ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

RADIO FREQUENCY ELECTROSTATIC IGNITION SYSTEM FEASIBILITY DEMONSTRATION

EISG AWARDEE

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Abstract

The purpose of this project was to demonstrate the feasibility of a radio frequency electrostatic ignition system (RFEIS) to improve efficiency and reduce emissions in a natural gas fueled, internal combustion engine.

Tests were conducted in a combustion test chamber igniting various ratios of propane and air and in a natural gas, single cylinder engine, with both lean air-fuel ratio and exhaust gas recirculation (EGR).

The RFEIS initiated a multi-zone flame front; the standard ignition initiated a single zone. In combustion test chamber tests, the RFEIS extended the lean limit by 30% (using propane), and at $\Phi=0.8$, reduced the ignition delay by 45% and pressure rise time by 60%.

In tests of the single cylinder engine with lean air-fuel ratio, the RFEIS ran a total of 40 hours at up to 13.8 Bar (200 psi) Brake Mean Effective Pressure (BMEP) and extended the lean misfire limit by 8%. At $\Phi=0.60$ and equivalent brake thermal efficiency (BTE), the RFEIS decreased NOx emissions by 20%
(0.5 gm/kW-hr). At $\Phi=0.62$, the RFEIS decreased the initial (0-10%) cumulative heat release time by 17%, the 10-50% time by 8%, and the 50-90% time by 4%.

In tests of the single cylinder engine with EGR, the RFEIS extended EGR misfire limit by 28%. At 0.75 gm/kW-hr NOx, the RFEIS improved indicated BTE by 7.2% (2 BTE points). At EGR rates above 22%, the RFEIS reduced turbine inlet temperature by 25ºC. At 22% EGR, the RFEIS decreased initial (0-10%) cumulative heat release time by 13%, the 10-50% time by 6%, and the 50-90% time by 1%.

Keywords: ignition, combustion, electrostatic, radio frequency, NOx, natural gas, industrial engines

Executive Summary

1. Introduction

In recent years, industry and government have been working together to develop the next generation of high efficiency, low emissions, natural gas fueled, industrial, reciprocating engines for power generation.

The Department of Energy and the Commission have both targeted 50% efficiency and 0.1 gm/BHP-hr NOx by 2010 [1, 2]. The engine manufacturers have determined that these goals cannot be met with current ignition system technology. They have jointly developed a specification for the next generation ignition system [3], which will support meeting the engine cost, efficiency and emissions goals.

The Radio Frequency Electrostatic Ignition System (RFEIS) is a new, patented technology, which is designed to meet or exceed this specification.

This project, funded through Energy Innovations Small Grant 02-23, has been an important means of demonstrating the feasibility of using the RFEIS to improve the efficiency and reduce the emissions in a natural gas fueled, internal combustion engine.

2. Project Objectives

This project had seven objectives:

- Design and machine a piston.
- Design and optimize RFEIS electrostatic discharge and combustion characteristics using finite element modeling and combustion bomb testing.
- Demonstrate at least 12 hours of durability of the RFEIS in a hot firing test engine.
- Demonstrate between 0.1 to 0.5 gm/BHP-hr NOx emissions with RFEIS in a single cylinder engine.
- Demonstrate stable engine operation at 90% of the lean limit (40 to 1 air-fuel ratio).
- Test a standard ignition system in a single cylinder engine and compare with RFEIS.
- Verify that the data generated from this research support the ignition system's projected capital cost of $8/kWe and life cycle cost of $.25/MWe-hr.

3. Project Outcomes

This project had nine outcomes:

- Designed RFEIS.
- Designed and optimized RFEIS electrostatic discharge and combustion characteristics using finite element modeling.
- Verified and further optimized RFEIS electrostatic discharge and combustion characteristics through combustion test chamber testing.
- Demonstrated 15 hours durability in a hot firing test engine.
- Measured NOx emissions of 0.72 gm/BHP-hr (at an equivalence of 0.6 in a single cylinder engine with lean air-fuel ratio), and of 0.51 gm/BHP-hr (in a single cylinder engine with cooled exhaust gas recirculation (EGR) and stoichiometric air-fuel ratio, at 29.4% EGR).
- Demonstrated stable engine operation at 90% of the lean limit.
- Tested a standard ignition system in a single cylinder engine with a lean air-fuel ratio to compare with RFEIS.

- Tested a standard ignition system in a single cylinder engine with EGR to compare with RFEIS.
- Verified that data generated from this research support the ignition system's projected capital cost of $8/kWe and life cycle cost of $.25/MWe-hr.

4. Conclusions

Conclusions are presented for tests conducted in the combustion test chamber, in a single cylinder engine with lean air-fuel ratio, and in a single cylinder engine with EGR.

Combustion Test Chamber

- RFEIS initiated a multi-zone flame front while the standard ignition initiated a single zone.
- RFEIS extended the lean limit by 30% (propane). [Note to Editor: Reason for propane is explained later.]
- At $\Phi = 0.8$, RFEIS reduced the ignition delay by 45% and reduced the rise time by 60%.

Single Cylinder Engine with Lean Air-Fuel Ratio Test Results

- RFEIS ran a total of 40 hours at up to 13.8 bar (200 psi) BMEP.
- RFEIS extended the lean misfire limit by 8% compared with the standard ignition.
- At $\Phi = 0.60$ and equivalent BTE, RFEIS decreased NOx emissions by 0.5 gm/kW-hr (0.37 gm/BHP-hr), or 20%.
- At $\Phi = 0.62$, RFEIS decreased the initial (0-10%) cumulative heat release time by 17%, the 10-50% time by 8%, and the 50-90% time by 4%.
- The fast initial burn rate with RFEIS was offset by a relatively slow end of burn. This indicates that in-cylinder turbulence is still required to speed up the end of the burn to further extend the lean misfire limit.
- The amount of corona energy per discharge and the electrode configuration significantly affected the heat release rate.

