oil was used for limited testing, with successful results, as shown in Appendix 20.

An optimized, 3-hole pilot fuel injector was developed by Delphi in conjunction with this project. The standard, 5-hole injector manufactured by Delphi performed adequately for Phase I proof-of-concept testing, as documented in Appendix 16, "Prototype Results and Analysis". However, some of the spray plumes impinged on the combustion cylinder wall and head, which indicated that ignition could be achieved with lower pilot fuel use. Resultantly, the injector nozzle design was modified to provide an optimal spray pattern, then demonstrated with the EECL's GMV-4 test engine as documented in Appendix 20, "Optimized System Results and Analysis".

Off-engine experimental results were obtained using the EECL's optical engine, as described in Appendix 19. The data was primarily visual in nature and supported the design of the optimized 3-hole injector. The optical engine studies will also be useful in future designs of retrofit micropilot ignition systems for various engine types.

RESULTS AND DISCUSSION

Improvement to Pipeline Compressor Engine Reliability through Retrofit Micro-Pilot Ignition System – PHASE II

Introduction

This report documents the second year's effort towards a 3-year program to develop micropilot ignition systems for pipeline compressor engines. In summary, all Phase II goals and objectives were met. We are underway with the Phase III efforts, as documented by the applicable Research Management Plan, transmitted under separate cover.

Account of Progress

The primary tool used for predetermining the research activities is the Research Management Plan, Appendix 13. The individual tasks and original timeline are shown below, followed by a description of the deliverable produced for each task.

PHASE II PROJECT SCHEDULE

Phase II Project	**PRIMARY RESPONSIBILITY**	**O '02**	**N '02**	**D '02**	**J '03**	**F '03**	**M '03**	**A '03**	**M '03**	**J '03**	**J '03**	**A '03**	**S '03**
Task 13: Research Management Plan	CSU	■											
Task 14: Evaluate Compression Ratio	CSU	■											
Task 15: Evaluate Pilot Fuels	CSU		■										
Task 16: Analyze Prototype Results	CSU	■	■	■									
Task 17: Revise Product Specifications	Woodward			■	■	■							
Task 18: Revise Dsn to Optimize Perf.	Woodward					■	■	■					
Task 19: Evaluate with Optical Engine	CSU							■	■				
Task 20: Lab Test to Verify Performance	CSU								■	■	■		
Task 21: Finalize Design for Field Test	Woodward										■	■	■
Task 22: Phase II Report	CSU											■	■
Task 23: DOE Contractors Meeting	CSU												■

Task 13: 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 14: Evaluation of Compression Ratio

The effects of compression ratio on the implementation of micropilot ignition were evaluated, although the desirability of implementing pilot ignition 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 TDC. The nominal 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 micropilot ignition 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.

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, as documented in Appendix 20.

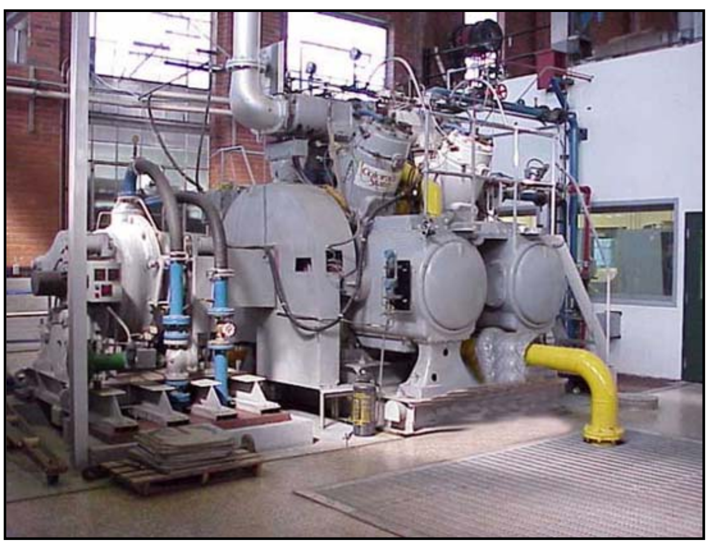

Figure 2. GMV-4 Test Engine at the EECL

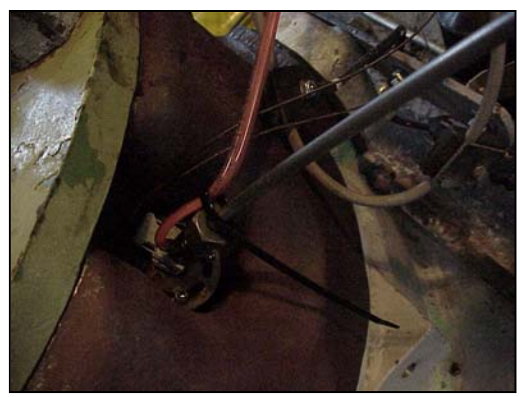

Figure 1. Closeup of Delphi pilot fuel injector installed in head

Figure 4. Pilot fuel pump and storage mounted on GMV test engine

Figure 3. Micropilot control system for engine operation

Task 15: Evaluation of Pilot Fuels

As discussed in the background section of the proposal, 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 will be required for each pilot fuel.

The results of the literature review are contained in Appendix 15 and 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 micropilot ignition systems. Based on limited on-engine testing, lube oil is also a promising pilot fuel, as shown in Appendix 20.

Task 16: Analysis of Product Prototype Results

The data collected in Phase I testing and Task 15 was analyzed by CSU and Woodward representatives to document the performance of the prototype micropilot ignition system. Particular emphasis was paid to comparisons of combustion stability, fuel consumption, NO_x production, and 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.

Task 17: Revision of Product Specifications

The product specifications were updated by Woodward based on the results of Task 16. 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 current set of specifications has been submitted to a cooperative of three (3) field implementation contractors (the "Vendor Team") for deployment at two (2) field demonstration sites to be completed during Phase III of this program.

Task 18: Design Revisions to Optimize Performance

Design changes and revisions have been made by Woodward and CSU to correspond to the new specifications developed in Task 17. The Vendor Team mentioned above will be responsible for further enhancements and engine-specific modifications.

Task 19: Evaluation of Optimized System in Optical Engine

The Micropilot ignition system hardware developed for the prototype tests was evaluated in the EECL's Optical Engine 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. The observations gained from this task are reported in Appendix 19.

Task 20: Laboratory Test to Verify Performance

The performance of the revised product was evaluated at CSU using the GMV-4 test engine as documented in Appendix 20. The following conclusions were drawn following the completion of the optimized 3-hole micropilot 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 5-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
- Micropilot ignition compares very favorably to other ignitions systems. The performance of micropilot ignition 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.

Task 21: Finalization of Design for Field Test

Field-testing will occur on two different engine models, yet similar to the laboratory engine, during Phase III of the program. These activities are underway. As mentioned previously, a Vendor Team managed and supported by the EECL will perform the field tests. Considerable engineering documentation has been transmitted to the Vendor Team and exchange of information will continue during the field demonstration phase.

Task 22: Phase II Report

Contained herein.

Task 23: DOE Contractors Meeting

CSU will report on the project results at the annual DOE Contractors Meeting in Morgantown, WV.

Problems Encountered

Very few problems arose during the testing and optimization and all were corrected without substantial difficulty. These included:

1. Pilot fuel injector fouling. After engine operation with the micropilot ignition system, some injectors would fail to operate during the next round of testing. It was determined that the injectors became "varnished" with diesel fuel residue as a result of high temperature operation. This problem was corrected with a water-cooled adapter as discussed for Task 16.
2. Piston crown insert failure. A bolt-on insert was used to decrease the clearance volume at TDC, and consequently, increase compression ratio. It was discovered that the sharp edges caused rapid heating of the insert and unstable combustion. The solution was to modify the pistons by shimming and machining to acceptable tolerances.

Significant Accomplishments

1. Design, installation, and testing of a 4-cylinder system micropilot ignition 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 micropilot technology to field demonstration sites.

Publications and Presentations

A Technical Progress report was presented to NETL and Gas Machinery Conference attendees on October 5, 2003.

Plans for Next Reporting Period

We are proceeding with the tasks defined for Phase III of the program as listed in the schedule below:

PHASE III PROJECT SCHEDULE

Phase III Project	PRIMARY RESPONS IBILITY	J '04	F '04	M '04	A '04	M '04	J '04	J '04	A '04	S '04	O '04	N '04	D '04
Task 3.1: Research Management Plan/NEPA	CSU	■											
Task 3.2: Identify Field Test Sites	GTI	■											
Task 3.3: Build Field Test Units	Woodward	■	■	■	■	■							
Task 3.4: Field Performance Tests	CSU					■	■	■	■				
Task 3.5: Field Durability Tests	CSU						■	■	■	■	■	■	
Task 3.6: Revise Product Specification	Woodward									■	■	■	
Task 3.7: Final Dsn./ Release Production	Woodward									■	■	■	■
Phase III Reports (Topical & Final)	CSU											■	■
DOE Contractors Meeting	CSU												■

These tasks are defined further in the Research Management Plan for Phase III, submitted previously under separate cover.

Assessment of the Prospects for Future Progress

The testing conducted for Task 20, described earlier demonstrated that the micropilot ignition technology being developed under this program will be successful in meeting the objectives. Reductions in both emissions and fuel consumption are substantial, and will be further demonstrated at two (2) operating field sites during Phase III of this program.

CONCLUSIONS

Phase II of the Retrofit Micropilot Ignition System 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.
4. Commercialization partners are currently engaged to deploy this technology at two (2) field demonstration sites.
5. In general the engine operated more stable with fewer misfires and partial combustion events when using the 3-hole injectors compared to the 5-hole injectors.
6. 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%.
7. 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
8. Micropilot ignition compares very favorably to other ignitions systems. The performance of micropilot ignition 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.

ABBREVIATIONS AND SYMBOLS

ATDC – After Top Dead Center
BHP - Brake Horse Power
BMEP – Brake Mean Effective Pressure
BSFC – Brake Specific Fuel Consumption
BTDC – Before Top Dead Center
CR – Compression Ratio
CSU – Colorado State University
DOE – Department of Energy
EECL – Engines and Energy Conversion Laboratory
HAPs –Hazardous Air Pollutants
LHV – Lower Heating Value
NETL – National Energy Technology Laboratory
SAE – Society of Automotive Engineers
TDC – Top Dead Center
TMFC – Total Modified Fuel Consumption
μL – Micro-Liter

APPENDIX 13

"Research Management Plan – Phase II"

Improvement to Pipeline Compressor Engine Reliability through Retrofit Micro-Pilot Ignition System – PHASE II

RESEARCH MANAGEMENT PLAN

Work to be Performed

The project team, CSU and Woodward, have adopted a technical approach that produces the highest probability of success and the shortest time-to-market. Woodward has an existing business and technical background in fuel system control for large, stationary, reciprocating engines and gas turbines; CSU has a well-developed engine laboratory for the research and development of combustion technology that is applicable to pipeline, reciprocating compressor engines. Woodward has many years of experience in product development and the commercialization of technology for the natural gas industry and natural gas pipelines. In Phase I of the program, we designed a common rail micro-pilot ignition system by combining Woodward controls and electronics with commercially available common-rail injectors. The injectors were modified to allow mounting in the test engine. The entire system is controlled with existing Woodward electronics. In Phase II of the program, the system will be refined and optimized. In Phase III of the program, the system will be field-tested.

Phase II: Refinement and Optimization – 2002/03

Activities in Year 2 will begin with continuation of the test program to examine effects of compression ratio and pilot fuel composition, and will then focus on optimization and refinement of the micro-pilot. The objective of Phase II is to develop the system to the point that pre-production hardware can be specified for a field test that will take place in Phase III.

PHASE II PROJECT SCHEDULE

Phase II Project	**PRIMARY RESPONSIBILITY**	**O '02**	**N '02**	**D '02**	**J '03**	**F '03**	**M '03**	**A '03**	**M '03**	**J '03**	**J '03**	**A '03**	**S '03**
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Task 13: Research Management Plan

STATUS: Complete

Develop a work breakdown structure and supporting narrative that concisely addresses the overall project as set forth in the agreement. Following the completion of Phase I, the Research Management Plan will be updated to reflect the status of the project and the understanding that was gained. This revision will be developed by CSU with DOE.

RESULTS: Contained Herein

Task 14: Evaluation of Compression Ratio

STATUS: Nearly Complete

Evaluate at CSU the effects of compression ratio on the implementation of micropilot ignition. The desirability of implementing pilot ignition without changing the compression ratio is acknowledged. We believe that successful pilot ignition can be achieved effectively at the 8.5:1 compression ratio typical of many pipeline engines. Evaluation of this can be achieved by using an insert to reduce the "bowl" volume in the piston, through "shimming" between the piston and connecting rod to decrease the clearance volume at TDC (although the increase achievable from the technique is limited), or by using smaller volume heads. The efficiency benefits of increasing compression ratio are well documented. 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. However, in order to quantify potential efficiency benefits from the use of higher compression ratios, a set of inserts will be fabricated which can then be bolted to the top of the piston to reduce bowl volume and to increase compression ratio. These modifications will be made to raise the compression ratio and the performance will be monitored to determine the impact of increased compression ratio on fuel consumption and emissions.

RESULTS: Results for the lower of 2 compression ratios is included in Appendix 16. Evaluation of the higher compression ratio (9.5:1) was suspended due to mechanical failures of the pistons. Testing will be completed during Task 20. Preliminary results during the early testing showed superior performance at the higher compression ratio when compared to the lower.

Task 15: Evaluation of Pilot Fuels

STATUS: Nearly Complete.

Collect data at CSU to evaluate the performance effects of different pilot fuels. As discussed in the background section, the choice of pilot fuel can have a large impact on ignition delay and therefore on system performance. We anticipate examining the effect of different pilot fuels, 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 will be required for each pilot fuel.

RESULTS: Selected pilot fuels will be evaluated in the Combustion Test Chamber, and certain fuels may be down-selected at this point. The engine test plan to be developed for Task 20 will be revised to include selected pilot fuels for on-engine evaluations.

Task 16: Analysis of Product Prototype Results

STATUS: Complete.

Analyze the data collected in Task 15 at CSU and with Woodward. The data from the initial laboratory tests will be analyzed to document the performance of the micropilot ignition system. Particular emphasis will be paid to comparisons of combustion stability, fuel consumption, NO_x production, and HAPs production. These results will be used to determine fuel selection, compression ratio, and other overall system parameters.

Task 17: Revision of Product Specifications

STATUS: Complete

Update the product specifications based on the results of Task 16 by Woodward. Based on the decisions made in the previous sub-task, new product specifications will be developed. The matrix of injection quantity, fuel pressure, and nozzle designs from the test program will be used to guide the development of the revised product specifications. It is unlikely that a single combination will emerge from the initial test program as the definitive design. Instead, the test program is likely to focus further refinement/ optimization efforts. It is anticipated that a new set of design specifications will be developed for evaluation in further Phase II testing.

Task 18: Design Revisions to Optimize Performance

STATUS: complete.

Design changes and revisions will be made by Woodward and CSU to correspond to the new specifications developed in Task 17.

RESULTS: primary changes will be to pilot injector nozzles. The standard, 5-hole automotive nozzles proved to be non-optimal. New, 3-hole nozzles have been manufactured and will be evaluated per Task 20.

Task 19: Evaluation of Optimized System in Optical Engine

STATUS: Complete.

Characterize the performance of the revised product at CSU. New hardware developed based on the prototype tests will be evaluated in the Optical Engine. Stationary tests will be performed as in Phase I.

RESULTS: attached per Appendix 19.

Task 20: Laboratory Test to Verify Performance

STATUS: Underway

Characterize the performance of the revised product at CSU. Based on the results from the single cylinder optical tests, a set of 4-cylinder hardware will be fabricated, installed on the EECL laboratory engine, and tested. The objective of the test program will be to evaluate the performance increases produced by optimization efforts, and to verify that the hardware is suitable for field-testing.

RESULTS: Currently readying the GMV-4 test engine for optimized injector operation, with expected completion of evaluation by 12/31/03.

Task 21: Finalization of Design for Field Test

Prepare for product field testing. Field-testing will occur on an engine similar to the laboratory engine. The laboratory engine is a 4-cylinder version of the GMV engine family. It is expected that field tests will be on an 8- or 10-cylinder version of the GMV engine family, since this engine model and configuration is widely used by the U. S. natural gas pipeline industry.

Task 22: Phase II Report

In the year-two report, CSU will document activities leading up to the field tests. The report is expected to document the development of specifications, testing of the single cylinder prototype, and startup / shakedown of the 4-cylinder product prototype.

Task 23: DOE Contractors Meeting

CSU will report on the project results at the annual DOE Contractors Meeting in Morgantown, WV.

APPENDIX 14

"Optimization of a Micropilot Ignition System Using Design of Experiments Technique"

"Procedure for Evaluating Compression Ratio"

"Cylinder Geometry – Compression Ratio Calculations"

Optimization Of A Micro Pilot Ignition System Using Design Of Experiments Techniques

Students: Vijay Srinivasachari
Jacob Brown

Advisor: Dr.William S.Duff
Co-Advisor: Dr.Bryan D.Willson
Member: Dr.Hari K. Iyer

Proposed Approach **Date: Feb 27,2003**

Introduction to Micro Pilot Injection System

The term "Pilot Injection" is used when diesel injection is used only for ignition. Typical injection quantities for pilot injection are 1%-10% of total energy content. The term "Micro Pilot" has come into prominence for its use in applications where less than 1% of the energy is supplied as pilot fuel. Here a small quantity of diesel fuel is injected into the cylinder to ignite the air/fuel mixture. It is estimated that a micro pilot ignition system of only 0.1% pilot fuel would deliver 1500 times more energy than a typical spark ignition system and distribute this energy over a larger volume. It would also eliminate the need for a spark plug and the corresponding problems encountered with spark plug life. A properly designed pilot ignition system requires very little maintenance and would represent a significant maintenance cost savings over spark ignition systems.

Obstacles faced

Improved exhaust emissions and engine performance are two objectives that play a vital role in the commercial viability of a new engine technology. The Micro Pilot Ignition system must address both of these.

Scope of Design of Experiments

The objective of undertaking a Design of Experiments study is to develop an optimum design point. Sets of experiments are structured find this point in the most efficient manner. It consists of two stages of experimentation:

1. The first stage experimentation has two objectives:

   a. Identify factors (settings) that significantly affect the performance of the system. The factors are screened to identify those that play a significant role in affecting the performance of the system (responses). The responses may be affected by individual factors or by a combination of factors.
   b. Establish models of the process for each response. Here, the experimentation objective is to develop an empirical model for each of the systems responses in terms of the factors.

2. Once empirical models are developed, a gradient search technique for optimization called the steepest ascent method is used to find an optimum point. The steepest ascent method requires:
   a. Calculating the "best" direction to search, according to an objective function that is based on the empirical model developed in stage 1.
   b. Finding the "best value" along the search direction by experimentation.

The experiment begins with an initial point in the center of the experimentation region. After establishing an empirical model for the systems responses, a search is performed along the direction of the steepest ascent gradient until an optimum for the process is found. This optimum becomes the starting point for the next set of experiments. A new empirical model is developed (Figure A), the gradient direction is recalculated, and the new direction followed. The process is repeated until an optimum is found.

The direction of the steepest ascent is the direction parallel to the normal of the fitted response surface as characterized by the model. The steps along the ascent path are determined via a one-dimensional search. Experiments are conducted along the path of steepest ascent until no statistically significant increase in response is found. Then a new model may be fit, a new path of steepest ascent determined and the procedure continued until no further improvement can be achieved.