Single Cylinder Engine with EGR Test Results

- RFEIS extended the EGR misfire limit by 28% compared with the standard ignition.
- At 0.75 gm/kW-hr NOx (0.56 gm/BHP-hr), the RFEIS improved the indicated BTE by 7.2% (2 BTE points) over the standard ignition.
- At EGR rates above 22%, RFEIS reduced the turbine inlet temperature by 25 deg C.
- At 22% EGR, RFEIS decreased the initial (0-10%) cumulative heat release time by 13%, the 10-50% time by 6%. The 50-90% time was 1% slower compared with the standard ignition.

The RFEIS-produced corona discharge has demonstrated the ability to ignite leaner, more dilute mixtures with greater consistency. The high voltage, low current characteristics of corona discharge should all but eliminate electrode erosion. In addition, because there is no electrode gap to maintain as in a spark plug, the life of the RFEIS ignitor should be orders of magnitude greater. This low maintenance will help the RFEIS to meet the life cycle cost goals of engine manufacturers.

5. Recommendations

The RFEIS shows promise, but much work remains to be done. We make the following recommendations:

- Conduct an analysis of fluid dynamics to determine optimum chamber geometry, corona discharge shape and intake port swirl.
- Test the developed system on a single cylinder test engine with sufficient data to demonstrate the NOx emissions goal.
- Run a series of knock limit tests. The RFEIS multi-zone flame front should significantly improve knock limited BMEP.
- Demonstrate durability of a natural gas engine in a field test.

6. Public Benefits to California

Based on results obtained to date, there is reason to believe that RFEIS may be the technology that will allow reciprocating gas engines to meet California's electrical generation needs and the goals of engine manufacturers for 50% efficiency and NOx levels of no more than 0.1 gm/BHP-hr by 2010.

Reduced NOx emissions is one very real benefit the RFEIS offers to the state of California. In terms of distributed generation and based on data from the Commission/EPRI [7], none of the reciprocating engines can meet the Air Resources Board's (ARB) 2007 NOx emissions standard of 0.07 lb/MW-hr (0.024 gm/BHP-hr). However, an engine with the RFEIS, operating stoichiometric with EGR, and with a three-way catalyst is able to meet this standard, which translates into NOx emissions' reduction of 85%. At present, the ARB has not set such a low emissions level for any but the South Coast Air Quality District, but if this standard is expanded to other districts, further and widespread NOx emissions' reduction can be realized.

In terms of truck engines, the 2007 emissions levels are almost impossible to achieve with current diesel technology. The gasoline fueled, cooled EGR technology with RFEIS will reduce NOx emissions from the current 2gm/BHP-hr for diesels to as low as the 0.015 gm/BHP-hr demonstrated in the ARICE program, at the same horsepower level as the current diesel.

Initial cost savings is another important benefit. RFEIS allows a 25% uprate over a standard ignition because of the extended knock limit with EGR, an advantage that will significantly reduce the initial cost of engines in both the industrial and transportation sectors.

RADIO FREQUENCY ELECTROSTATIC IGNITION SYSTEM FEASIBILITY DEMONSTRATION

FINAL REPORT

Introduction

Over the past few years, there has been industry and government interest in developing high efficiency, low emissions, natural gas fueled, industrial engines for power generation. The Department of Energy and California Energy Commission both have programs in place to fund industry, national labs, and universities to support the development and commercialization of a new class of reciprocating natural gas engines. They have targeted fuel-to-electricity efficiency at over 50% and NOx emissions as low as 0.01 gm/BHP-hr [1, 2]. To meet theses goals, a new type of ignition system is needed. The industry has jointly developed a specification for the next generation ignition system [3], which will meet the engine cost, efficiency and emissions goals by reliably igniting leaner (for lean combustion) or more dilute (for cooled exhaust gas recirculation (EGR) combustion) mixtures at higher pressures and power levels with lower life cycle cost. Only then will these performance goals be attainable.

Ignition systems for spark ignited, high brake mean effective pressure (BMEP), low emissions engines have historically been a problem from a performance and reliability standpoint. Low emissions, high BMEP engines usually have high compression ratios and operate with high turbocharger boost levels, both of which help to produce high cylinder pressures at the point of ignition. This high cylinder pressure and a lean/dilute mixture require higher voltage from the ignition system to initiate combustion. The high voltage demand required to initiate ionization at the spark plug gap puts additional stress on the secondary system, which delivers the coil voltage to the spark plug. High voltages are difficult to contain in the secondary system, and often, the secondary dielectric strength is not sufficient to deliver the energy to the spark plug gap. This problem requires that small electrode spark gaps be used to reduce the voltage demand.

Unfortunately, small spark gaps often do not deliver sufficient ignition energy to a lean air-fuel mix in the cylinder to consistently initiate a flame kernel, the beginning of combustion. Thus, the lean/dilute mixture ignitability limit is insufficient to meet emissions and efficiency goals.

Precombustion chambers are often used to enhance the ignition energy to light off leaner/more dilute main chamber mixtures to reduce emissions and extend the knock limited BMEP. The prechamber is usually filled with fuel to maintain a nearly stoichiometric mixture at the point of ignition. The burning prechamber charge then escapes the prechamber through orifices into the main chamber and ignites the lean/dilute main chamber. This system allows very lean/dilute main chamber mixtures to consistently ignite, due to the added ignition energy. The lean/dilute mixture cools the combustion, which lowers emissions and extends the knock limited BMEP. However, these performance gains put added stress on the spark plug. Raising the BMEP of the engine (to improve engine efficiency and power density) increases the compression pressure and thermal loading on the spark plug. These factors reduce the useful life of the spark plug because as the electrodes erode, the secondary voltage increases until the dielectric strength of the secondary is exceeded and the spark plug quits firing.

Inductive ignition systems and capacitive discharge systems are the two main types of ignition systems used today. From the literature, it is unclear which offers better performance. Inductive ignition systems store energy in the ignition coil and deliver longer duration sparks at lower peak power than capacitive discharge systems. The duration of the inductive system is usually from

1 to 2 milliseconds and it delivers a total spark energy of around 50 to 100 millijoules (mj). Capacitive discharge systems store energy in a capacitor and deliver shorter duration sparks at higher peak power levels. The spark duration of capacitive discharge systems is around 0.5 milliseconds and delivers a spark energy of around 50 mj. Capacitive discharge systems are most commonly used on industrial natural gas engines. These systems have been available for about twenty years and have served the market well, but combined with the spark plugs, their performance and durability is becoming the weak link in industrial natural gas engines. Spark plugs are particularly a problem with today's ignition systems. Other than electrode materials, their design is relatively unchanged since they were invented in the 1860s [4]. The plugs and secondary system have a very difficult time containing the high voltage, and as the spark plug gap wears, the voltage required to fire increases until the electrical insulation system fails, and the engine misfires.

Alternative Ignition Systems

Research has been conducted for many years to develop an alternative ignition system that could consistently and reliably ignite lean mixtures at high pressures and temperatures. It is estimated that the goals of the Advanced Reciprocating Engine Systems (ARES) and Advanced Reciprocating Internal Combustion Engine (ARICE) programs – to achieve 50% brake thermal efficiency (BTE) at less than 0.1 gm/BHP-hr NOx emissions – will require a rating of at least 300 psi BMEP. To meet this goal, the engine must consistently ignite a mixture with an excess air ratio of approximately 2.5 and withstand peak firing pressure of nearly 3300 psi. It is clear that current ignition technology will not be sufficient to support this goal. The industry [3] has targeted an initial cost of approximately $4.00/kWe, life cycle cost of $0.25/MWe-hr and a repair cost of $0.15/MWe-hr (see Appendix 1, page 2). Current ignition systems cost between $3.00 and 5.00 per kWe; their life cycle cost is between $0.80 and $1.50 per MWe-hr.

Over the years, a number of alternative ignition technologies have been developed. All spark discharge technologies (plasma gun, plasma rail, "thunderplug," etc.) rely on high energy, high power electrical discharge to ionize the mixture and initiate combustion. Heat is the primary source of energy for ionization. Unfortunately, high energy and power put much higher thermal loading on the discharge electrodes and erosion becomes a problem. Short-term demonstrations show promise but long-term reliability is the weak link.

Laser ignition has been tried numerous times but commercial acceptance is limited by the cost and complexity of a laser. Also, the laser must fire into the combustion chamber through a window, which is subjected to high temperature and pressure as well as reduced transmissivity over time due to dirt buildup. Also, the ignition volume is still relatively small. Work continues on laser ignition but its commercial viability has not been proven.

Open chamber micropilot and prechamber micropilot combustion systems use a small amount of diesel or engine oil to light off the main chamber filled with a lean/dilute natural gas mixture. This system is similar to the spark ignited prechamber system discussed earlier, but replaces the spark plug with a small diesel injection system. The open chamber system injects a small quantity of liquid fuel directly into the main chamber while the prechamber system injects fuel into the prechamber. These systems are more expensive than conventional ignition systems and require two fuels to operate the engine. They have only been commercially introduced on large bore, slow speed engines to date. Research continues on the smaller bore, higher speed engines.

Ignition Fundamentals

Classical combustion theory states that when the fuel and oxidant reach a sufficient energy level, intermediate unstable radicals are formed by stripping electrons from the molecules. These radicals participate in intermediate reactions. Finally, the overall reaction progresses to completion (if the heat released by combustion is greater than the heat loss): the heat of combustion is released and the combustion products are formed. The key issue for ignition is to supply enough energy to the fuel and air mixture to initiate the formation of the radicals in sufficient concentration for the forward reaction (combustion) to proceed to completion.

The fundamental problem with standard ignition systems is that they use heat to initiate combustion. When heat is used, heat losses greatly affect the ignition process. The intense heat is produced by the high current and relatively low voltage generated across the spark plug gap after the gas in the plug gap is initially ionized. This high temperature plasma erodes the spark plug electrodes. It is also difficult to distribute this ignition energy across the combustion chamber to initiate multiple flame fronts and speed combustion. Multiple spark plugs per cylinder have been tried, but cost and complexity have prohibited their adoption.

Radio Frequency Electrostatic Ignition System (RFEIS)

Heat is not the only way to strip electrons from the fuel and oxidizer molecules to form radicals. An alternating, high voltage, low current (electrostatic) field can be used to ionize gases, as it has been used in other applications, particularly in the chemical vapor deposition industry.

The use of a radio frequency electrostatic field is key to the RFEIS ignition concept. The generated electrostatic field creates a high flux density of energetic electrons. These electrons strip off the electrons from the fuel and oxidizer and form highly unstable radicals. These radicals then form intermediate reactions, which proceed through exothermic reactions and complete the ignition process. A relatively large amount of ionizing energy (up to an order of magnitude greater than conventional ignition systems) can be delivered to the combustion chamber. This greater energy initiates multiple flame fronts because of its large ionized volume, and since the ionizing energy is non-thermal, electrode erosion is all but eliminated.

Figure 1 shows a diagram of the RFEIS ignitor. The secondary coil and its inductance, the secondary coil capacitance and the capacitance to ground formed in the combustion chamber form a tuned circuit.