Figure A14-1: Path of steepest ascent for two factors

(For example: Fuel Rail Pressure vs. Pilot Injection Timing)

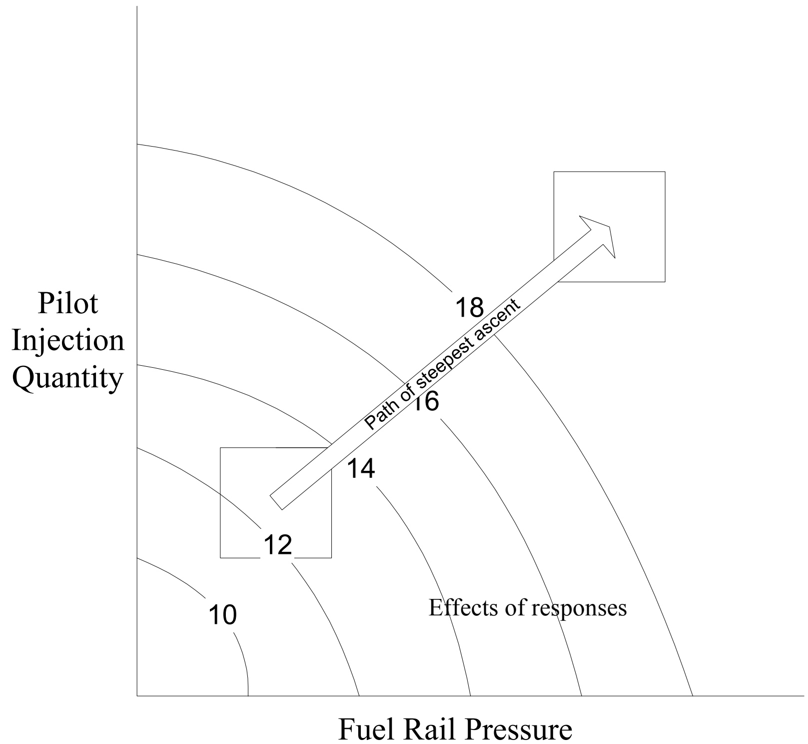
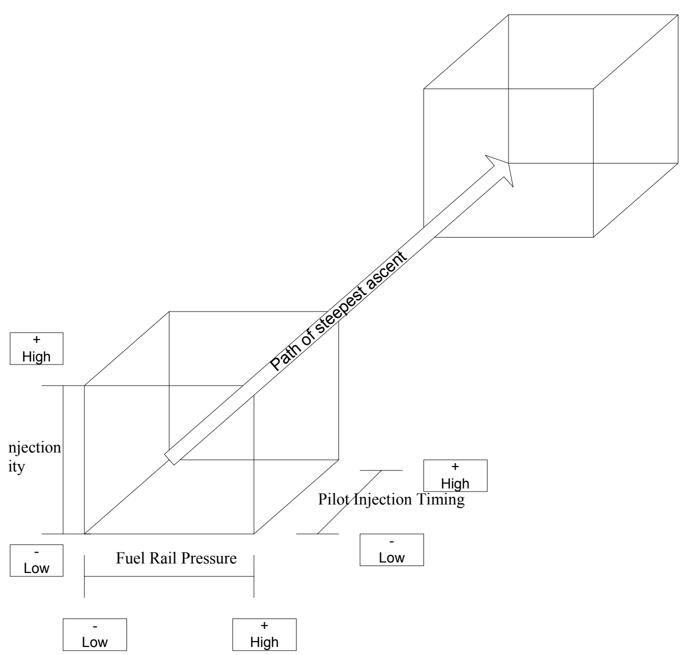


Figure A14-2: Geometric view of 2^3 Factorial Design



Research

The research will involve the application of Design of Experiments techniques to the Micro-Pilot Ignition System. This includes:

1. Identifying the appropriate controllable factors.
2. Conducting preliminary sets of experiments to find out which factors are important and how they interact.
3. Establishing empirical models of the process/systems in terms of the factors.
4. Formulating on objective function that involves these models.
5. Conducting experiments along the path of steepest ascent, usually starting with the center of the experimentation region as the initial point until no statistically significant increase in response is found.
6. Fitting a new model, determining a new path of steepest ascent and continuing with the same procedure.
7. Possibly conducting an expanded set of experiments once we arrive at the vicinity of the optimum to obtain a higher order model that may provide the means for continuing the optimization process.
8. Finding optimal solutions.
9. Verifying and refining the analysis.

Initially a full factorial design with 3 center points and no replications will be used for stage 1. Three factors and 3 center points in a designed experiment require 11 separate points of data.

Optimizing the Micro-Pilot System

The application of Design of Experiments techniques will provide an effective and efficient experimentation path to micro-pilot optimization by considering the factors and their interactions that influence exhaust emissions and engine performance.

Optimizing the micro-pilot system will involve 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 will discover which factors or combination of factors contribute in a significant way towards performance responses. For example, the screening experiments might identify fuel rail pressure and pilot injection timing as more important factors than the pilot injection quantity and pilot injection timing as significantly affecting emissions. All significant factors and interactions will be incorporated into the model.

Once the empirical models are established and the objective function formulated, the search for the optimum values of the responses along the path of steepest ascent will be carried out.

Procedure

All experimental points will be taken with the engine at a rated load and 13" Hg boost. The procedure will be performed twice. The first time through the NOx response will be minimized and the second time will minimize the total modified fuel cost response. The total modified fuel cost will be calculated by adding the NG cost to ten times the pilot fuel cost per cylinder per day.

The controllable factors are:

a. Fuel Rail Pressure

b. Pilot Injection Quantity

c. Pilot Injection Timing

The procedure consists of the following steps:

1. Run an initial 11 point set of experiments to find corresponding values of the various responses (Table 2).
2. Perform a statistical analysis to find out which factors and interactions are important.
3. Establish empirical models of the system response in terms of the factors.
4. Calculate the expression for the gradient.
5. Select an end point for the search by performing a preliminary set of experiments.
6. Using the center of the experimentation region and the end point established in Step 5, 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.
7. The midpoint of this optimum becomes the center point for a new 11 point matrix (Table 1)
8. Steps 1 through 7 are iterated until an overall optimum is found.

The Design of Experiment matrix indicating the run order, standard order, and the factors is shown in Table 1.

Table A14-1: Initial Experiment Design Matrix Using Coded Variables

Run Order	Std Order	Center Pt	Blocks	Rail Pressure (psi)	Pilot Injection Quantity (μL)	Pilot Injection Timing (deg)
1	10	0	1	0	0	0
2	2	1	1	1	-1	-1
3	7	1	1	-1	1	1
4	5	1	1	-1	-1	1
5	6	1	1	1	-1	1
6	9	0	1	0	0	0
7	1	1	1	-1	-1	-1
8	4	1	1	1	1	-1
9	3	1	1	-1	1	-1
10	8	1	1	1	1	1
11	11	0	1	0	0	0

The center point, high and low values for each of the factors are given below:

Values:	-1	0	1
Rail Pressure	- 2,000 psi	10,000 psi	+ 2,000 psi
Pilot Injection Quantity	- 1.5 µL	12 µL	+ 1.5 µL
Pilot Injection Timing	- 1°	- 8° BTDC	+ 1°
	Negative Δ Value	Initial Center Point	Positive Δ Value

Table A14-2: Initial Experiment Design Matrix Using Natural Variables

Run Order	Std Order	Center Pt	Blocks	Rail Pressure (psi)	Pilot Injection Quantity (µL)	Pilot Injection Timing (deg)
1	10	0	1	10,000	12	- 8
2	2	1	1	12,000	10.5	- 9
3	7	1	1	8,000	13.5	- 7
4	5	1	1	8,000	10.5	- 7
5	6	1	1	12,000	10.5	- 7
6	9	0	1	10,000	12	8
7	1	1	1	8,000	10.5	- 9
8	4	1	1	12,000	13.5	- 9
9	3	1	1	8,000	13.5	- 9
10	8	1	1	12,000	13.5	- 7
11	11	0	1	10,000	12	8

Procedure for Evaluating Compression Ratio – Task 14

A baseline with spark ignition will be taken for each compression ratio prior to any experimental points at each compression ratio. The baseline will include: 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 are begun, the timing of the MP system will be adjusted to place the peak pressures as close to 18 ATDC as possible. This timing point will be the first center point for testing.

All experimental points will be taken with the engine at a rated load and 13" Hg boost. For each compression ratio, the procedure will be performed twice: the first run will minimize Total Modified Fuel Consumption and the second will maximize combustion stability. Two compression ratios will be investigated resulting in a total of four tests. With reference to cylinders 1 and 3, the first compression ratio to be studied will be 9.5:1 and the second, 8.7:1. The test map is unique because it is open ended. After the first set of 11 test points (Table 1), calculations will be performed to determine the next set of points which will optimize the variable being studied, i.e. fuel consumption or combustion stability. In this manner, we will continually be searching to optimize the dependent variable.

After a minimum fuel consumption and an optimum combustion stability point have been found. The combustion stability point will be tested for a maximum lean limit.

Table A14-3:Initial Experiment Design Matrix Using Natural Variables

Run Order	Std Order	Center Pt	Blocks	Rail Pressure (psi)	Pilot Injection Quantity (μL)	Pilot Injection Timing (deg)
1	10	0	1	10,000	12	TBD
2	2	1	1	12,000	10.5	
3	7	1	1	8,000	13.5	
4	5	1	1	8,000	10.5	
5	6	1	1	12,000	10.5	
6	9	0	1	10,000	12	
7	1	1	1	8,000	10.5	
8	4	1	1	12,000	13.5	
9	3	1	1	8,000	13.5	
10	8	1	1	12,000	13.5	
11	11	0	1	10,000	12	

The controllable factors are:

a. Fuel Rail Pressure

b. Pilot Injection Quantity

c. Pilot Injection Timing

2. Run the initial 11 point center to find corresponding values of the various responses (Table 1).
3. Perform a statistical analysis to find out which factors and interactions are important.
4. Establish empirical models of the process/systems in terms of the factors.
5. Calculate the expression for the gradient.
6. Calculate an end point for the search and develop a map that will dictate the "golden section search."
7. Using the center of the experimentation region and the end point established in Step 6, use "golden section search" technique to narrow the interval along the path of steepest

ascent (Figures A and B) until the interval containing the optimum has been reduced to an acceptable small length.

8. The midpoint of this optimum becomes the center point for a new 11 point matrix (Table 2).
9. Steps 2 through 8 are iterated until an overall optimum is found for maximizing combustion stability or minimizing Total Modified Fuel Cost.

All of the center point testing matrixes are based on a Design of Experiment matrix shown in Table 2.

Table A14-4: Initial Experiment Design Matrix Using Coded Variables

Run Order	Std Order	Center Pt	Blocks	Rail Pressure (psi)	Pilot Injection Quantity (µL)	Pilot Injection Timing (deg)
1	10	0	1	0	0	0
2	2	1	1	1	-1	-1
3	7	1	1	-1	1	1
4	5	1	1	-1	-1	1
5	6	1	1	1	-1	1
6	9	0	1	0	0	0
7	1	1	1	-1	-1	-1
8	4	1	1	1	1	-1
9	3	1	1	-1	1	-1
10	8	1	1	1	1	1
11	11	0	1	0	0	0

Values:	-1	0	1
Rail Pressure	- 2,000 psi	10,000 psi	+ 2,000 psi
Pilot Injection Quantity	- 1.5 µL	12 µL	+ 1.5 µL
Pilot Injection Timing	- 1°	- 8° BTDC	+ 1°
	Negative Δ Value	Initial Center Point	Positive Δ Value

Figure A14-3: Path of steepest ascent for two factors

(For example: Fuel Rail Pressure vs. Pilot Injection Timing)

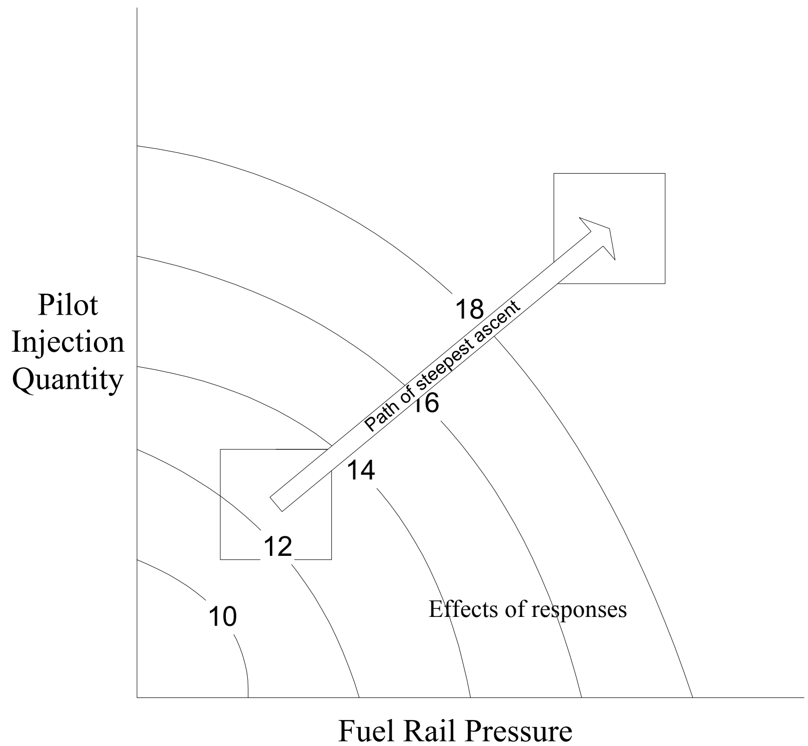
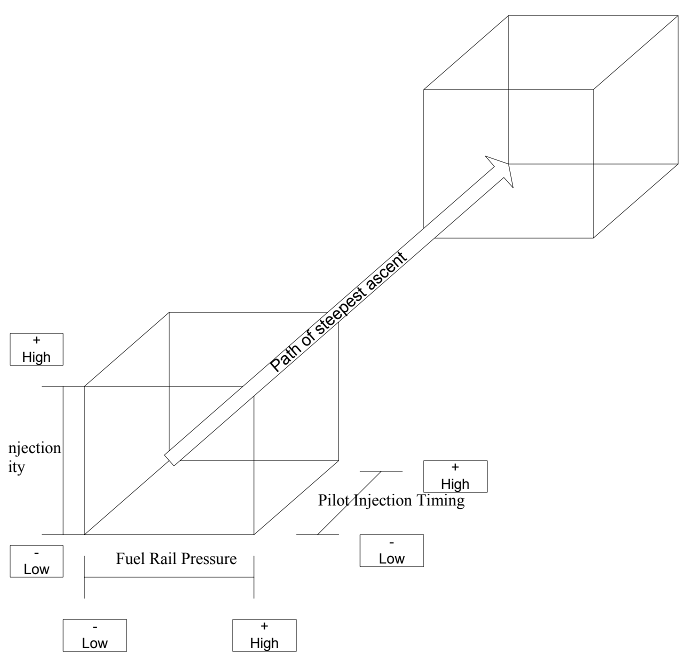


Figure A14-4: Geometric view of 2^3 Factorial Design



Compression Ratios on GMV with and without pancakes

	Cylinders 1 and 3	Cylinders 2 and 4
Diameter of Cylinder:	$Dia := 14in$	$Dia = 14\,in$
Distance from port closure to end of stroke:	$St_{1and3} := 10.25in$	$St_{2and4} := 10.15in$

These measurements were taken from the top of ports to TDC in each cylinder.

Clearance Volume: $Cv_{2and4} := 190in^3$

190 in³ agrees with Walt's ProE mold. A rubber mold was made years back that measured 208 in³.

Because the pistons in cylinders 2 and 4 do not rise up into the cylinder as far, there is extra clearance volume in these cylinders, Cvx:

$$Cvx_{2and4} := \pi \cdot \left(\frac{Dia}{2}\right)^2 \cdot \left(St_{1and3} - St_{2and4}\right) \qquad Cvx_{2and4} = 15.394\,in^3$$

$$Cv_{1and3} := Cv_{2and4} - Cvx_{2and4}$$

$$Cv_{1and3} = 174.606\,in^3$$

Total volume at port closure:

$$Vtr_{1and3} := Cv_{1and3} + \pi \cdot \left(\frac{Dia}{2}\right)^2 \cdot St_{1and3} \qquad Vtr_{2and4} := Cv_{2and4} + \pi \cdot \left(\frac{Dia}{2}\right)^2 \cdot St_{2and4}$$

$$Vtr_{1and3} = 1752.471\,in^3 \qquad Vtr_{2and4} = 1752.471\,in^3$$

$$V_{tr} = Vtr_{1and3} = Vtr_{2and4} \qquad V_{tr} := Vtr_{2and4}$$

Compression Ratios without pancakes:

$$CR_{1and3} := \frac{V_{tr}}{Cv_{1and3}} \qquad CR_{2and4} := \frac{V_{tr}}{Cv_{2and4}}$$

$$CR_{1and3} = 10.037 \qquad CR_{2and4} = 9.224$$

Pancake volume: "11 to 1" $P_v := 19.5in^3$

Clearance volume: $Cvp_{1and3} := Cv_{1and3} - P_v$ $Cvp_{2and4} := Cv_{2and4} - P_v$

Total volume at port closure: $V_{trp} := V_{tr} - P_v$

Compression Ratios: $CRp_{1and3} := \frac{V_{tr}}{Cvp_{1and3}}$ $CRp_{2and4} := \frac{V_{tr}}{Cvp_{2and4}}$

$CRp_{1and3} = 11.299$ $CRp_{2and4} = 10.278$

Pancake volume: "12 to 1" $P_v := 30.1in^3$

Clearance volume: $Cvp_{1and3} := Cv_{1and3} - P_v$ $Cvp_{2and4} := Cv_{2and4} - P_v$

Total volume at port closure: $V_{trp} := V_{tr} - P_v$

Compression Ratios: $CRp_{1and3} := \frac{V_{tr}}{Cvp_{1and3}}$ $CRp_{2and4} := \frac{V_{tr}}{Cvp_{2and4}}$

$CRp_{1and3} = 12.127$ $CRp_{2and4} = 10.96$

Presently we have eliminated the "12 to 1" compression ratio based on the December 19th testing. We could not advance the pilot fuel past 9 BTDC without significant knocking while our peak pressures were a few degrees retarded from where we would like them. The second two compression ratios have yet to be studied.

APPENDIX 15

"A Summary of Information on Possible Fuels for the Micropilot Ignition System"

"Procedure for Evaluating Pilot Fuels"

A Summary of Information on Possible Fuels for the Micropilot Ignition System

Diesel: Currently used. Cetane number 40-45 (our supply is 42.8 [1])

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. [2]

Advantages: High cetane numbers (ranging from 40-77 averaging in the 50's [3]). High lubricity [5]. Contains no sulfur [3]. 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 [3] [6]. Renewable energy source. Should work well with current fuel delivery system [3].

Disadvantages: Unavailability. Poor fuel property repeatability in manufacturing [3] [4]. Tests indicate higher NOx and particulate matter (volatile organic fraction) emissions [3] [6]. Higher fuel costs [6].

Fischer-Tropsh Fuel: A synthetic diesel fuel made from coal or natural gas [7].

Advantages: High cetane number (72 [9]). Can be made from natural gas [7]. Would work with current fuel delivery system. Contain low/no sulfur (<0.3% by weight) and aromatic chemical compounds (<5-10 ppm) [7] [14]. Tests indicate lower NOx and PM emissions [7] [8] [14]. Slightly less energy dense than diesel [8] [14]. Production plants being built by Conoco (OK), Syntroleum (OK), and British Petroleum (AK) [13]. Mass production and usage would make F-T fuels similar or cheaper in price than diesel [13]. Nearly odorless [14].

Disadvantages: Limited availability currently in the US. Higher fuel costs compared to conventional diesel [8]. Low lubricity [13] [14]. Properties can vary substantially depending on catalyst and reactor technologies used for the production [14].

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 [10]). No carbon-carbon bonds and high oxygen content resulting in low amounts of soot and hydrocarbons in the exhaust [10] [12]. Vaporizes easily [10]. Decomposes quickly in the atmosphere [12]. Much lower energy density than diesel [12]. Faster flame propagation and shorter combustion time [12].

Disadvantages: Poor Lubricity [11]. Physical properties present fuel delivery difficulties [12]. High testing costs. Unknown cost of reformers (unable to find specific information).

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.

References

1. Sample taken by Southern Petroleum Laboratories, Houston Laboratory 8880 Interchange Dr. Houston, Texas. Bob Rannals.

2. Midwest Biofuels. "Biodiesel CetaneNumber Engine Testing Comparison to Calculated Cetane Index Number," 1994.

3. Colorado Institute for Fuels and Engine Research, Colorado School of Mines. "Effect of Biodiesel Composition on NOx and PM Emissions from a DDC Series 60 Engine," prepared for National Renewable Energy Laboratory, Dec. 29, 1999.