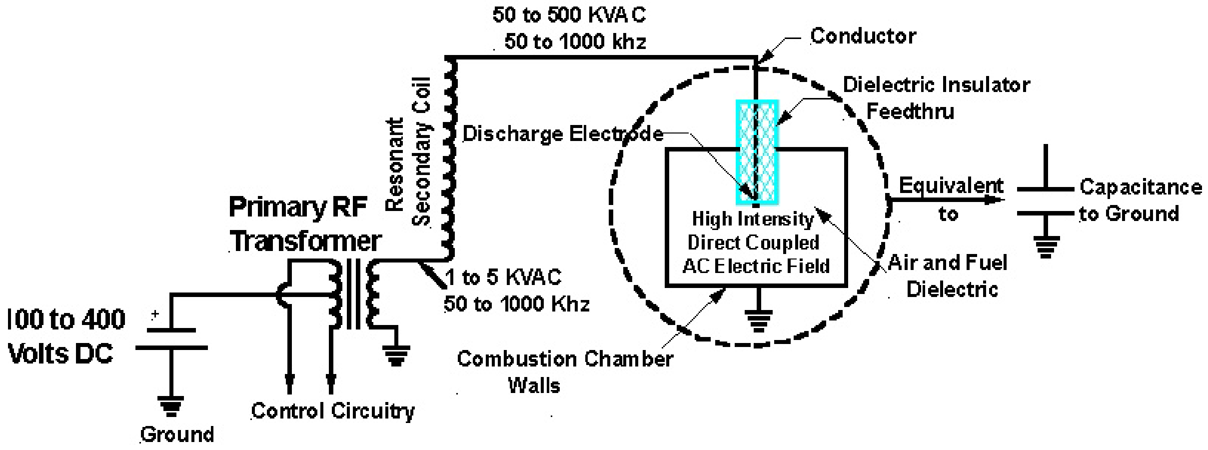

Figure 1. Electrical Schematic of RFEIS Ignitor

The values of the capacitance and inductance are selected such that the tuned circuit resonates at a frequency between 50 and 2000 kHz. When the tuned circuit is excited by the primary coil (a radio frequency step-up transformer) at its resonant frequency, a large radio frequency AC voltage potential is created across the combustion chamber "discharge capacitor." Since the current through the discharge capacitor is a function of the capacitance times the derivative of voltage with respect to time, it can be shown that at resonance, extremely high currents flow alternately between the two plates of the discharge capacitor, with the only losses being associated with DC resistance. The current flow through the capacitor is a function of the number of electrons flowing between the two plates. The energy of the electrons is a function of the voltage potential between the plates. This alternating high voltage forms a radio frequency AC electric field. The area between the two plates of the discharge capacitor is the combustion chamber. As described above, this highly energetic electric field initially ionizes and then ignites the mixture.

Prior to this grant award, the RFEIS had been tested in a combustion bomb igniting propane and air mixtures. The data obtained show that at atmospheric temperature and pressure, the RFEIS system almost doubled the lean limit as compared with a conventional capacitive discharge/ standard spark plug ignition system typically used in industrial natural gas engines. This dramatic extension of the lean limit over the conventional ignition system substantiated the merits of the RFEIS and led to the next stage in development of this ignition system. This report describes that stage – to test the RFEIS in a single cylinder engine where the combustion characteristics and engine performance benefits could be quantified. This report also identifies and discusses ignition system durability issues.

The work described in this report was conducted under the PIER subject area Environmentally Preferred Advanced Generation. The goal of this project was to demonstrate the feasibility of using a Radio Frequency Electrostatic Ignition System (RFEIS) to improve the efficiency and reduce the emissions in a natural gas fueled, internal combustion engine.

Following the introduction, this report presents specific objectives, the approach taken and outcomes that occurred within the scope of this project. It offers conclusions, based on factual findings, recommendations for follow-on efforts, and a discussion of the RFEIS's public benefits to California.

Project Objectives

This project had seven objectives:

- Design and machine a piston.
- Design and optimize RFEIS electrostatic discharge and combustion characteristics using finite element modeling and combustion bomb testing.
- Demonstrate at least 12 hours of durability of the RFEIS in a hot firing test engine.
- Demonstrate between 0.1 to 0.5 gm/BHP-hr NOx emissions with RFEIS in a single cylinder engine.
- Demonstrate stable engine operation at 90% of the lean limit (40 to 1 air-fuel ratio)
- Test a standard ignition system in a single cylinder engine and compare with RFEIS.
- Verify that the data generated from this research support the ignition system's projected capital cost of $8/kWe and life cycle cost of $.25/MWe-hr.

Project Approach

The approach undertaken to complete this project was divided into five tasks.

Task 1 included two subtasks: first, to design a piston, and second, to obtain the piston blank and machine the piston bowl.

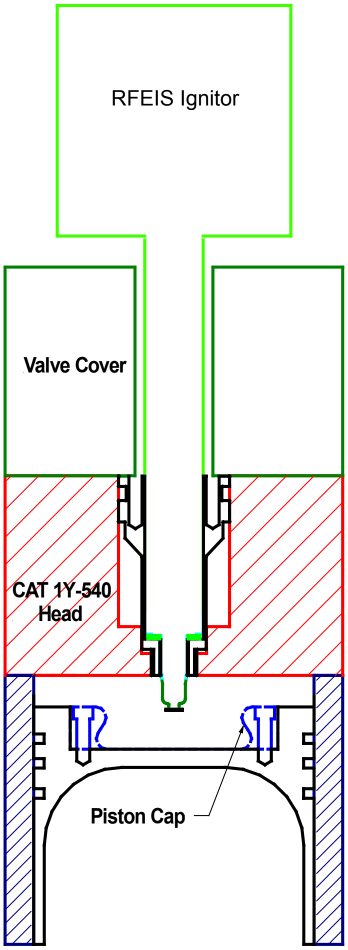

Figure 2. Side View of RFEIS installed in CAT 1Y540

Figure 2 shows a schematic of the RFEIS ignitor installed in the Caterpillar 1Y540 engine. The RFEIS ignitor is physically similar to a conventional ignition system's coil, extension and spark plug, except it is one assembly, not separate components. In this configuration, the ignitor end, which screws into the head, is a standard 14mm spark plug thread.

The combustion chamber was modified to optimize the flame propagation as well as electric field/electrostatic discharge characteristics. The piston and its bowl shape, key components which define the combustion chamber in most four valve industrial engines, were designed to optimize both the discharge and flame front propagation to improve combustion efficiency by increasing lean limit, reducing unburned hydrocarbon emissions and increasing combustion rate.

Figure 2 shows a drawing of the piston, bowl and RFEIS included in the 1Y540. The standard diesel piston was modified to accept a number of different piston bowls. The actual bowl selected gave a compression ratio of 11 to 1. The final bowl design was selected in Task 2 based upon electric field modeling and combustion-test-chamber tests.

Once a final bowl design was chosen in Task 2, we procured the diesel piston, modified it to accept the piston bowl and machined the selected bowl.

Task 2 included three subtasks: design the RFEIS; model the electric field distribution; and procure parts, assemble and test.

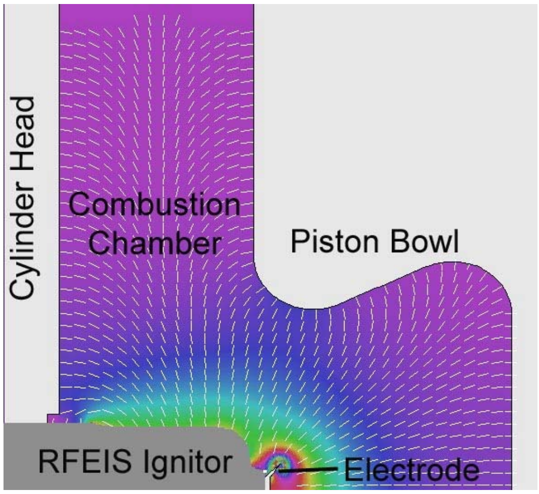

Figure 3. Finite Element Modeling of RFEIS Shows the Electric Field Distribution

The RFEIS design had to be modified to physically fit into the engine's cylinder head. The discharge electrodes and insulator design were also modified, along with the piston bowl design, to optimize the electrostatic discharge, as discussed under Task 1.

Thus, finite element modeling of the electric field distribution was conducted (Figure 3).

The RFEIS was then tested (Task 3) in a combustion bomb, with a simulated piston bowl installed, to verify the results of electric field modeling and verify electrostatic discharge characteristics.

Task 3 comprised three subtasks: test RFEIS in a combustion bomb non-firing; test RFEIS in a combustion bomb firing; and conduct hot firing tests for at least 12 hours.

In **Subtask 3.1**, the RFEIS was installed in a combustion bomb with a simulated piston bowl. The chamber was pressurized with dry air at room temperature to simulate engine density conditions at the time of ignition. The RFEIS was then fired to verify modeling results and document the electrostatic discharge characteristics. The goal was to design the RFEIS and combustion chamber to give as large a discharge as possible.

The procedure for charging the test chamber was to evacuate for 15 minutes. The test chamber was then charged with 85 mbar of propane, and the feed lines to the chamber were evacuated. The unit was then charged with the correct amount of dry ultra zero air (using the partial pressure method) to obtain the desired equivalence ratio. After two minutes, the air-fuel mixture was released and chamber pressure fell to atmospheric pressure. Then, the video capture was started and the digital scope trigger armed. The ignition button was pressed, which triggered the scope, and the combustion event was recorded.

This test method was developed experimentally to minimize air and fuel stratification. If the mixing time were too short, then diffusion mixing would not complete. If the mixing time were too long, then the air and fuel would separate due to density differences. Tests were periodically conducted twice to ensure repeatability. Attempts were made to test methane-air mixtures, but the results were not repeatable. These inconsistent results were due to the fact that methane is very light compared with air and the mixture stratified in the test chamber before ignition.

Figure 4 shows a schematic of the combustion test chamber. The piston bowl was installed in the chamber to simulate the actual combustion chamber in the engine. Its position in the chamber represents the actual piston position with the crankshaft at 25 deg before top dead center (BTDC). The copper screen was installed to simulate electrically a solid metal piston while providing visual access to the chamber. The screen was required because the RFEIS interacts electrically with the combustion chamber to generate the electric field. The pressure in the chamber was monitored by a 6.9 bar full scale pressure transducer connected to a digital oscilloscope. The camera, a standard National Television System Committee (NTSC) video camera, was connected directly to a computer through a video capture card. The interlaced video frames were split into the two fields; each field was recorded at 60 frames per second. The video resolution was 640 x 480.

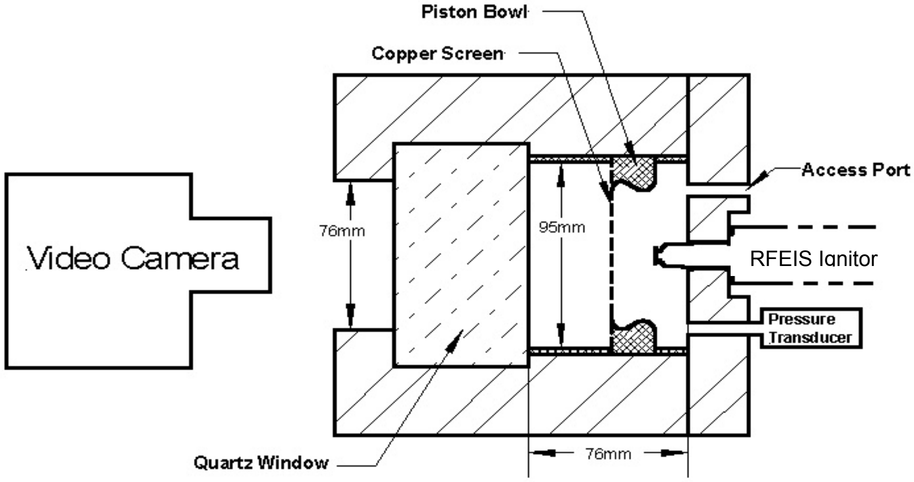

Figure 4. Combustion Test Chamber

In **Subtask 3.2**, the RFEIS was tested in a firing combustion-test-chamber to determine ignition and combustion characteristics at four different air-fuel ratios. The standard ignition was also evaluated to provide a baseline for comparison.