4. Van Gerpen, Jon. "Cetane Number Testing of Biodiesel." Mechanical Engineering, Iowa State University, Ames, Iowa.

5. Adams, Prisella; Suppes, Galen; Heppert, Joseph. "Soy Fuel Additive May Help Cut Fuel Prices," University of Kansas, Office of University Relations, Feb. 18, 2000.

6. "Summary Results from NBB/USEPA Tier I Health and Environmental Effects Testing for Biodiesel Under the Requirements for USEPA Registration of Fuels and Fuel Additives," March 1998.

7. Barba, Sara. "NREL and California Air Agency to Test Clean Diesel Fuels," USDOE, NREL, Golden, CO, Oct. 4, 2000.

8. Environmental Protection Agency. "Clean Alternative Fuels: Fischer-Tropsch," EPA, March 2002.

9. Schubert, Paul; Russell, Branch; Freerks, Robert; Tomlinson, H. Lynn. "Fischer-Tropsch Fuels and Lubricants I: Germany 1923-1939," Syntroleum Corporation, Tulsa, OK, Aug. 22, 2000.

10. Daly, Catherine. "Burning Velocities of Dimethyl Ether + Air," Department of Chemistry, national University of Ireland, Galway, Ireland.

11. The Energy Institute at Penn State. "Penn State Staff Shuttle Bus Operates on Dimethyl Ether Fuel," Dr. Andre Boehman.

12. NKK Corp. "DME (Dimethyl Ether) PROJECT, Environmental Business," Japan, 2000.

13. Shen, John; Schmetz, Edward. "Oppoertunities for the Early Production of Fischer-Tropsch (F-T) Fuels in the U.S. – An Overview." U.S. Department of Energy (DOE), Germantown, MD.

14. Norton, Paul… "Emissions from Trucks Using Fischer-Tropsch Diesel Fuel." NREL, DOE, West Virginia University.

Procedure for Evaluating Pilot Fuels – Task 15

Alternative pilot fuels to diesel have been researched including: dimethyl ether, bio-diesel, and engine lube oil. The ability to use engine lube oil as a pilot fuel has the most benefit for the industry. Therefore, further testing will investigate the performance of this fuel. Initial testing will be conducted off the engine in order to evaluate the capability of the fuel delivery system to deliver the engine oil fuel. On engine testing will commence only if a capable delivery system can be created.

All on engine experimental points will be taken with the engine at a rated load and 13” Hg boost. The results from Task 14 will determine the compression ratio chosen and the initial timing. The engine testing procedure will be performed twice: the first run will minimize Total Modified Fuel Consumption and the second will optimize combustion stability. The test map is unique because it is open-ended. After the first set of 11 test points (Table 1), calculations will be performed to determine the next set of points which will optimize the variable being studied. These first 11 points are likely to change based on the results of Task 14. We will begin the testing at the optimum points for diesel found in Task 14.

Table A15-1: Initial Experiment Design Matrix Using Natural Variables

Run Order	Std Order	Center Pt	Blocks	Rail Pressure (psi)	Pilot Injection Quantity (μL)	Pilot Injection Timing (deg)
1	10	0	1	10,000	12	TBD
2	2	1	1	12,000	10.5	TBD
3	7	1	1	8,000	13.5	TBD
4	5	1	1	8,000	10.5	TBD
5	6	1	1	12,000	10.5	TBD
6	9	0	1	10,000	12	TBD
7	1	1	1	8,000	10.5	TBD
8	4	1	1	12,000	13.5	TBD
9	3	1	1	8,000	13.5	TBD
10	8	1	1	12,000	13.5	TBD
11	11	0	1	10,000	12	TBD

The controllable factors are:

a. Fuel Rail Pressure
b. Pilot Injection Quantity
c. Pilot Injection Timing

10. Run the initial 11 point center to find corresponding values of the various responses (Table 1).
11. Perform a statistical analysis to find out which factors and interactions are important.
12. Establish empirical models of the process/systems in terms of the factors.
13. Calculate the expression for the gradient.
14. Calculate an end point for the search and develop a map that will dictate the "golden section search."
15. Using the center of the experimentation region and the end point established in Step 6, use "golden section search" technique to narrow the interval along the path of steepest ascent (Figures A and B) until the interval containing the optimum has been reduced to an acceptable small length.
16. The midpoint of this optimum becomes the center point for a new 11 point matrix (Table 2).
17. Steps 2 through 8 are iterated until an overall optimum is found for minimizing NOx or minimizing Total Modified Fuel Cost.

All of the center point testing matrixes are based on a Design of Experiment matrix shown in Table 2.

Table A15-2: Initial Experiment Design Matrix Using Coded Variables

Run Order	Std Order	Center Pt	Blocks	Rail Pressure (psi)	Pilot Injection Quantity (μL)	Pilot Injection Timing (deg)
1	10	0	1	0	0	0
2	2	1	1	1	-1	-1
3	7	1	1	-1	1	1
4	5	1	1	-1	-1	1
5	6	1	1	1	-1	1
6	9	0	1	0	0	0
7	1	1	1	-1	-1	-1
8	4	1	1	1	1	-1
9	3	1	1	-1	1	-1
10	8	1	1	1	1	1
11	11	0	1	0	0	0

Values:	-1	0	1
Rail Pressure	- 2,000 psi	10,000 psi	+ 2,000 psi
Pilot Injection Quantity	- 1.5 μL	12 μL	+ 1.5 μL
Pilot Injection Timing	- 1°	- 8° BTDC	+ 1°
	Negative Δ Value	Initial Center Point	Positive Δ Value

Figure A15-1: Path of steepest ascent for two factors

(For example: Fuel Rail Pressure vs. Pilot Injection Timing)

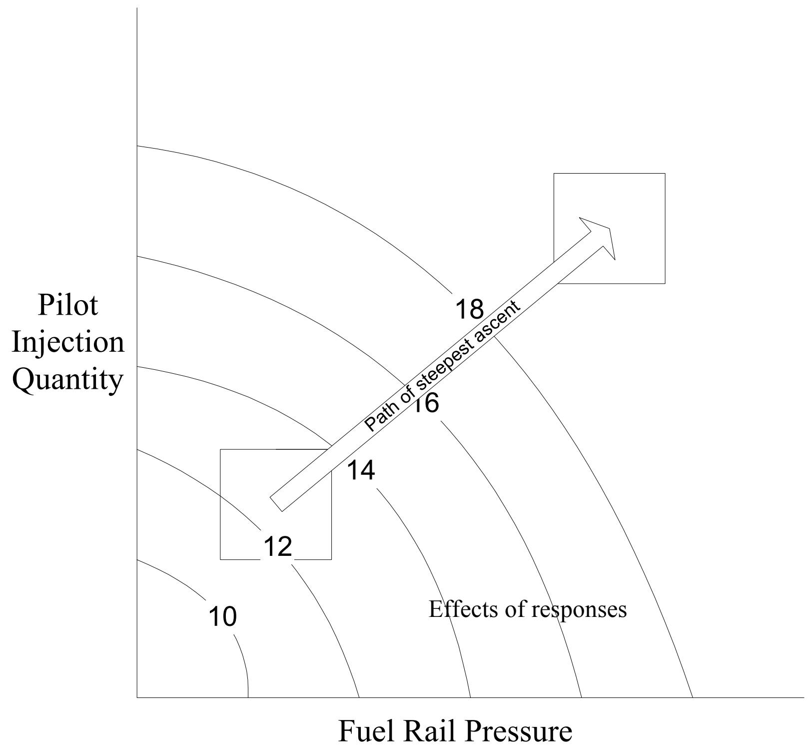
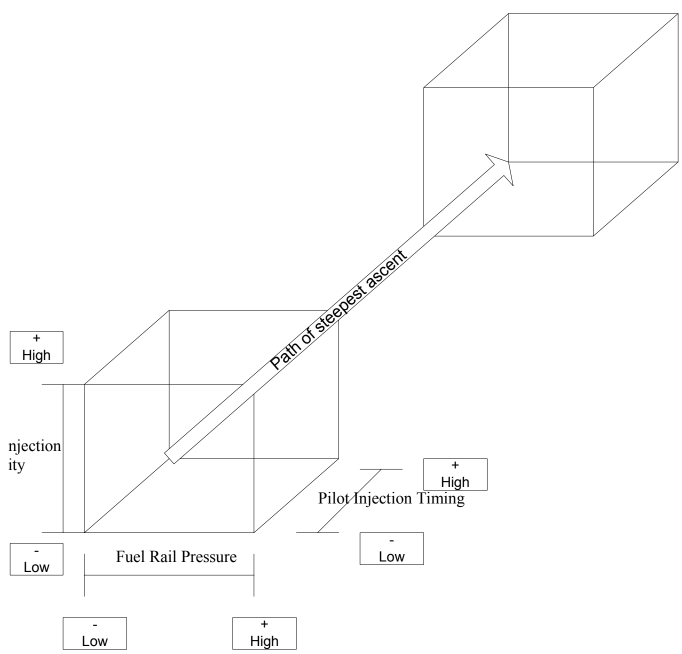


Figure A15-2: Geometric view of 2^3 Factorial Design



APPENDIX 16

"Prototype System Results & Analysis"

"Natural Gas vs. Diesel Cost Analysis/ Optimization"

"Solid Model of Injector Adapter Modified for Water Cooling"

"IMPROVEMENT TO PIPELINE COMPRESSOR ENGINE RELIABILITY THROUGH RETROFIT MICRO-PILOT IGNITION SYSTEM"

DE-FC26-01NT41162

PROTOTYPE RESULTS

June 23, 2003

EXPERIMENTAL EQUIPMENT AND CONDITIONS

The Large Bore Engine Test-bed (LBET) is housed in the Engines and Energy Conversion Laboratory (EECL) at Colorado State University. At the core of the test-bed is a highly instrumented Cooper-Bessemer GMV-4TF engine. A photograph of the engine is shown in Figure 1. The GMV-4TF is a 4 cylinder two-stroke cycle, 14" (36 cm) bore, 14" (36 cm) stroke, natural gas fired engine. The GMV-4TF has a sea level brake power rating of 440 bhp (330 kW) at 300 rpm. The GMV-4TF uses Mechanical Gas Admission Valves (MGAV), which deliver fuel to each cylinder individually at an injection pressure of about 22 psig (152 kPag). The engine is nominally operated with spark ignition.

The LBET includes a combustion analysis system that uses cylinder pressure profiles to calculate peak pressure, location of peak pressure, misfire frequency, and combustion stability parameters. The test-bed has a computer controlled water brake dynamometer for precise load control. A turbocharger simulation package controls intake and exhaust manifold pressures, allowing the simulation of a wide range of engine "breathing" configurations. The turbocharger simulation package is composed of two main components, a super charger (Roots blower) to pressurize the intake air and a motorized, computer controlled backpressure valve. The facility also has the ability to control jacket water temperature, air manifold temperature, and air manifold relative humidity. The test-bed utilizes a standard five-gas analyzer rack for measuring THC, NO, O_2, CO_2, and CO, and a Fourier Transform Infrared (FTIR) spectrometer for examination of a wide range of species including criteria pollutants and formaldehyde.

Variations in engine operating parameters and changes to engine hardware configuration are performed relative to the nominal operating conditions and hardware configuration. The nominal operating conditions and hardware configuration are summarized in Table 1.

Injection of the micro-pilot fuel is performed by a combination of Delphi, Woodward, and custom hardware and software (Figure 2). A Delphi diesel common rail injection pump and injectors deliver the pilot fuel. The system is capable of creating 1,000 to 24,000 psig of fuel pressure to inject through a 24 volt electronically controlled injector. This Delphi system is 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 are driven with a modified Woodward Inpulse engine control unit. The In-Pulse creates the specific current waveform needed to actuate each injector and times each injection event with the engine's speed and crank angle. The timing and duration of the pilot event for each cylinder can be independently tuned using Woodward software.

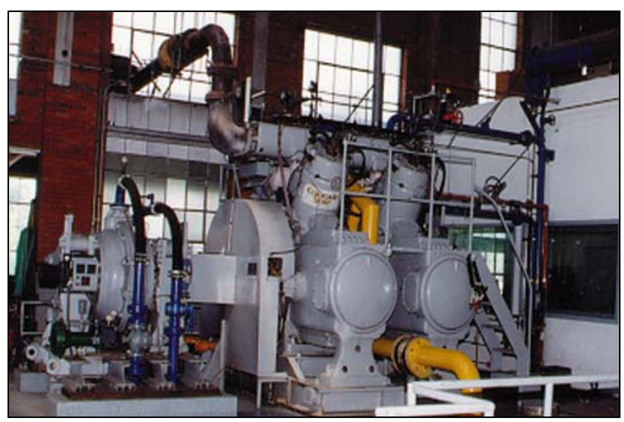


Figure A16-1: The Cooper Bessemer GMV-4TF Large Bore Natural Gas Engine.

ENGINE PARAMETER	NOMINAL VALUE
Brake Power	440 hp (330 kW)
Dynamometer Torque	7730 ft-lb (10.5 kN-m)
Engine Speed	300 rpm (5 Hz)
Ignition Timing	10.1° BTDC
Intake Manifold Pressure	
	Direct Injection, Mechanical, 22 p

Table A16-1: Nominal operating conditions for the GMV-4TF.

INVESTIGATED MICRO-PILOT 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:

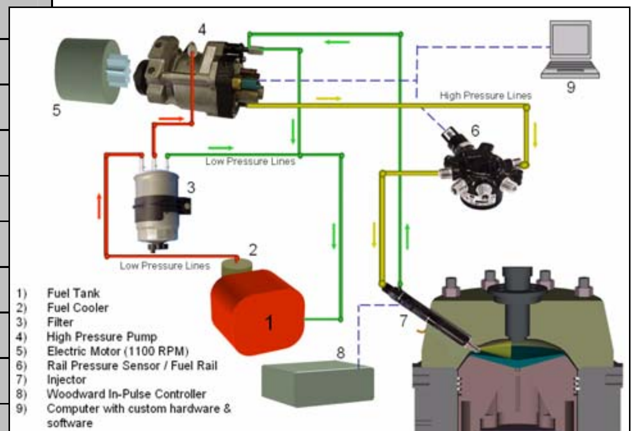
- Compression ratio in the cylinder
- Temperature in the cylinder
- Pressure in the cylinder
- Air/Fuel ratio

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 holds 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 are easily identified.

It is important to note that the design of the pilot injector nozzle, and therefore the spray pattern, are not designed for this engine. They are 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 will test other nozzle designs in the future.



<u>Pilot Injection Timing</u>

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 micropilot injection ignition delay varies 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 vaporizes and mixes with surrounding gases before cylinder conditions are favorable for ignition. It is desirable to have liquid droplets present when ignition temperature is reached, whereby ignition occurs at the stoichiometric zone surrounding the droplet. Given that ignition occurs, ignition delay decreases when pilot fuel is injected later in the cycle because the reactant temperature increases as the cylinder gases are compressed by the piston.

Modeling of the GMV predicts a pressure of 250 psi and a temperature of 764 K at 15 BTDC. Two previous studies of diesel ignition delay have been reviewed. A quiescent chamber based study by Wolfer predicts 6.64 ms and an engine based study by Hardenberg and Hase, which considers piston speed, predicts 5.07 ms at these conditions.

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

<u>Pilot Fuel Quantity</u>

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

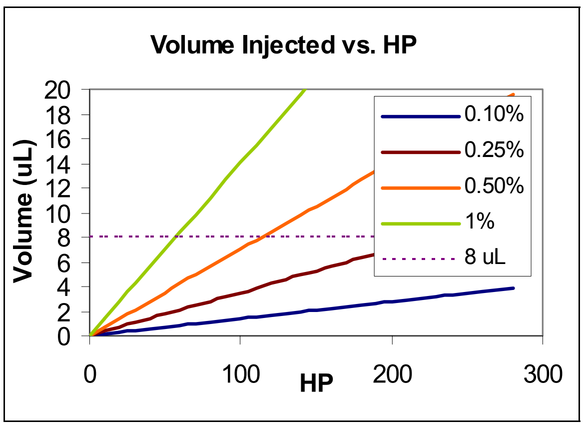


Figure A16-3: Volume as a function of

As indicated in Figure 2, 8 µL of pilot fuel will supply a 110 HP cylinder with 0.5% of its total energy. Therefore, this will be the targeted fuel quantity.

In addition, the quantity of pilot fuel largely determines the penetration distance of the spray. Many experiments of spray penetration in diesel engines have been conducted. Largely accepted is the model developed by Dent [3], based on a gas jet mixing model for the spray. This model shows the influence spray quantity has on penetration depth, plotted in Figure 3.

It is interesting to note that Figure 3 shows that for a given injector hole geometry the injection pressure has little to no effect on the final penetration distance. This distance is strictly a function of the quantity injected.

<u>Pilot Delivery Pressure</u>

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.

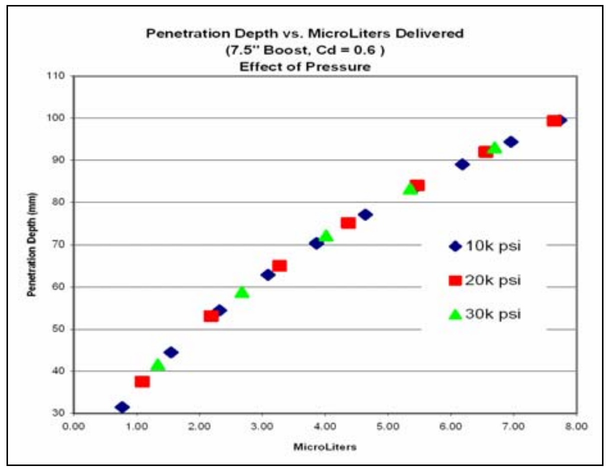


Figure A16-4: Penetration Depth vs. Quantity Delivered

TESTING PROCEDURE

Testing was performed with the unoptimized nozzle to demonstrate micro-pilot 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.

Optimizing the engine with three independent variables traditionally would require a very large map of data over all of the variables' ranges and combinations. To minimize the testing time, a Design of Experiments statistical technique was used. The test map is unique because it is open ended. A base matrix of data was taken and used to develop an empirical model. The matrix (Table 1) began with a center point and adjusted each of the three independent variables (Pressure, Timing, and Quantity) in a positive and negative step to acquire data at every possible combination of high and low for each variable. The center point "cube" required too many data points to test in one run so the matrix was broken into two blocks. The empirical model developed from the center point testing was used to create a linear vector that optimized fuel consumption by specifying a series of center points for the three independent pilot variables. This search vector was followed until a local optimum point was found. At this local optimum the experiment was repeated using the local optimum as a new center point and then determining and following a new search vector. This cycle was repeated until a true optimum was found.

Table A16-2: Initial Center Point "Cube" Matrix

Block	Run Order	Center Point	Rail Press (psi)	Pilot Qty (µL)	Timing (BTDC)
1	1	X	10000	14.5	14
	2		12000	13	13
	3		8000	16	13
	4		8000	13	15
	5		12000	16	15
	6	X	10000	14.5	14
2	7	X	10000	14.5	14
	8		8000	13	15
	9		12000	16	15
	10		8000	16	13
	11		12000	13	13
	12	X	10000	14.5	14

All experimental points were taken with the engine at a rated load and 13.5" Hg boost. No transient studies were performed. Before any micro-pilot 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.

RESULTS

The resulting Total Modified Fuel Consumption (TMFC) for the test points in Table 1 are shown in Figure 4. This cube shows that the system favored lower pilot quantities, lower pilot injection pressure, and more advanced timing.

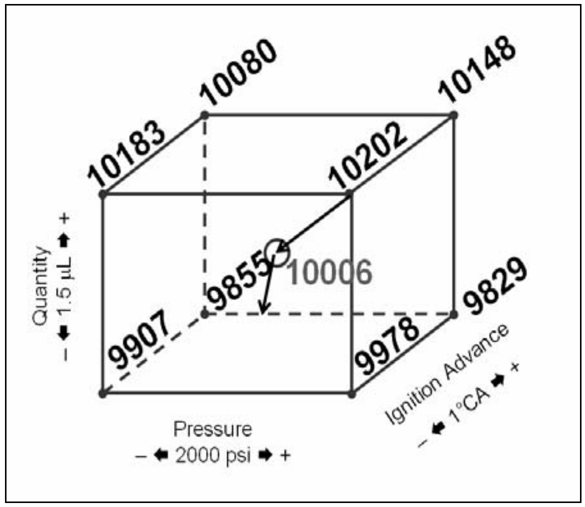


Figure A16-5: TMFC (BTU/hp-hr) values for initial center point matrix. Arrows show trend for lower TMFC.