The standard ignition system used was a capacitive discharge type. It had a 1.5 microfarad capacitor and stored 68 mj of energy when it was charged to 300 volts. The ignition coil was a capacitive discharge type with a primary inductance of 2 millihenries. The spark plug was an 18mm thread, 19mm reach, Champion RB77WPC spark plug.

The standard gap for the RB77WPC is 0.30 mm. However, with this gap, it would not ignite the mixture at any equivalence ratio. Further investigation revealed that the quenching distance for stoichiometric propane mixtures at atmospheric pressure and 25 deg C is 2.03 mm [5]. For this reason, the plug gap was opened up to 2 mm. The plug voltage was measured using a Tektronics P6015A probe and a Pearson model 410 inductive current sensor. The energy delivered to the plug increased from 26 mj to 37.6 mj. The breakdown voltage also increased from 3.5 kilovolts to 7.0 kilovolts. Figure 5 shows the current and voltage waveforms for the standard plug with a 2 mm plug gap. All combustion testing reported in this paper used this plug with the 2 mm gap.

Subtask 3.3 was to conduct hot fire tests for at least 12 hours. The RFEIS was installed in a small propane fueled engine where it was subjected to hot firing engine conditions for 15 hours to ensure reliable operation during upcoming single cylinder testing at Southwest Research Institute (SwRI).

Task 4, testing the RFEIS in a single cylinder engine, was conducted at SwRI's engine lab in San Antonio, Texas. It comprised two subtasks.

Subtask 4.1 was to install the piston and RFEIS in a single cylinder engine. At low speed and load, the engine was fired with the RFEIS to debug the instrumentation, engine and RFEIS.

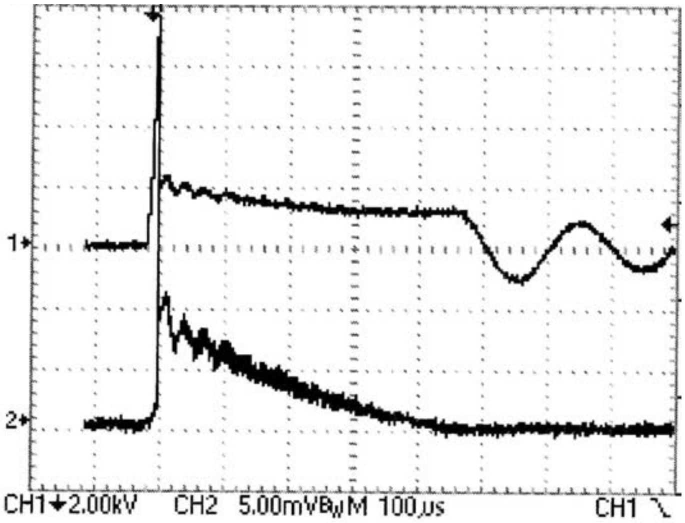

Figure 5. Voltage and Current Waveforms for Standard Ignition System, 1 Bar, 2 mm Plug Gap

Subtask 4.2 was to run a test matrix. The matrix included points at 50%, 75%, 100% load, 1 speed, lean limit, 90% lean limit and three ignition timing settings. Knock limit testing, which had originally been planned, was not conducted; test time at SwRI ran out. The following variables were measured: fuel consumption, emissions, combustion and RFEIS electrical and thermal characteristics. These data would then be compared with the baseline to be obtained with the standard ignition system (under Task 5).

The engine used to evaluate the RFEIS was a Caterpillar 1Y540. The 1Y540 is a single cylinder diesel test engine with a four-valve arrangement having a 5.4-inch bore and a 6.5-inch stroke, resulting in a displacement of 148.8 cubic inches. The engine fueling system was converted to deliver homogeneous gaseous fuel mixtures. The cylinder head has been modified to accommodate various types of ignition apparatus including open-chamber spark and diesel micro-pilot. The engine was controlled with a SwRI Rapid Prototype Engine Control System

(RPECS). The engine control unit provided air-fuel ratio control, ignition timing control, and simulated turbocharger back pressure. The engine boost was supercharged, up to 30 psig, and temperature controlled.

The engine was connected to a wet gap eddy current dynamometer capable of governing either steady-state load or speed. The dynamometer setup also utilized a load cell for measuring engine torque. Engine coolant and intake air temperatures were controlled with annular heat exchangers. The fuel used during the testing was a commercial, compressed natural gas with a stoichiometric air-fuel ratio of around 16.5.

Task 5 involved testing a standard ignition system in a single cylinder engine and was also conducted at SwRI's engine lab in San Antonio, Texas. The data generated were used to establish a baseline for comparison with the RFEIS.

Subtask 5.1 was to install the standard ignition system in the single cylinder engine. The engine and instrumentation were then debugged.

Subtask 5.2 was to run a test matrix. The matrix included points at 50%, 75%, 100% load, 1 speed, lean limit, 90% lean limit and three ignition timing settings. Knock limit was determined (at 90% lean limit and 100% load) by advancing the timing. The following variables were measured: fuel consumption, emissions and combustion characteristics.

Project Outcomes

This project had nine outcomes:

- Designed RFEIS
- Designed and optimized RFEIS electrostatic discharge and combustion characteristics using finite element modeling
- Verified and further optimized RFEIS electrostatic discharge and combustion characteristics through combustion-test-chamber testing
- Demonstrated 15 hours durability in a hot firing test engine
- Measured NOx emissions of 0.72 gm/BHP-hr (at an equivalence of 0.6 in a single cylinder engine with lean air-fuel ratio), and of 0.51 gm/BHP-hr (in a single cylinder engine with cooled exhaust gas recirculation (EGR) and stoichiometric air-fuel ratio, at 29.4% EGR)
- Demonstrated stable engine operation at 90% of the lean limit.
- Tested a standard ignition in a single cylinder engine with a lean air-fuel ratio to compare with RFEIS
- Tested a standard ignition in a single cylinder engine with EGR to compare with RFEIS.
- Verified that data generated from this research support the ignition system's projected capital cost of $8/kWe and life cycle cost of $.25/MWe-hr.

Outcome 1. Designed RFEIS

Objective 1, to design and machine a piston, was an essential first step that allowed us to complete all remaining objectives and their related outcomes. This objective was a success. Figure 6 shows the original diesel piston blank that was modified to accept the RFEIS.

Outcome 2. Finite Element Modeling

Outcome 2 corresponds with Objective 2 and was a success. The piston was designed as described under Outcome 1; however, the bowl shape (center of the piston in Figure 6 below) was determined by finite element modeling.

Figure 6. Diesel Piston (Left) was Modified (Right) to Accept RFEIS

Outcome 3. Combustion Test Chamber Results

This outcome also corresponds with Objective 2 – the electrostatic discharge and combustion characteristics were optimized through non-firing and firing combustion chamber tests. To study and analyze the corona discharge, firing tests were captured on videotape.

Although the electrode voltage and current of the RFEIS system could not be measured, Figures 7 through 10 show the RFEIS corona discharge at various air pressures. (Because the discharge voltage is hundreds of kilovolts, measuring this voltage would alter the characteristics of the system, as it is a resonant circuit and the capacitance of the measurement probe would alter the circuit impedance.)

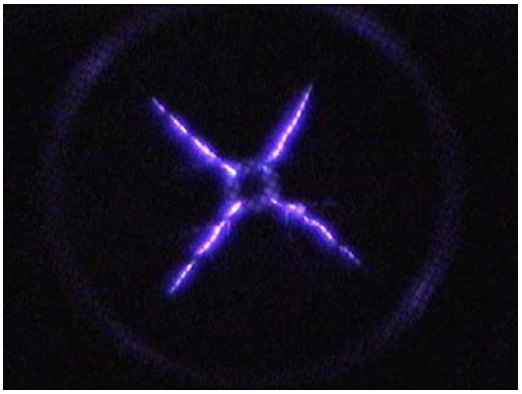

Figure 7. RFEIS Discharge, O Bar, 200 mj

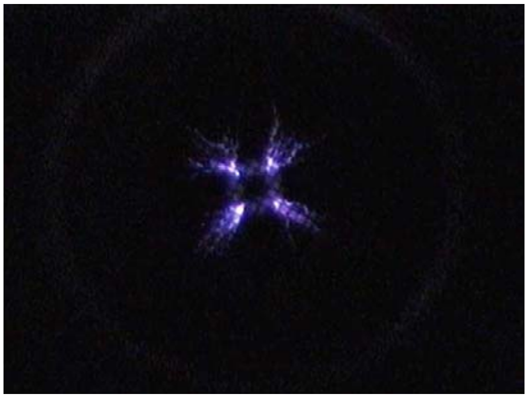

Figure 8. RFEIS Discharge, 6.9 Bar, 1600 mj

Figures 7 through 10 also show the total discharge input energy. This energy is based upon time, in this case one millisecond. The discharges shown are at the maximum power where the corona discharge is sustainable and does not progress to a low impedance power arc (plasma arc). It is interesting that the discharge energy required to sustain the maximum corona is lower at 20.7 bar than at 13.8 bar.

A possible explanation for this is that at the medium pressures, the discharge has multiple streamers, each of which requires energy to generate. Compare Figures 8 and 10. In Figure 8 (6.9 bar of pressure) many streamers are visible. In Figure 10 (20.7 bar of pressure), the multiple streamers appear to collapse together. This is also the case at 0 bar pressure. The discharge shown in Figure 7 (0 bar pressure) is representative of the RFEIS discharge for all combustion-test-chamber firing tests. In general, the corona discharge extended between 50 and 80% of the combustion chamber diameter.

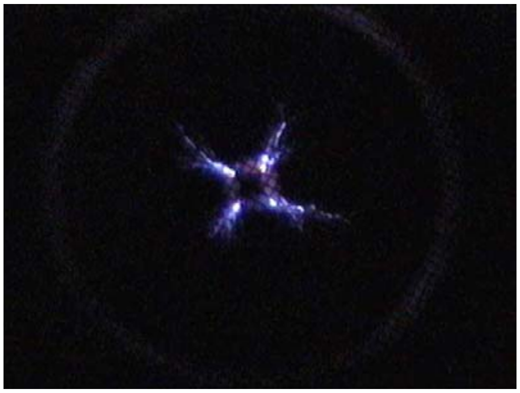

Figure 9. RFEIS Discharge, 13.8 Bar, 1800 mj

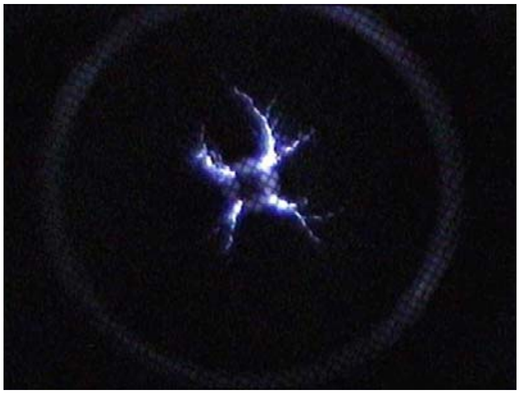

Figure 10. RFEIS Discharge, 20.7 Bar, 1700 mj

Figure 11 shows the definitions for ignition delay and rise time. This is the method used by reference [6]. Figure 12 shows ignition delay and rise time for the RFEIS and standard ignition.