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 values used for the optimization vector are shown in Table 2 and TMFC values are plotted in Figure 5.

Table A16-3: Optimization Vector Set Points

Run Order	Rail Press (psi)	Pilot Qty (μL)	Pilot % Total Energy	Timing (BTDC)
1	10000	14.50	0.90	14.00
2	8944	14.19	0.89	14.22
3	7888	13.88	0.87	14.45
4	6832	13.57	0.85	14.67
5	5776	13.25	0.83	14.89
6	4720	12.95	0.81	15.12
7	3664	12.64	0.79	15.34
8	3000	12.33	0.77	15.56
9	3000	11.50	0.72	15.56

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

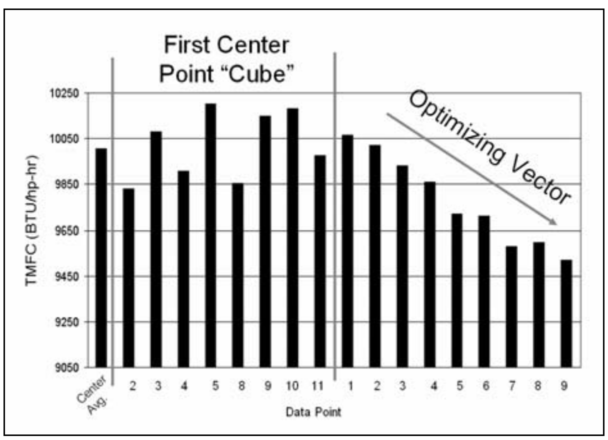


Figure A16-6: TMFC Values for Center Point and Optimizing Vector

During the 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 6. 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. With the 9th optimization vector point, pilot quantity was reduced further, which resulted in lowering TMFC but raising natural gas consumption.

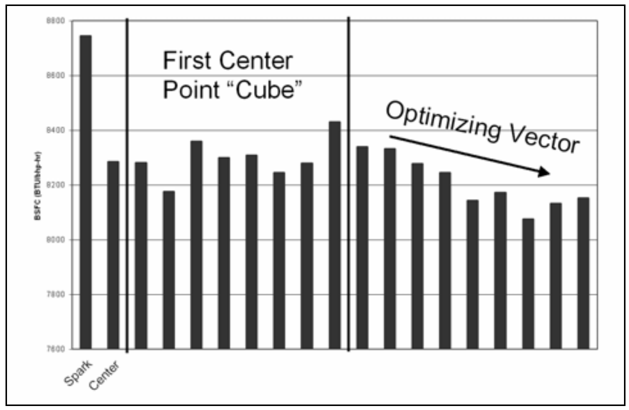


Figure A16-7: Natural Gas Consumption for Spark, Center Point, and Optimizing Vector

Other significant measurements made during this testing are shown in Figures 7-12. 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.

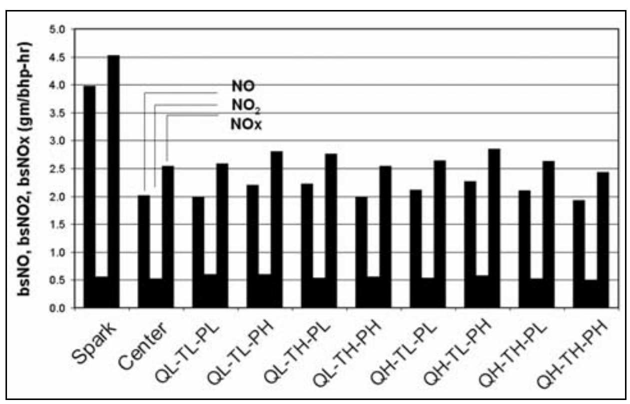


Figure A16-8: Brake Specific NO_x formation

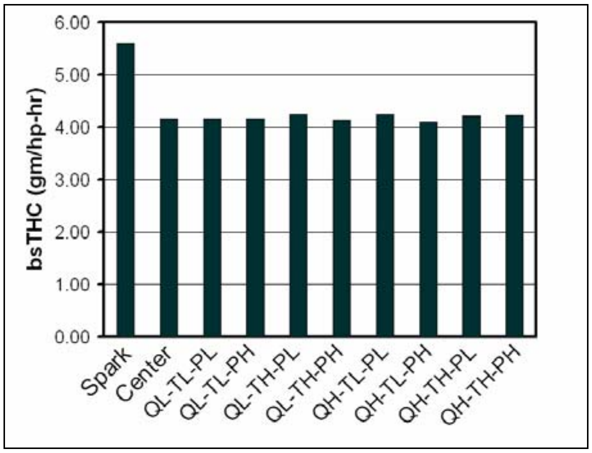


Figure A16-9: Brake Specific Total Hydrocarbon Formation

Brake specific oxides of nitrogen ($bsNO_x$) emissions, along with Total Hydrocarbon (bsTHC) emissions were reduced across the board but did not seem to trend with changes in the micro-pilot settings.

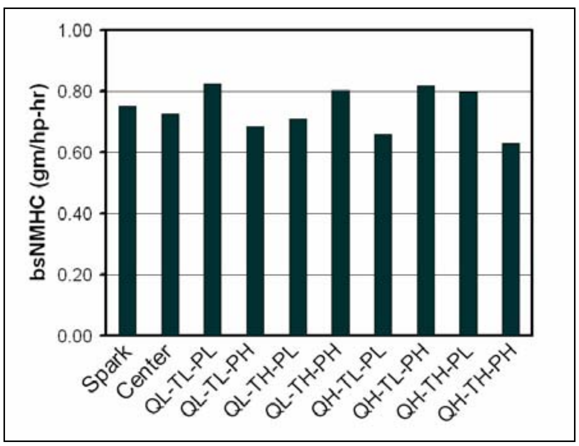


Figure A16-10: Brake Specific Non Methane Hydrocarbon Formation

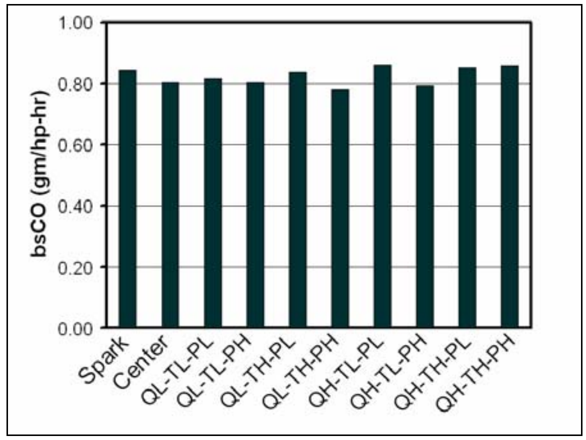


Figure A16-11: Brake Specific Carbon-monoxide Formation

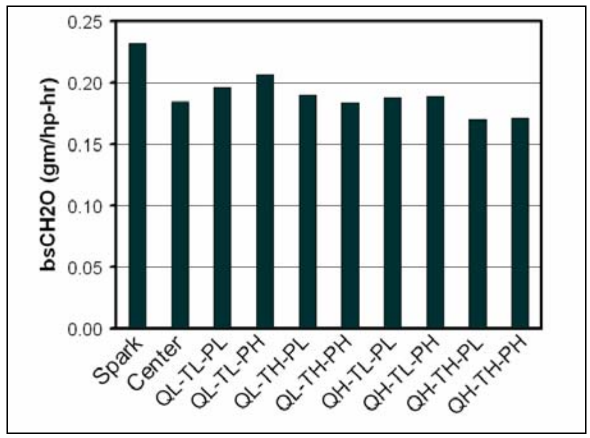


Figure A16-12: Brake Specific Formaldehyde Formation

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

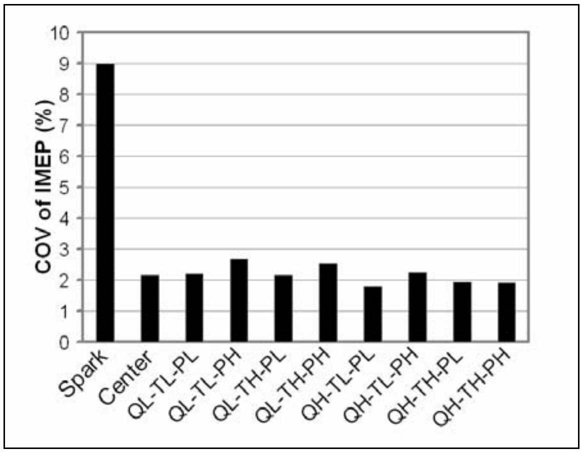


Figure A16-13: Indicated Mean Effective Pressure Coefficient of Variance

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.

CONCLUSIONS

The results were very promising and the potential for an effective retrofit micro-pilot injection system for large-bore, 2-stoke cycle natural gas engines is high. 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.

In future studies we anticipate the quantity of pilot fuel used to be reduced below 11.5 µL (0.72% total energy). As noted above, the nozzle design tested is non-optimal for this application. It was selected for its availability and mass flow range. Post-test inspections show that it impinges both on the head and the piston. Custom nozzles are being designed for the next phase of experimental investigation

TOTAL MODIFIED FUEL COST - Fixed Inputs

Units defined:

$dollars := 1 \quad million := 1000000 \quad BHP := 1 \cdot hp \quad injection := 1 \quad cylinder := 1$

Diesel Properties:

Delivery Cost Penalty: $CP_d := 10$

Lower Heating Value: $LHV_d := 43.2 \cdot 10^6 \frac{J}{kg}$

Density: $\rho_d := 0.82 \frac{kg}{L}$

Price per gal: $DP_{gal} := 1.259 \frac{dollars}{gal}$

Quote from Cox Oil Co. on 500 gallons delivered. 2.21.2003

Diesel Price per million BTU:

$$DP_{BTU} := \frac{DP_{gal}}{LHV_d \cdot \rho_d} \qquad DP_{BTU} = 9.906 \frac{dollars}{million\,BTU}$$

NG Price per million BTU: $NGP_{BTU} := 4.5 \cdot \frac{dollars}{million \cdot BTU}$

DATA POINT: MP4 1 12.19.2002 (MP ignition)

Engine and Natural Gas Data:

$$BHP_1 := 441hp \qquad BSFC := 8070 \cdot \frac{BTU}{BHP \cdot hr} \qquad FC_{NG} := BSFC \cdot BHP_1 \cdot \frac{NGP_{BTU}}{4 \cdot cylinder}$$

$$FC_{NG} = 96.089 \frac{dollars}{day \cdot cylinder}$$

Micro Pilot Data:

$$Q_{MP} := 8.36 \cdot \frac{mm^3}{injection \cdot cylinder} \qquad FC_{MP} := Q_{MP} \cdot DP_{gal} \cdot \frac{300 \cdot injection}{min}$$

$$FC_{MP} = 1.2012 \frac{dollars}{day \cdot cylinder}$$

Total Modified Fuel Cost:

$$FC_{tm} := FC_{NG} + CP_d FC_{MP} \qquad FC_{tm} = 108.101 \frac{dollars}{day \cdot cylinder}$$

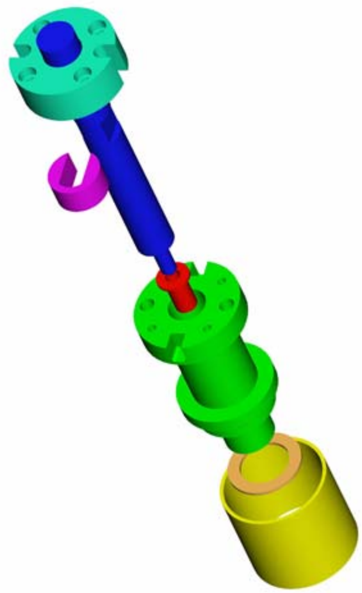
DATA POINT: SP4 1 12.19.2002 (Spark ignition)

Engine and Natural Gas Data:

$BHP_1 := 441hp$ $BSFC := 8147 \cdot \frac{BTU}{BHP \cdot hr}$ $FC_{NG} := BSFC \cdot BHP_1 \cdot \frac{NGP_{BTU}}{4 \cdot cylinder}$

$$FC_{NG} = 97.006 \frac{dollars}{day \cdot cylinder}$$

At these two data points, MP is about $11 dollars more per cylinder per day. This is based on a 10 times cost penalty on the diesel fuel and current industrial diesel fuel prices.



APPENDIX 19

"Procedure for Evaluation of Optimized System in Optical Engine"

Procedure for Evaluation of Optimized System in Optical Engine – Task 19

Evaluating the micropilot system with the optical engine setup would tell us how other engine characteristics affect the 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 would allow 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. Also, a flat cylinder head is used rather than a curved one. The engine motion is at a reduced speed of 3.33 Hz (about 200 rpm) verses 5 Hz (300 rpm). The optical engine is operating at an 11" stroke versus 14" on the GMV.

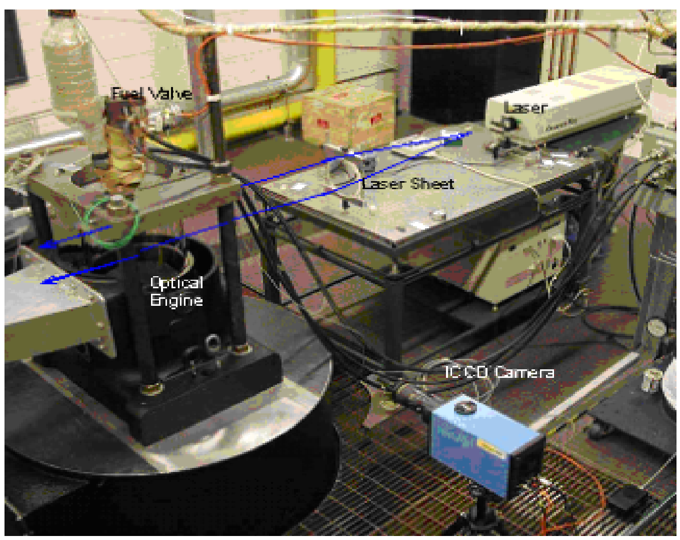


Figure A19-1: Optical Engine Experimental Test Set-up

The optical imaging technique used is Mie scattering, where a 532 nm light sheet from an Nd:YAG (Neodymium Yttrium Aluminum Garnet) laser illuminates, or scatters, off the diesel droplets. The laser will not reflect off of evaporated fuel and so only un-evaporated fuel will show up in the image.

The setup is known as a Galilean telescope arrangement. The pulsed laser shoots through a plano-concave cylindrical lens and then through a convex lens creating a two-dimensional sheet of light that passes through the quartz test cylinder illuminating the fuel droplets. The camera (a 1280x1024 DiCAM-PRO ICCD) is positioned 90 degrees from the laser light sheet to capture the image. A pulse generator orchestrates the experiment timing. It controls the diesel injection, natural gas fuel valve, camera trigger, and both the flash lamp and Q-switch signals for the laser.

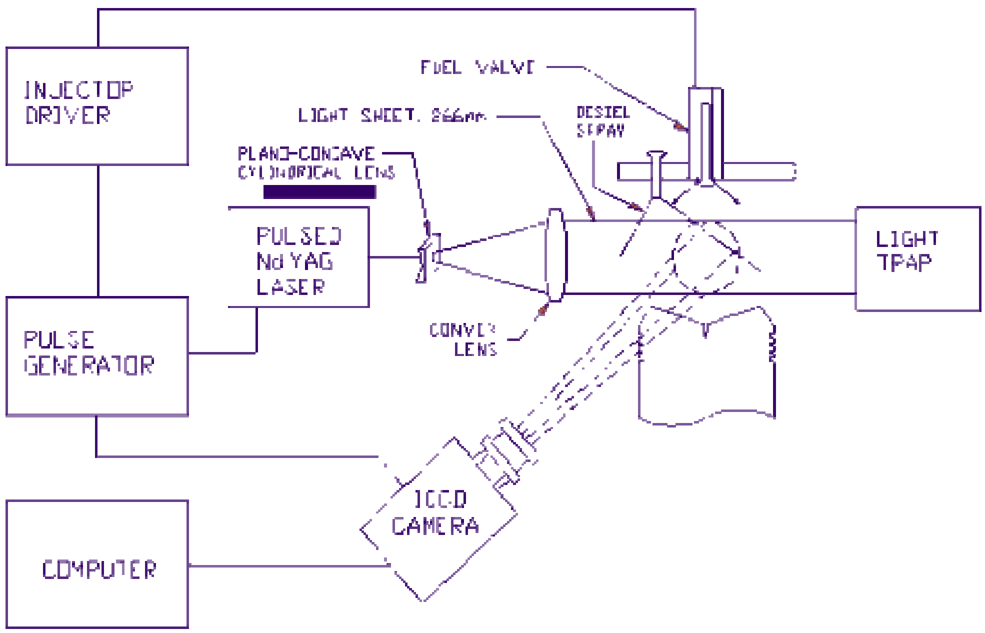


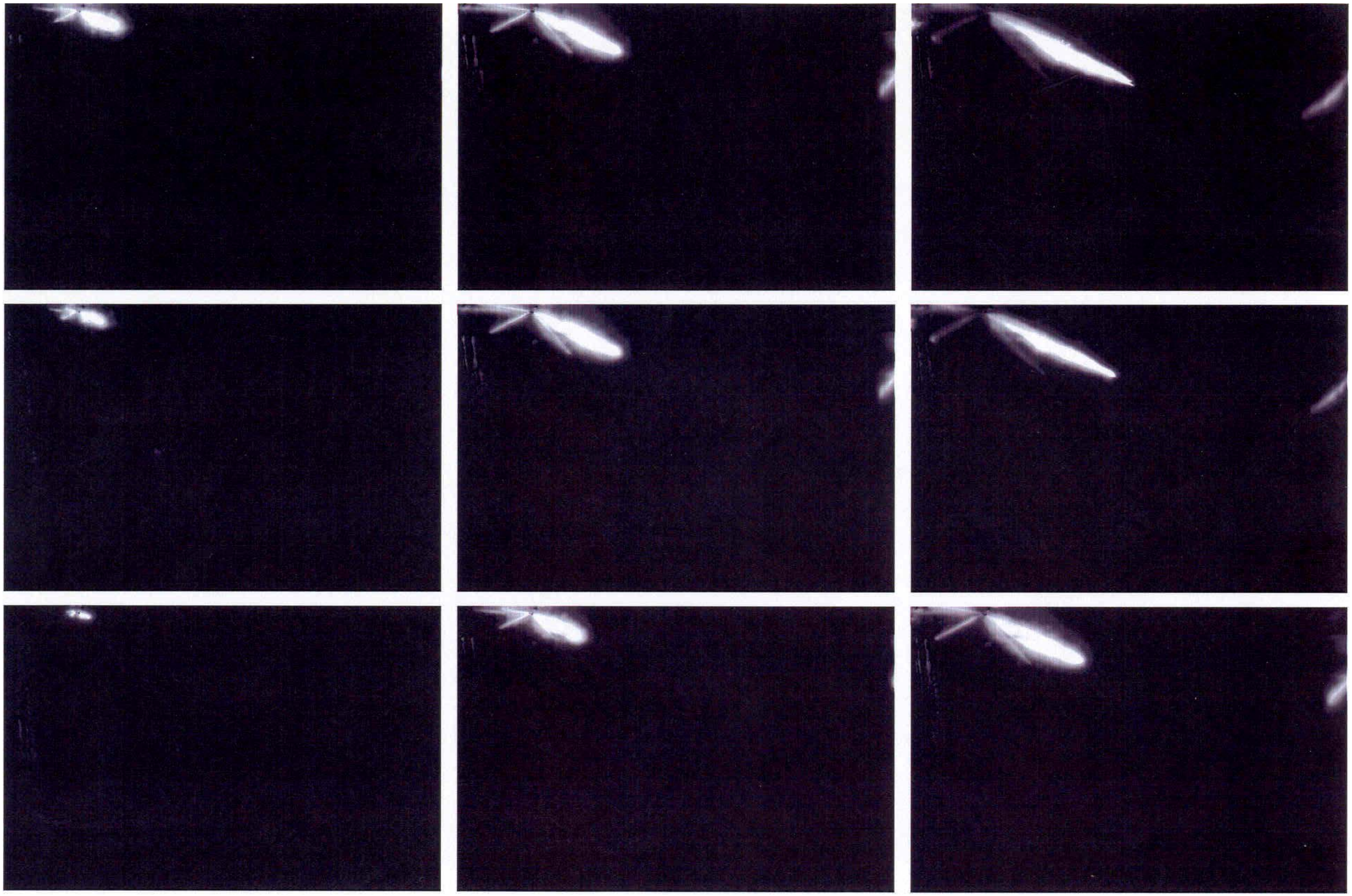
Figure A19-2: PLIF Imaging Technique Schematic.

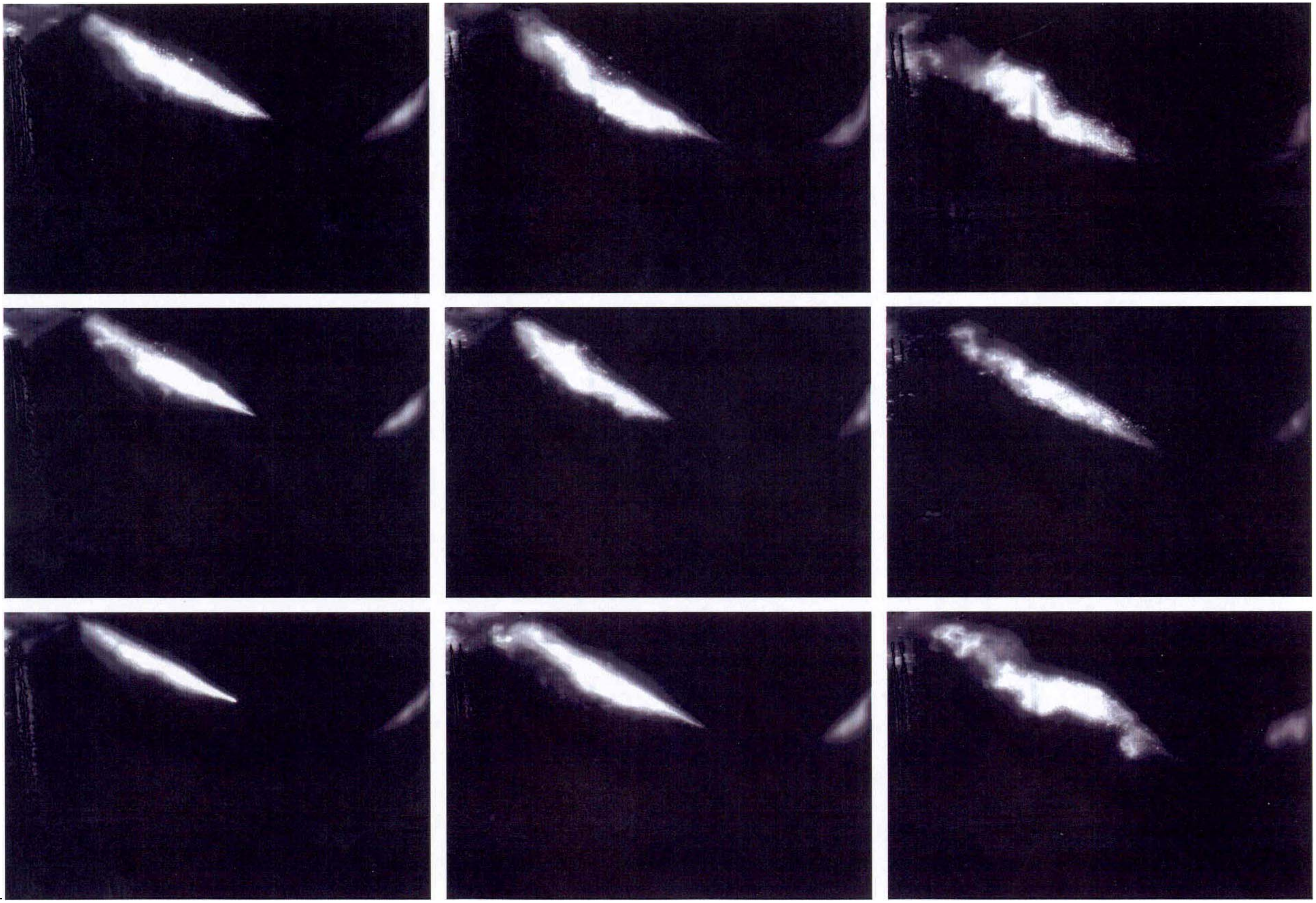
Results from Evaluating the Optimized System in the Optical Engine – Task 19

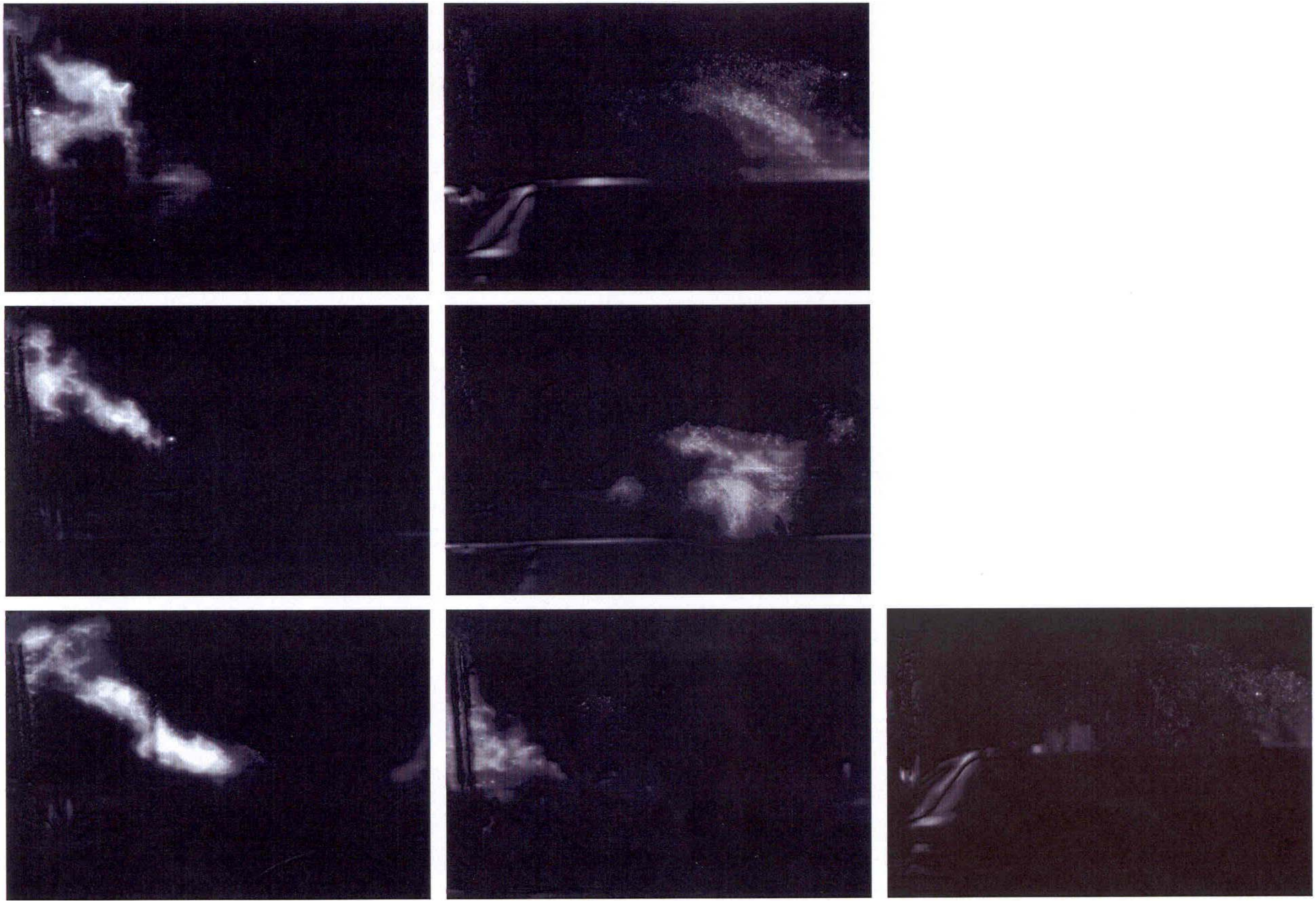
This system was used successfully and a variety of pictures were taken (see attached). Multiple sets were taken at many different times throughout the injection. The images were processed removing reflections from the quartz cylinder, and Teflon residue by subtracting a background picture with an image processing program. Images were then compiled into a movie showing the entire injection in the cylinder. This allowed for an easier analysis of the injection.

Conclusions:

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 diesel 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.







APPENDIX 20

"Optimized System Results & Analysis"

Improvement to Pipeline Compressor Engine Reliability through Retrofit Micro-Pilot Ignition System – PHASE II

Optimized system results & Analysis

Abstract

This report documents the latest optimization testing for the micropilot ignition system performed on the GMV-4 test engine. Recent changes to the prototype system include the installation of newly optimized 3-hole fuel injectors, redesigned to correct the impingement of pilot fuel on the cylinder head and piston, as experienced with the previously tested five-hole injectors. Experimental points were conducted at a rated load and a variety of boost levels ranging from 14.5" to 18.5" of Hg. At each load and boost, a test matrix consisting of three independent parameters was created in order to minimize a "response variable", consisting of total modified fuel consumption and brake specific NO_x emission. The testing procedure was conducted at both a medium and stock compression ratio.

Testing Procedure

Testing was performed on the optimized nozzles to obtain the optimal operating parameters for the micropilot ignition system. In order to quantify the optimization testing, a "response variable" q was created which consisted of both brake specific NO_x emissions and Total Modified Fuel Consumption (TMFC) components. TMFC represents the combined fuel consumption of pilot fuel and natural gas, on an energy basis, with a penalty of 5 on the pilot fuel as shown in Equation 1. The penalty assessed to the pilot fuel accounts for the additional cost of the pilot fuel, along with storage and delivery costs. Values of the brake specific NO_x and TMFC are normalized against reference values obtained during pre-chamber testing at similar engine operating conditions. Equation 2 displays the response variable q to be optimized.

$$\mathrm{TMFC} = \mathrm{BSFC}_{ng} + 5\mathrm{BSFC}_{pilot}$$

Equation 1: Total Modified Fuel Consumption

$$q = \left(\frac{BS\_NO_x}{BS\_NO_{x\_ref}} + \frac{TMFC}{BSFC_{ref}} \right)$$

Equation 2: Test Variable q

At each subsequent boost level, a base three dimensional text matrix was created consisting of the three independent test parameters:

- Pilot fuel delivery pressure
- Pilot fuel quantity
- Pilot injection timing

The base test matrix consists of a center point, along with eight additional points, obtained by varying the three test parameters in positive and negative steps to acquire data at the corners of the test cube. At each data point, the response variable *q* was evaluated along with various operating engine parameters such as air manifold pressures, cylinder exhaust temperatures, etc. Table 1 displays the parameters values of the initial test matrix conducted at 14.5" of Hg and the stock compression ratio of 8.67/8.07:1.

Table A20-1: Initial Test Cube – Stock Compression

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	5000	9	12	1.49
2	5000	13	12	1.49
3	5000	9	20	1.92
4	5000	13	20	1.92
5	6250	11	16	1.49
6	7500	13	20	1.53
7	7500	9	20	1.53
8	7500	13	12	1.2
9	7500	9	12	1.2

Upon completion of the test cube at the various data points, a statistical technique was used to create a linear vector that minimized the response variable. The developed empirical model weights the influence of each independent parameter to the response variable. This linear vector is searched until a local optimum is located. Upon identification of the local optimum an additional test matrix was created and the experiment was repeated. This procedure was repeated until testing converged on the global optimum. The global optimum was determined by evaluating the ratio of the test matrix center point to the overall cube standard deviation. In order to facilitate this technique the center point of the test matrix was evaluated a total of four times. Following completion of the optimization technique, additional values of boost were investigated in a similar fashion. Initial testing was performed at the stock compression ratio of 8.67/8.07:1. Upon completion of the low compression ratio testing, the GMV-4 test engine was modified to a medium compression ratio of 9.48/8.75:1 and the testing procedure was repeated. Optimization testing at the medium compression ratio accessed a penalty of 10 to the diesel fuel along with an additional penalty of 1.5 to the BSFC term within the response variable equation. Table 2 displays a summary of the variables investigated during testing.

Table A20-2: Variables Controlled During Study

Variable	Value	
Compression Ratio	9.48/8.75:1	8.67/8.07:1
Cyl Pressure near Injection	320 psi	275 psi
Trapped Air/Fuel Ratio	24	22.7
Cetane # of Pilot Fuel	42.8	
Injector Nozzle Design	3 hole, symmetric, off axis	
Pilot Timing	Independent	
Pilot Quantity	Independent	
Pilot Rail Pressure	Independent	

Results

-STOCK COMPRESSION RATIO

The calculated values of q for the initial test matrix displayed in Table 1 are shown in Figure 1.

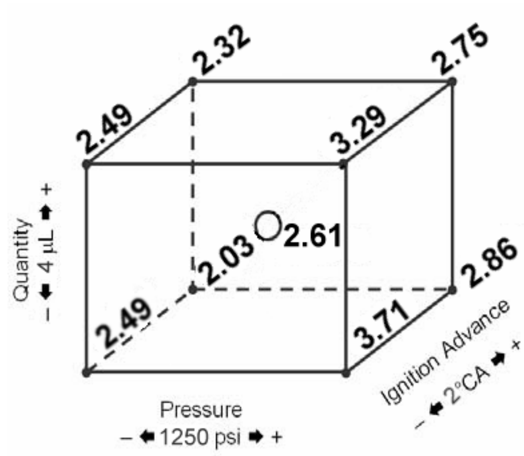


Figure A20-1: q Values for Initial Test Matrix

The resulting empirical model produced an optimizing vector that predicted the direction and step size that pilot pressure, pilot quantity, and timing should be altered to decrease the response variable. The optimizing vector determined that the system favored advanced timing and decreased pilot pressures, while holding pilot quantities nearly constant. This linear vector was tracked until the local optimum of the vector was located. Table 3 displays the values of the independent parameters tested along the optimizing vector.

Table A20-3: Optimizing Vector Test Points

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	6250	11	16	1.49
2	4960	12.26	16	1.49
3	4200	13.02	16	1.95
4	3655	13.52	16	2.08
5	3068	14.16	16	2.31

Calculated values of the response variable corresponding to Table 3 are displayed in Figure 2. The local minimum of the optimization vector was experienced at data point 3 with the following parameters:

- Pilot Pressure - 4200 psi
- Injection Timing -13.02° BTDC
- Injection Quantity – 16 µL

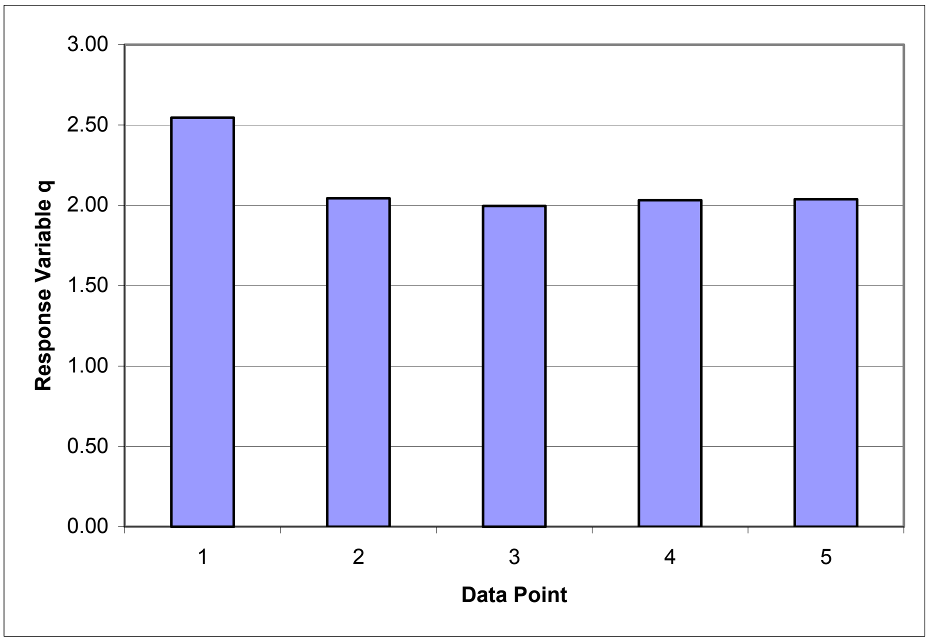


Figure A20-2: Optimizing Vector at 14.5" of Hg

Subsequent to location of the local optimum, a new test cube was created centered at the minimum and the previous experiment was repeated. The new empirical model predicted a minimum in the direction of deceasing pilot pressure, while both pilot quantity and timing no longer had a significant influence on the reduction of the response variable.

Table A20-4: Second Optimizing Vector Test Points

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	4200	13	16	1.95
2	3900	13	16	2.04
3	3600	13	16	2.12
4	3300	13	16	2.2
5	3000	13	16	2.33

Table 4 displays the values of the independent parameters tested along the linear vector. A new optimum of the linear vector was located at Data Point 3 as shown in Figure 3.

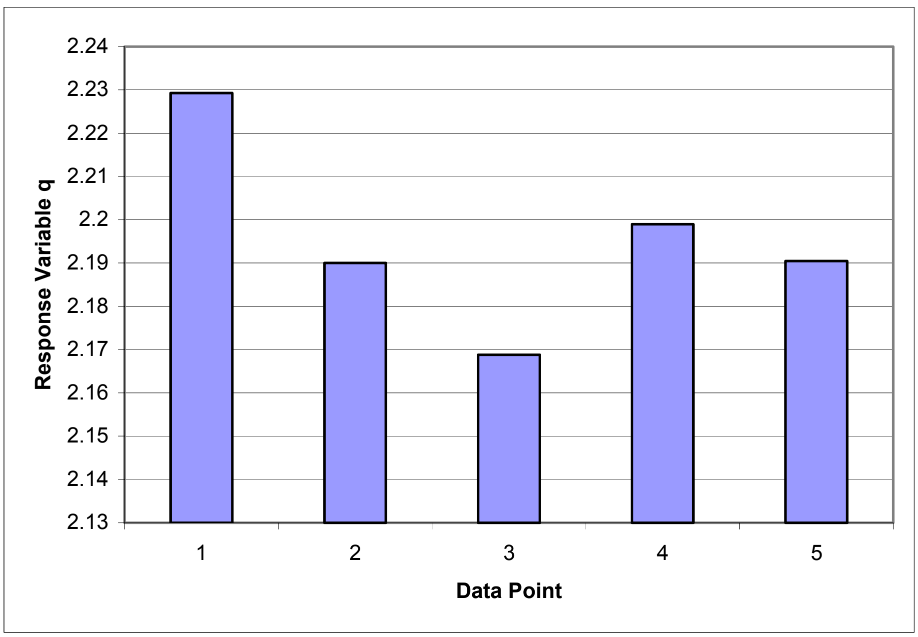


Figure A20-3: Second Optimizing Vector at 14.5" of Hg

In order to determine if a global optimum had been located, the standard deviation of the cube center points were compared with the standard deviation of the overall cube. The center point standard deviation represents inherent "noise" of testing, thus the ratio of the center point to overall cube standard deviation measures the variability within the data. As the standard deviation ratio approaches unity, the variability of the center points will equal that of the cube; therefore, achieving a more accurate optimum location is not possible.

Table A20-5: Standard Deviation of Test Matrices

Test Matrix	Cube Standard Deviation (σ cube)	Center Point Standard Deviation (σ c.p.)	σ c.p. / σ cube
Test Cube 1	0.449	0.137	0.30
Test Cube 2	0.078	0.144	1.85

Upon calculation of the standard deviation ratios, it was determined that a global optimum was located at the following parameters:

- Pilot Pressure - 3600 psi
- Injection Timing -13° BTDC
- Injection Quantity – 16 μL

At the optimized micropilot parameters, the energy contribution of the pilot fuel during the combustion event was .96 %. A sample calculation of the percent energy can be found in Appendix A.

Results of the points collected at 14.5" of boost and stock compression contained a considerable amount of variability. The standard deviations of the first and second matrix center points were 0.137 and 0.144, respectively as shown in Table 5. The first test matrix showed up to an 11.7% difference between the extremes of the four center points collected. Engine parameters such as natural gas composition, air manifold temperature, oil temp, etc. were investigated to quantify the variability of the data. At the current time no source of variability has been located and further investigation is required.

In addition to the previous experiment, values of 16.5" and 18.5" of boost were investigated. Figure 18 through 22 displays various exhaust constituents of the stock compression ratio testing over a range of boost levels compared with the various ignition systems. Additionally, the lean limit of engine operation and the low load, low boost point of the engine at the stock compression ratio was determined. The lean limit of engine operation at the stock compression ratio was determined to be 22.5" of Hg while the low load, low boost point was determined to be 10.07" of Hg and 85% load.

-MEDIUM COMPRESSION RATIO

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 as shown in Figure 4. 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 5. Engineering Drawings of both the modified piston and piston shim are available in Appendix 20B.

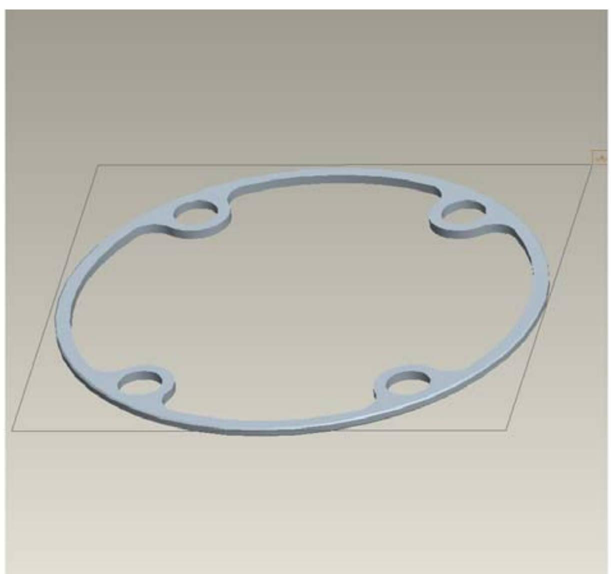


Figure A20-4: Piston Shim

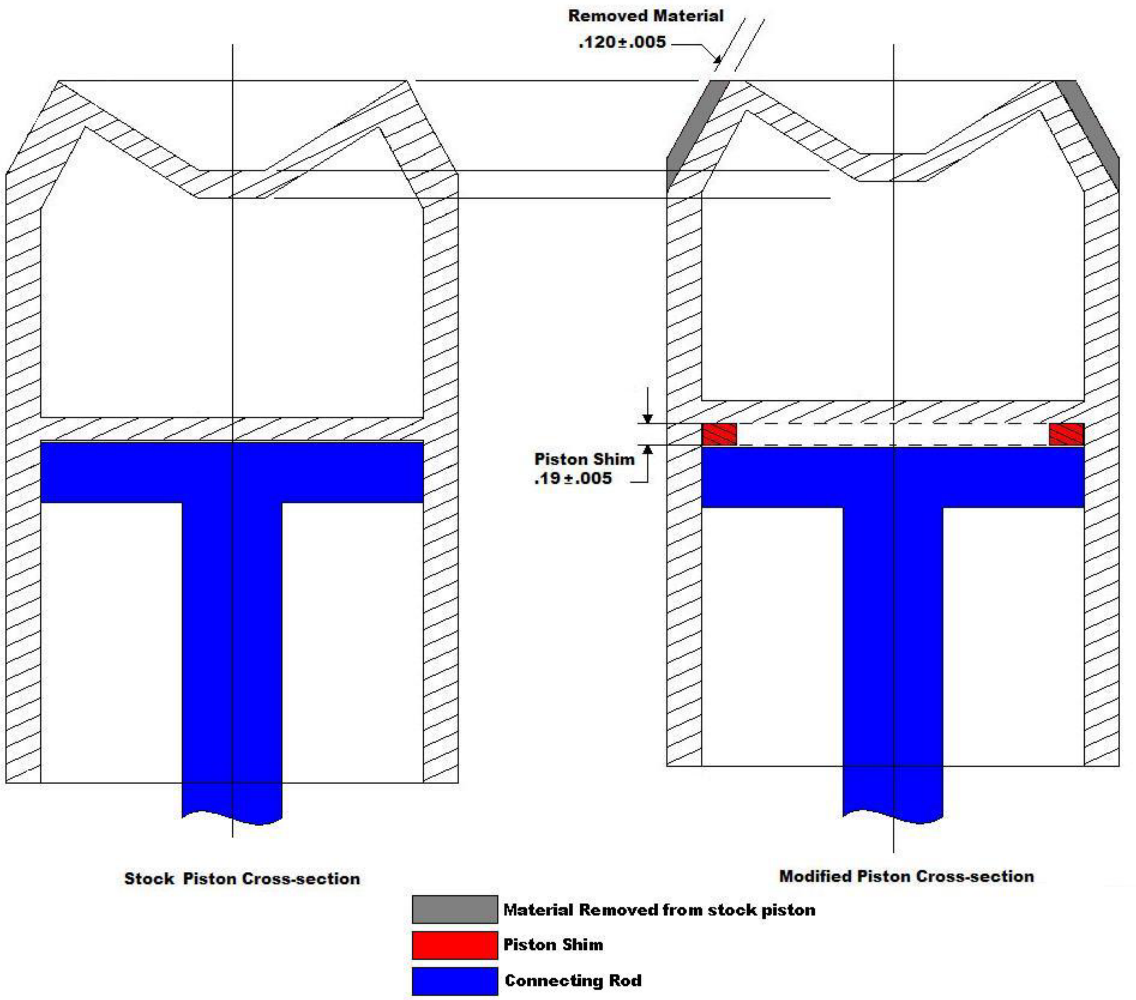


Figure A20-5: Comparison of Stock and Modified Pistons

Several modifications were made to the optimization testing at the medium compression ratio. 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 1.5 to the BSFC term. Modifications were made to the response variable due to previous results skewed toward higher B.S. NO_x and lower TMFC. In addition to the response variable, several modifications were made to the testing procedure used in the stock compression ratio testing. The modified testing procedure is as follows:

- Set Pilot Pressure to Optimum from Stock Compression Ratio Testing

- Set Location of Peak Pressures to 18° ATDC
- Minimize *q* by Adjusting Pilot Quantity

The modified testing procedure greatly increased the speed of optimization testing by holding both timing and pilot pressure constant. Table 6 lists the experimental points tested employing the modified testing procedure at 14.5" of Hg. The calculated values of the response variable are also displayed in Figure 6.

Table A20-6: Optimization Points at 14.5" of Hg

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	4200	11.5	4	1.12
2	4200	11.5	6	1.3
3	4200	11.5	10	1.59

The minimum value of the response variable was found at the second data point with an injection quantity of 6 µL.

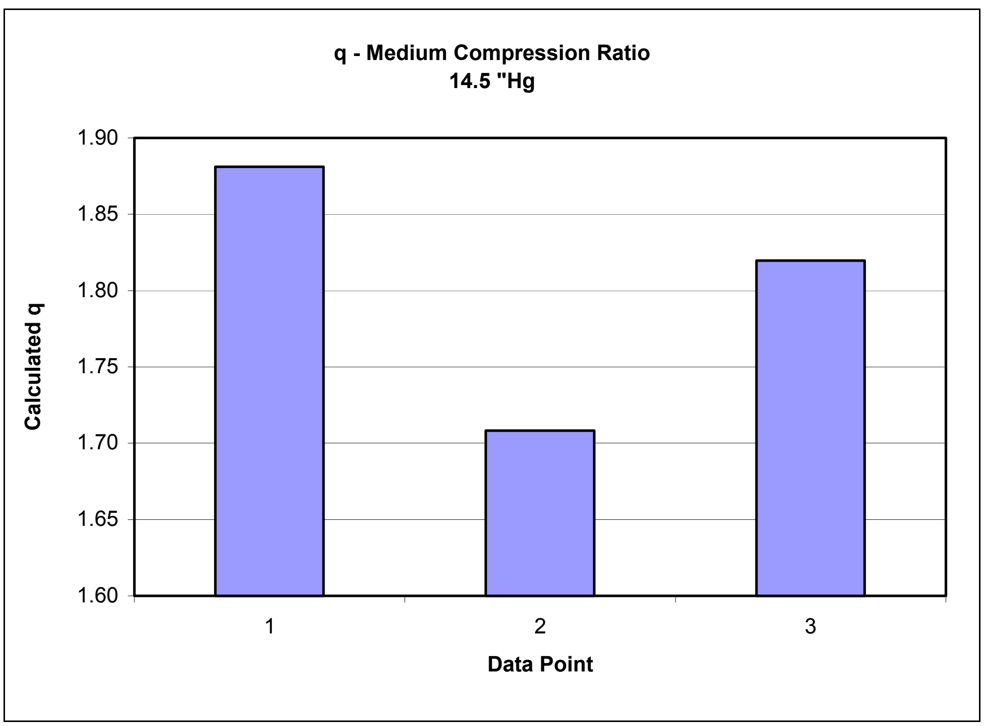


Figure A20-6: Response Variable at 14.5" of Hg and Medium Compression

Similar optimization testing procedures were conducted at both 16.5” and 18.5” of Hg. Table 7 and 8 display the experimental points tested at 16.5” and 18.5” of boost, respectively. Figures 7 and 8 present the calculated response variables at the two boost levels.

Table A20-7: Optimization Points at 16.5" of Hg

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	4200	11	16	1.95
2	4200	11	13	1.78
3	4200	11	10	1.59
4	4200	11	7	1.37

Table A20-8: Optimization Points at 18.5" of Hg

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	4200	9.94	10	1.59
2	4200	9.94	13	1.78
3	4200	9.94	16	1.95

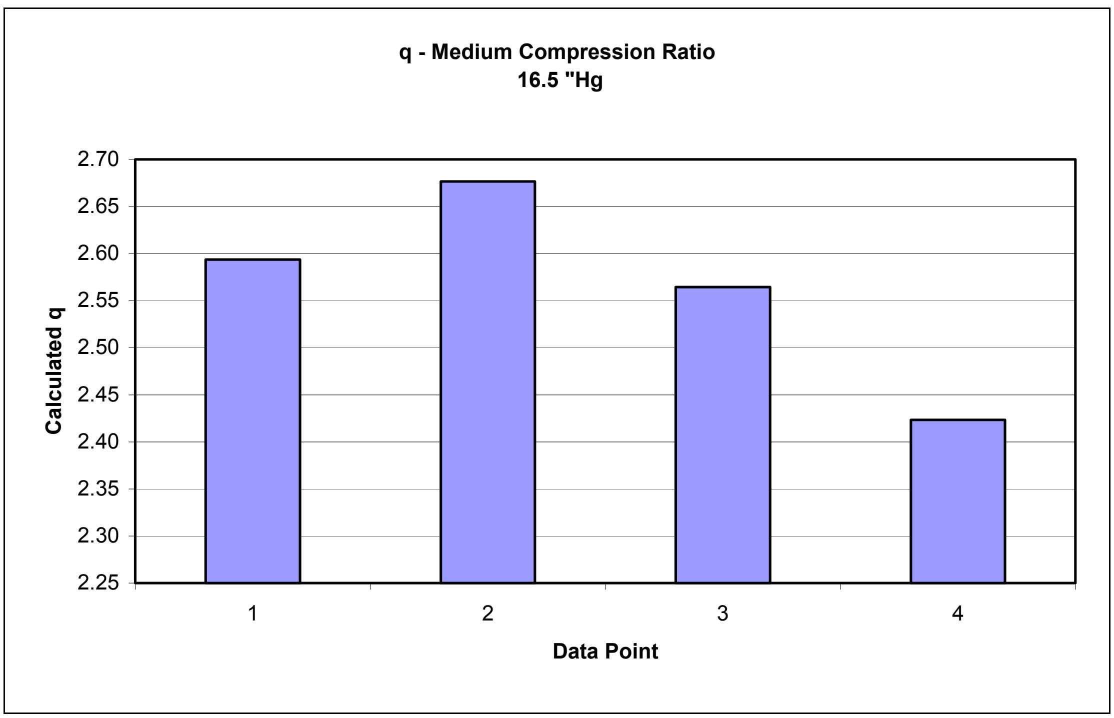


Figure A20-7: Response Variable at 16.5" of Hg and Medium Compression

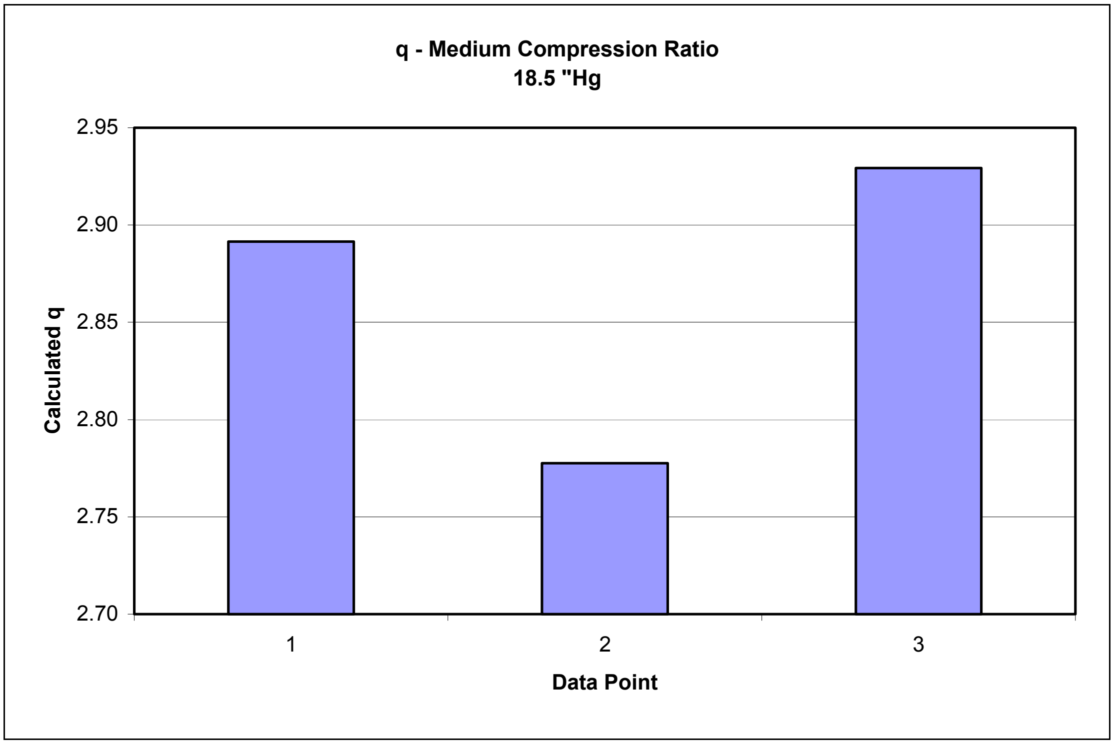


Figure A20-8: Response Variable at 18.5" of Hg and Medium Compression

At 16.5" of Hg, the micropilot injection system experienced a minimum at an injection quantity of 7 μL while the minimum at 18.5" of Hg proved to be an injection quantity of 13 μL. Evaluation of the lean limit of engine operation at the medium compression ratio resulted in a boost level of 23.5" of Hg.

In addition to the modified testing procedure conducted at the medium compression ratio, a standard cube optimization was conducted at 16.5" of Hg employing the testing procedure used at the stock compression ratio. Table 9 displays the base test matrix centered at 4200 psi, 11° BTDC, and 13 μL. Following evaluation of the modified response variable, a linear search vector was created and tracked until an optimum was located. The micropilot parameters investigated along the search vector are displayed in Table 10.

Table A20-9: Test Matrix at Medium Compression and 16.5" of Hg

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	4200	11	13	1.78
2	5400	14	8.5	1.48
3	4200	11	13	1.78
4	5400	8	8.5	1.48
5	5400	8	17.5	2.05
6	3000	8	17.5	2.05
7	3000	14	8.5	1.48
8	3000	14	17.5	2.05
9	4200	11	13	1.78
10	3000	8	8.5	1.48
11	5400	14	17.5	2.05
12	4200	11	13	1.78

Table A20-10: Linear Search Vector at Medium Compression and 16.5” of Hg

Run Order	Rail Pressure (psi)	Injection Timing (deg BTDC)	Injection Quantity (µl/shot)	Injection Duration (deg)
1	3851	11	11.8	1.78
2	3525	11	10.6	1.77
3	3198	11	9.41	1.75
4	3003	11	8.61	1.73

Calculated values of the modified response variable continually decreased along the linear search vector up to Data Point 4. A limit of the micropilot injection system was experience at Data Point 4 due to the inability of the pilot fuel pump to stably maintain the pilot fuel pressure. Values of the calculated response variable are shown in Figure 9.

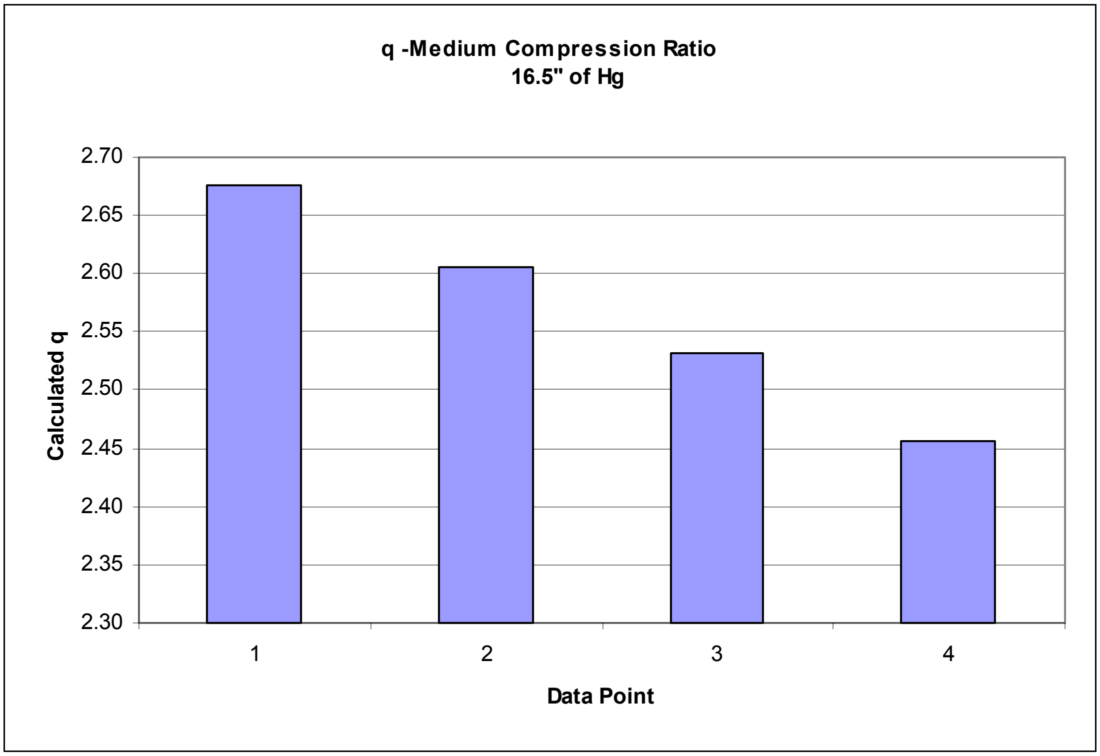


Figure A20-9: Linear Search Vector at Medium Compression and 16.5" of Hg

-INJECTOR EVALUATION AND COMPARISON

Figures 10 through 16 compare the optimized 3-hole injectors to the previously tested 5-hole injectors by various exhaust constituents and engine parameters. The newly optimized three hole injectors considerably improved combustion stability while also increasing the boost range of engine operation. The optimized 3-hole nozzles displayed considerably higher TMFC and BSFC than the previously tested five hole injectors. In addition, NO_x emissions during 3-hole testing were lower than that of the 5-hole injector testing. Previously conducted 5-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.

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 15 and 16) 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 dynamometer problems were experienced near the end of testing. The problems experienced with the dynamometer created difficulty maintaining calibration and upon inspection it was determined that the bearings were worn out. These problems with the dynamometer could very well have resulted in a lower actual load than reported causing an increase in brake specific fuel consumption. In general the engine is more efficient (efficiency$\propto$BSFC^{-1}) at higher loads. 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). The SAE 30 analysis results can be found in Appendix 20C.

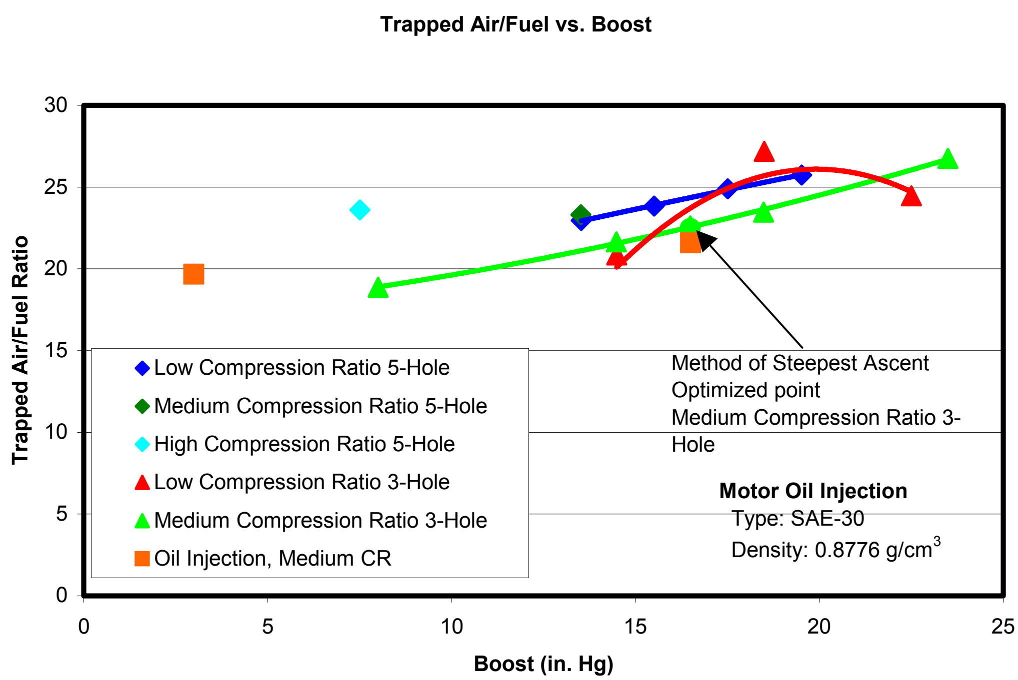


Figure A20-10: Air Fuel Ratio vs. Boost

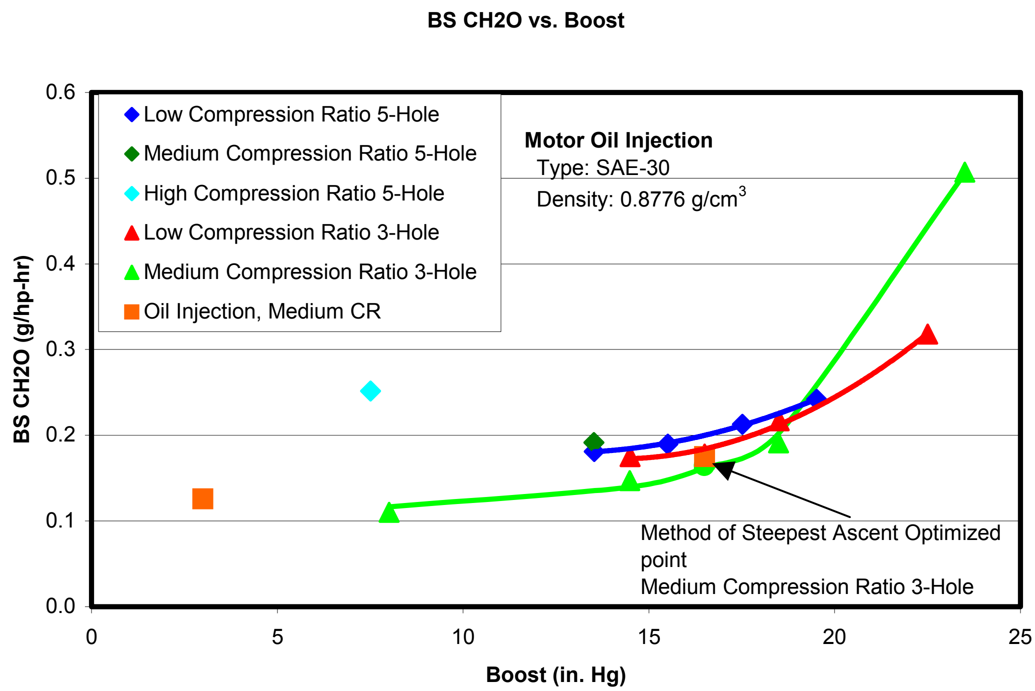


Figure A20-11: B.S. CH20 vs. Boost

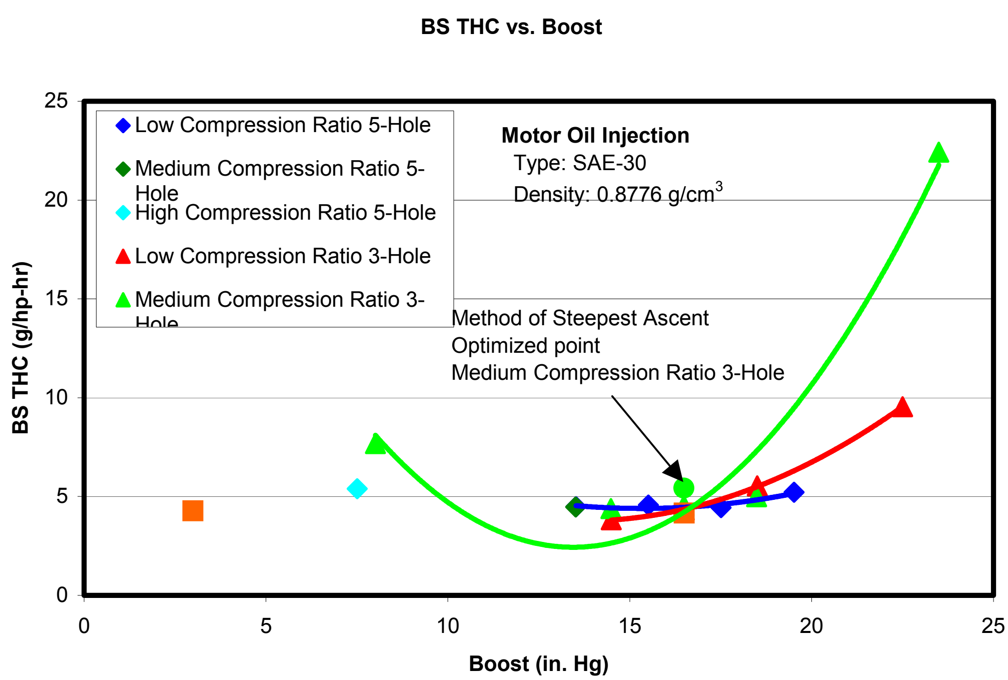


Figure A20-12: B.S. THC vs. Boost

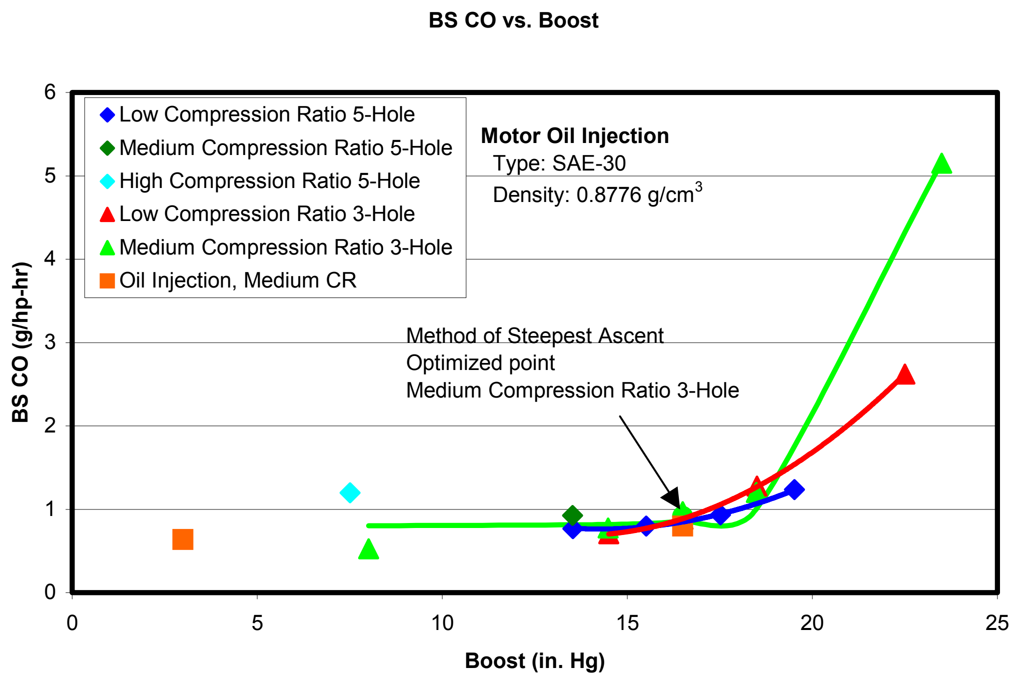


Figure A20-13: B.S. CO vs. Boost

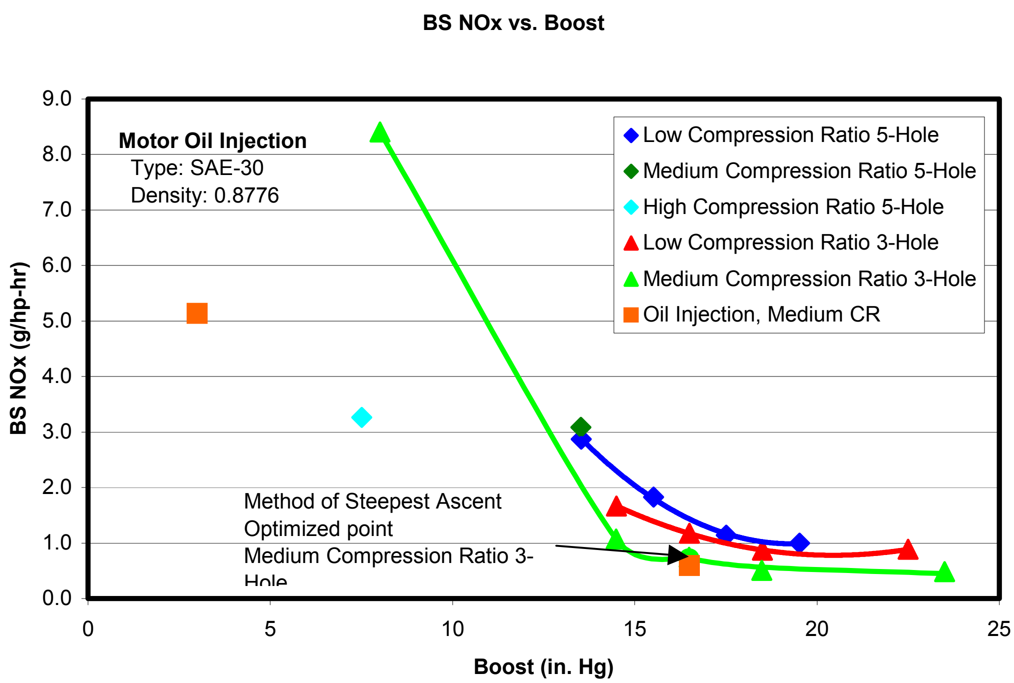


Figure A20-14: B.S. NO_x vs. Boost

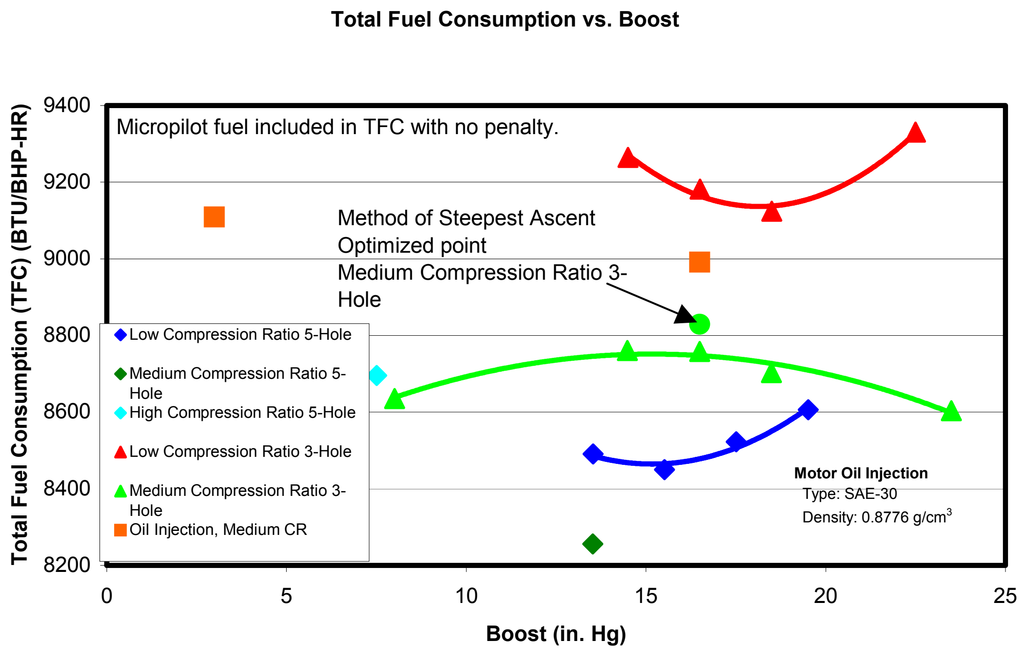


Figure A20-15: Total Fuel Consumption vs. Boost

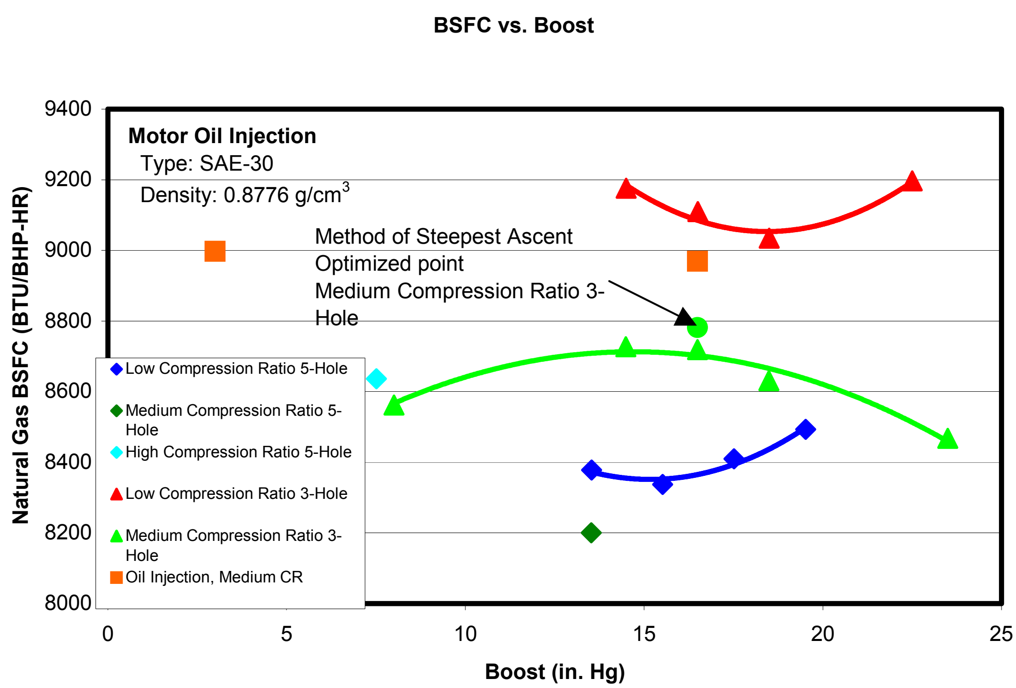


Figure A20-16: BSFC vs. Boost

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 5-hole injectors. Figure 17 displays the cylinder 1 modified piston oriented at the pilot fuel injector location.

Figure A20-17: Cylinder 1 Modified Piston - Pilot Fuel Injector

Table A20-11: Injector Comparison

Description	Minimum Boost Engine Could Run At (Corresponding Quantity)	Minimum Quantity Engine Could Run At (Corresponding Boost)	Ignition Temperature (Corresponding Engine Condition)
5-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 11 displays the minimum boost and injection quantities of the 3 and 5-hole injectors at various compression ratios. The optimized 3-hole injectors allowed for lower pilot fuel injection quantities than the previously tested 5-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 micropilot parameters, duration and pressure.

-Ignition System Comparisons

Figures 18 through 21 displays various emissions constituents over a range of boost compared to various ignition systems. Figure 21 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 micropilot data in the following figures were taken from stock compression ratio testing.

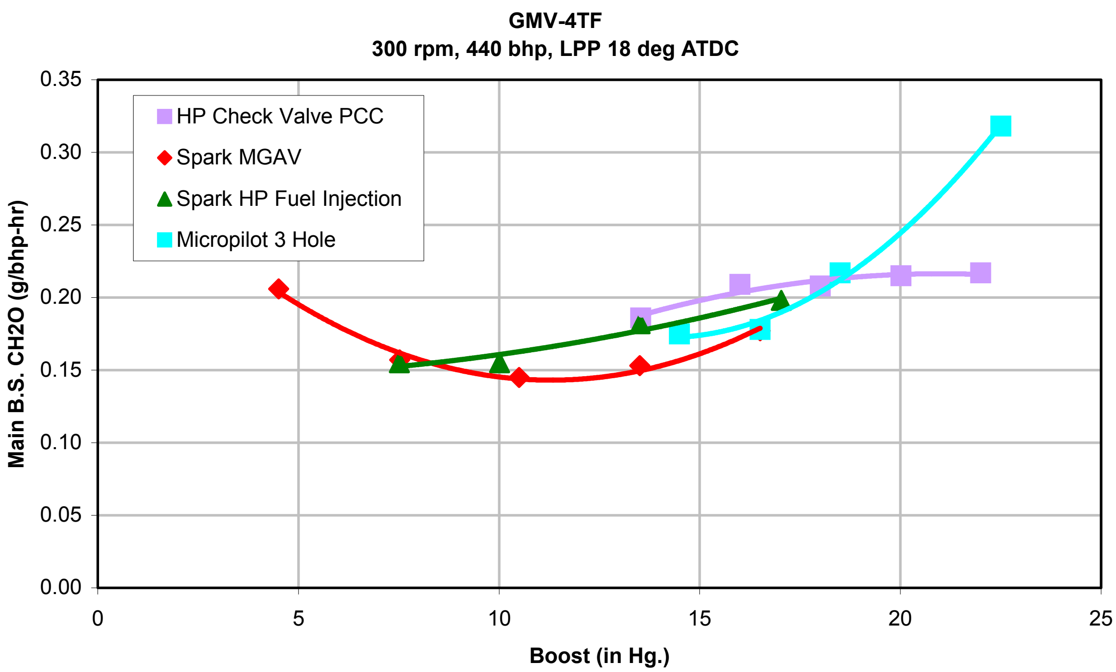


Figure A20-18: Main B.S. CH_20 vs. Boost

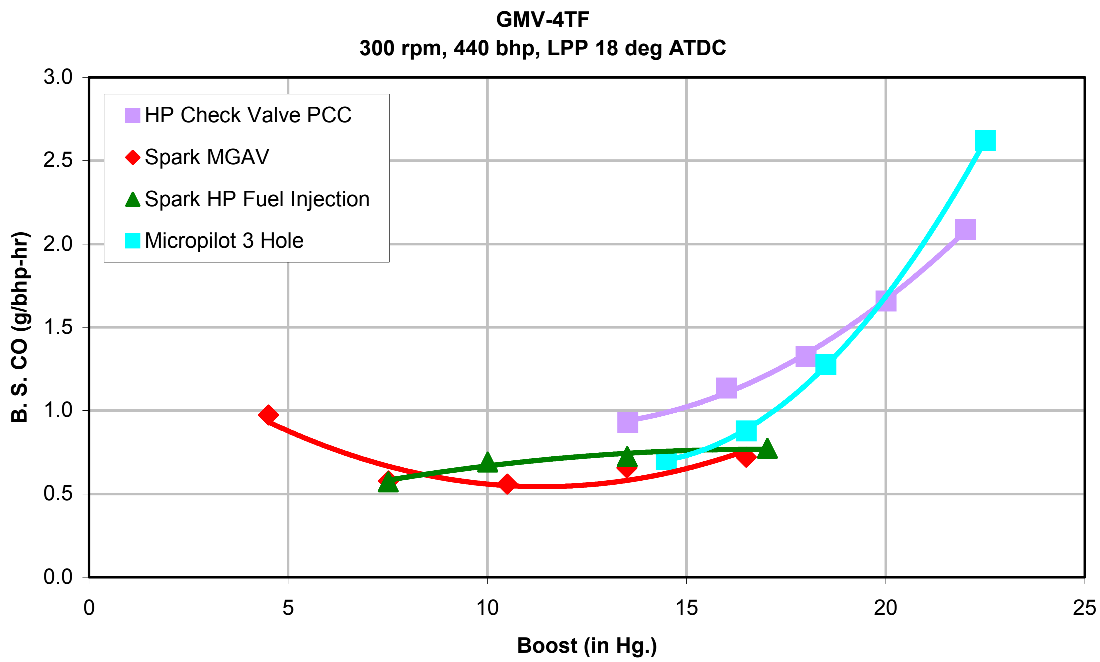


Figure A20-19: B.S. CO vs. Boost

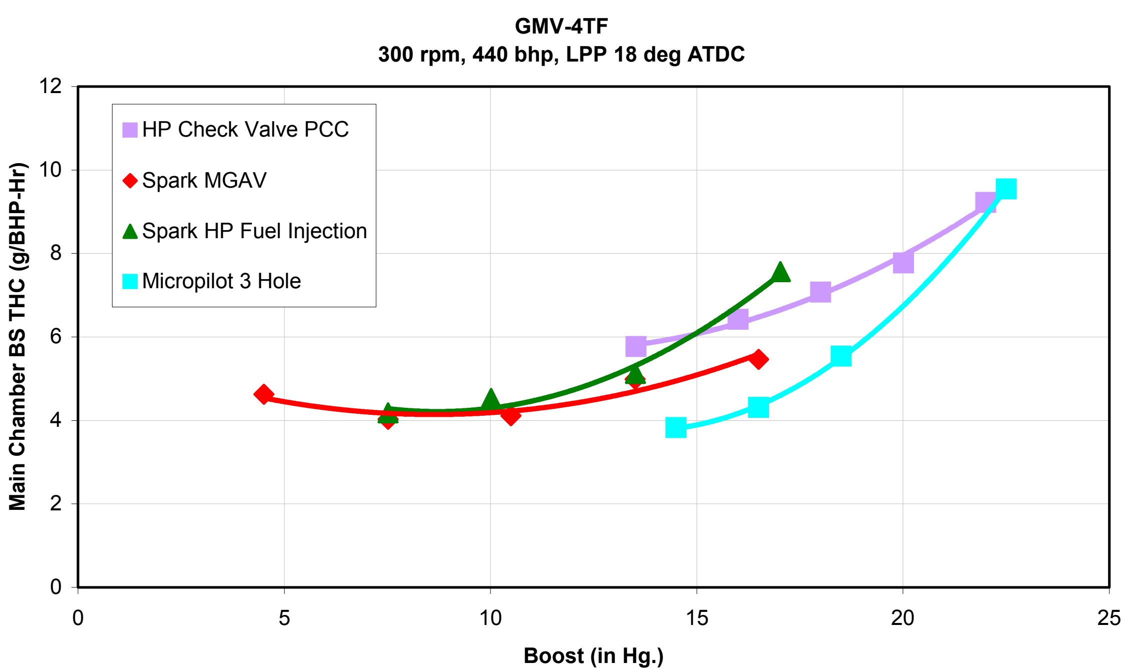


Figure A20-20: BS THC vs. Boost

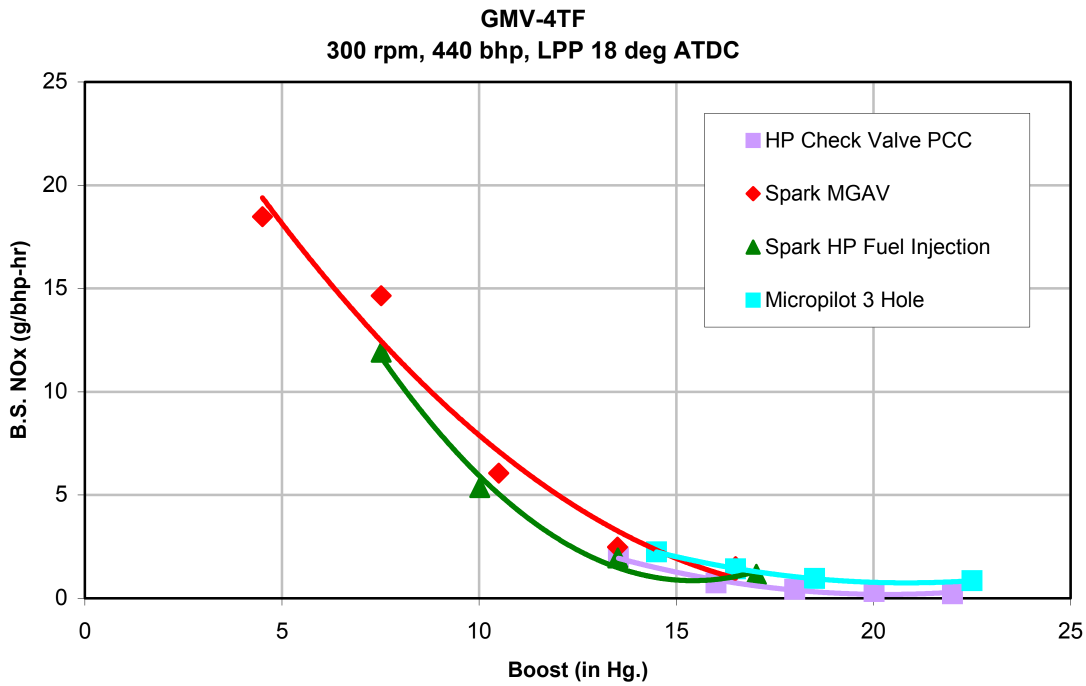


Figure A20-21: B.S. NOx vs. Boost

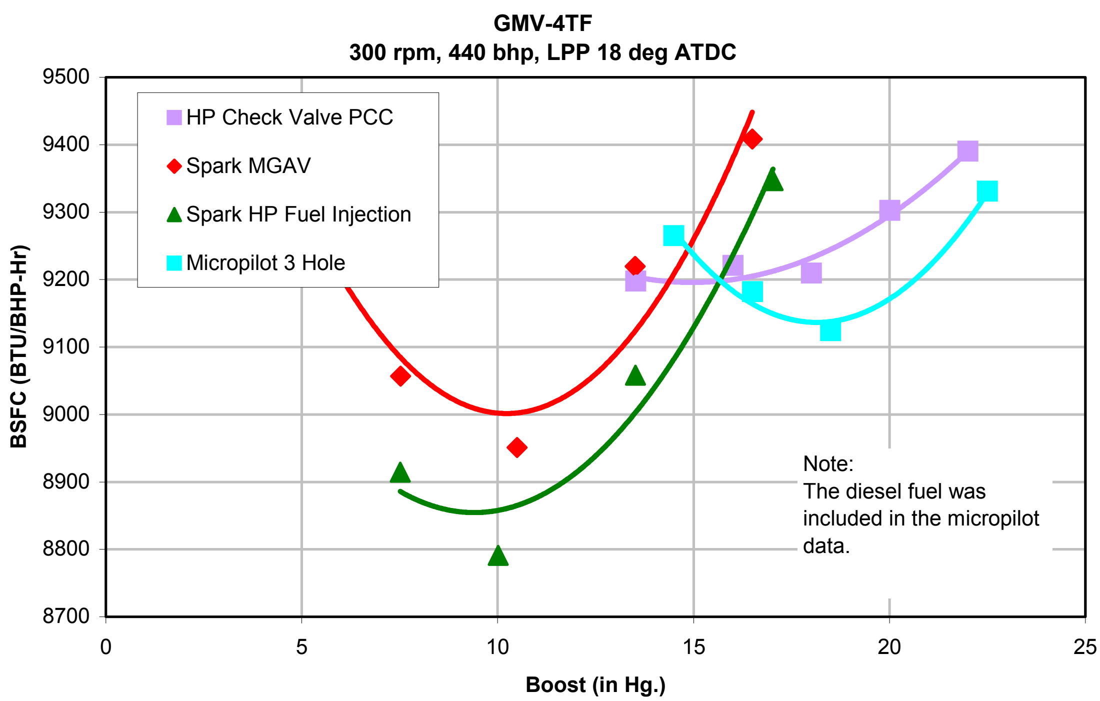


Figure A20-22: BSFC vs. Boost

Conclusions

The following conclusions were drawn following the completion of the optimized 3-hole micropilot 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 5-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
- Micropilot ignition compares very favorably to other ignitions systems. The performance of micropilot ignition 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.

APPENDIX 20.A

"Percentage Pilot Fuel Energy Calculation"

$BHp := 441 hp$ $\mu L := 1 \cdot 10^{-6} \cdot L$ $rev := 1$

$BSFC := 9176 \frac{BTU}{hp \cdot hr}$

$V_{mp} := 16 \cdot \mu L$

$RPM := 300 \cdot \frac{rev}{min}$

$\rho_{diesel} := .82 \cdot \frac{kg}{L}$

$LHV_{diesel} := 43.2 \cdot 10^6 \frac{J}{kg}$

Energy of Natural Gas per Cylinder per combustion event

$NG_{energy} := BSFC \cdot BHp \cdot \frac{1}{RPM} \cdot \frac{1}{4}$

Energy of Pilot fuel per cylinder per combustion event

$m_{mp} := \rho_{diesel} \cdot V_{mp}$

$mp_{energy} := m_{mp} \cdot LHV_{diesel}$

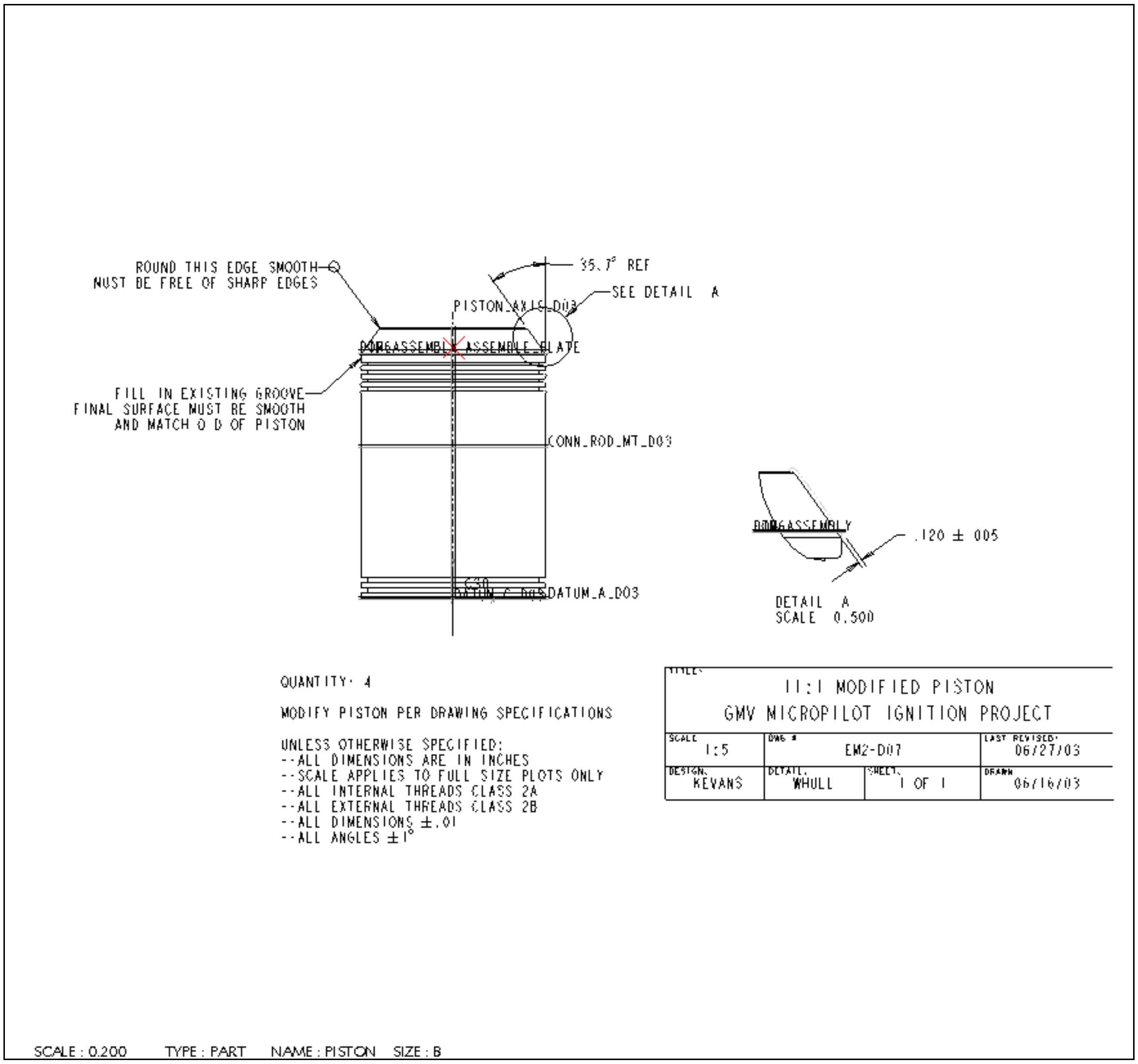
Percent of Total Fuel Energy from Pilot fuel per cylinder per combustion event

$\% := \frac{mp_{energy}}{NG_{energy}} \cdot 100$ $\% = 0.955834$

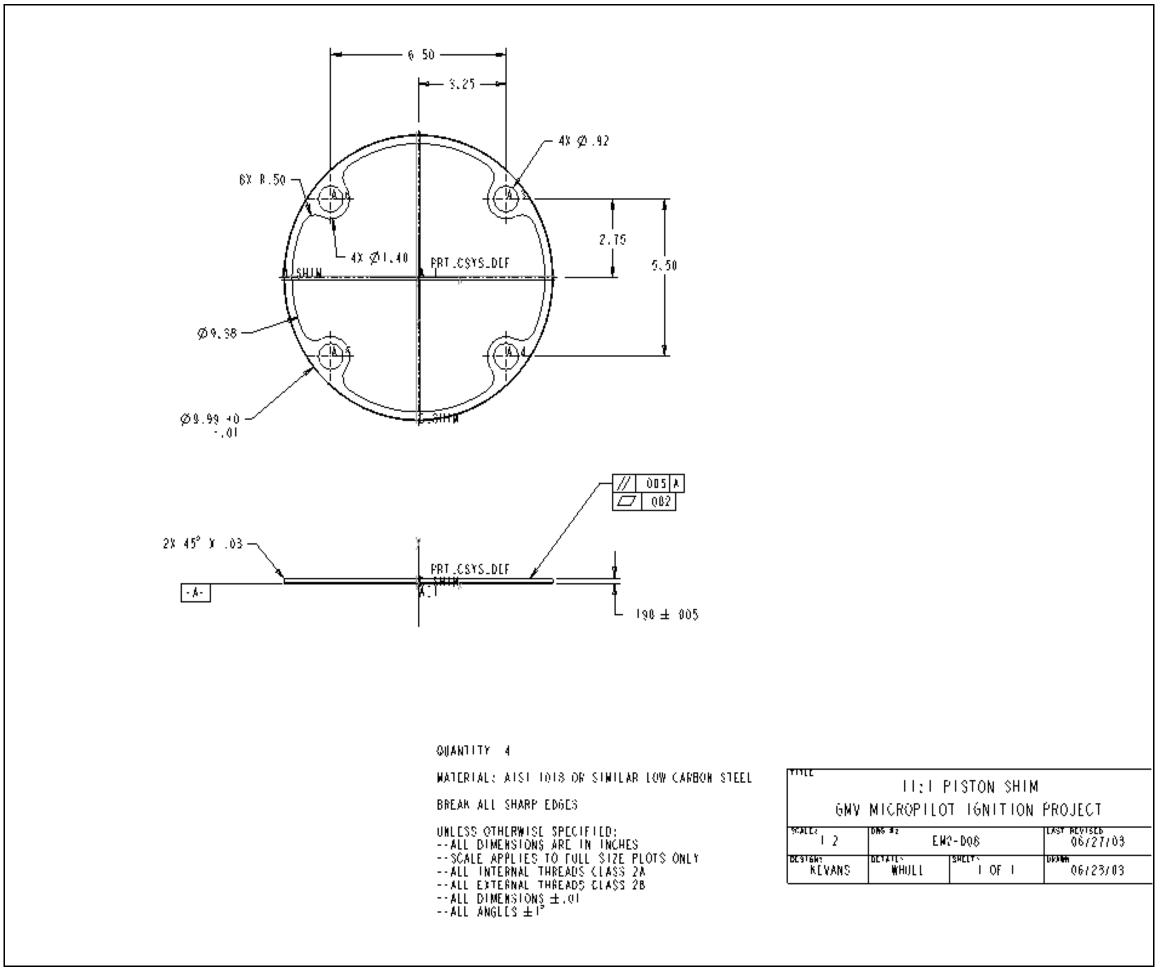
APPENDIX 20.B

"Modified Piston Drawings"

PISTON MODIFICATION



PISTON SHIM


6.50
3.25
4X Ø .92
6X R.50
2.75
5.50
4X Ø1.40
PRT_CSYS_DEF
SHIM
Ø9.38
Ø9.99 +0 -.01
.005 A
.002
2X 45° X .03
-A-
.198 ± .005
QUANTITY 4
MATERIAL: AISI 1018 OR SIMILAR LOW CARBON STEEL
BREAK ALL SHARP EDGES
UNLESS OTHERWISE SPECIFIED:
--ALL DIMENSIONS ARE IN INCHES
--SCALE APPLIES TO FULL SIZE PLOTS ONLY
--ALL INTERNAL THREADS CLASS 2A
--ALL EXTERNAL THREADS CLASS 2B
--ALL DIMENSIONS ±.01
--ALL ANGLES ±1°
TITLE
11:1 PISTON SHIM
GMV MICROPILOT IGNITION PROJECT
SCALE: 1:2
DWG #: EM2-D08
LAST REVISED 06/27/03
DESIGN: KEVANS
DETAIL: WHULL
SHEET: 1 OF 1
DRAWN 06/23/03

APPENDIX 20.C

"SAE 30 Analysis"

Herguth Laboratories, Inc.

Certificate of Analysis

Lab Number 722904

Tori Rupp
Colorado State Univ, Dept of Mech Eng.
Engines & Energy Conversion Labs
Fort Collins CO 80523-1374

04/16/04

Page 1

P.O. Number : PD CC# Client Code : COLOTR Sample Date : 04/11/04

Oil Code : GN_031 SAE 30

Description : Geotex LA SAE 30

Test Performed	Proc-Rev	Result
Calorific Value, ASTM D240	0240-1.6	19661 BTU/lb
Sulfur, X-Ray Fluorescence, ASTM D4294	4294-2.6	0.2688 % Wt

Respectfully Submitted,
Herguth Laboratories, Inc.

D E Kelley

Dennis E. Kelley, Lab Manager

cc: Tori Rupp

These results are submitted pursuant to our current Terms, Conditions and Limitations and Laboratory Pricing Policy.
No responsibility or liability is assumed for the manner in which these results are used or interpreted.

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