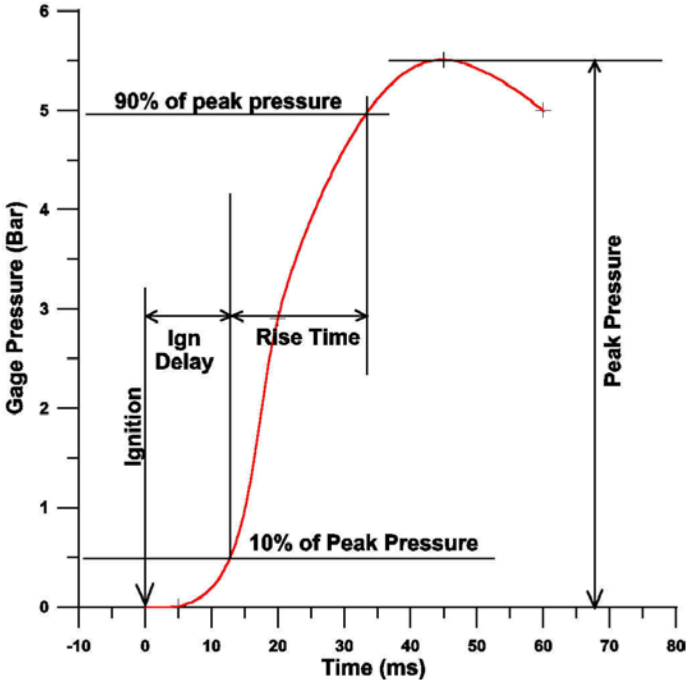

Figure 11. Definition of Ignition Delay and Rise Time for Combustion Test Chamber Tests

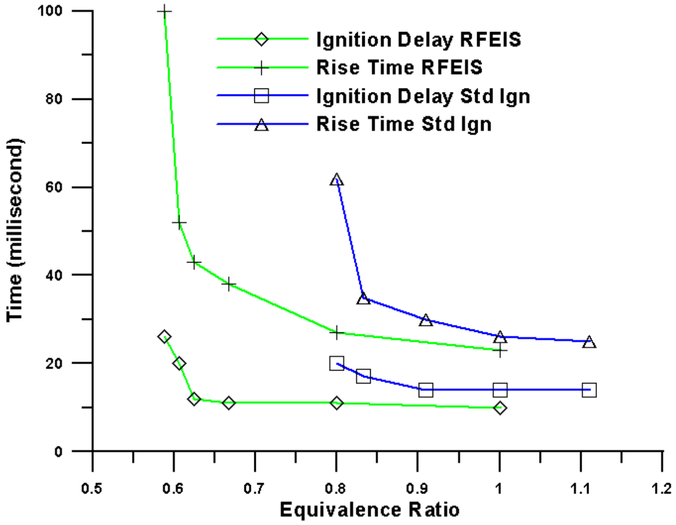

Figure 12. Ignition Delay and Rise Time for RFEIS and Standard Ignition

The lean misfire limit for the RFEIS was at 0.589 equivalence ratio. This point is distinguished by a very long combustion duration.

For the standard ignition system, the lean misfire limit occurred at 0.769 equivalence ratio. The input energy to the RFEIS ignition at atmospheric pressure and 25 deg C was 200 mj. The input energy for the standard ignition was 68 mj. Both ignition delay and rise time were significantly reduced with the RFEIS ignitor compared with the standard ignition at the same equivalence ratio. Ignition delay times were further reduced at leaner equivalence ratios. At 0.8 equivalence ratio, the ignition delay was decreased from 20 milliseconds to 11 milliseconds. The rise time was reduced from 68 milliseconds to 27 milliseconds.

Figures 13 and 14 illustrate the difference in combustion characteristics between the RFEIS and standard ignition systems. The two tests were conducted at a stoichiometric air-fuel ratio. These photographs are the first frames recorded. The initial combustion from the RFEIS discharge is large in area. It appears similar to a diesel (with a four hole injector nozzle) start of combustion. The standard ignition system initiates a small kernel from which the flame front traverses the chamber.

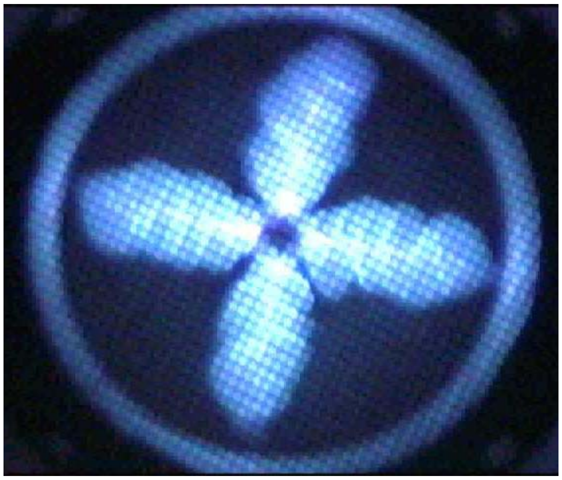

Figure 13. RFEIS Combustion at 16 ms, $\phi = 1.0$

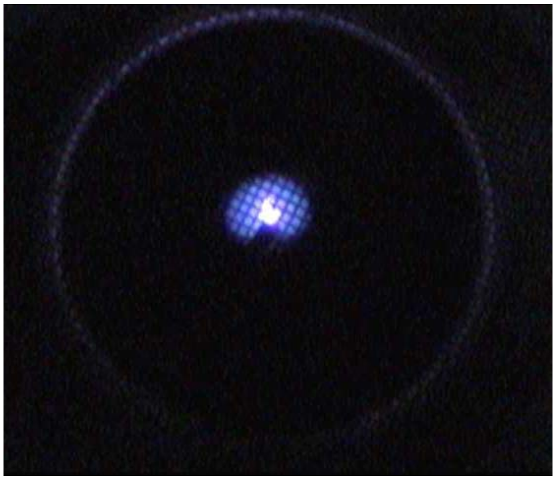

Figure 14. Std. Ignition Combustion at 16 ms, $\phi = 1.0$

Figure 15 illustrates the flame propagation of the standard ignition system. The video camera could not record many frames at relatively rich air-fuel ratios because the combustion event was too fast. However, the difference between Figures 13 and 14 illustrates why the combustion and rise times were so much faster with the RFEIS ignitor. With the RFEIS ignitor, the initiated flame front is orders of magnitude larger in volume than the standard ignition flame kernel.

Figure 15. Combustion Sequence for Std. Ignition $\Phi = 0.770$ (Lean Limit), 16 ms per Frame

Figure 16 shows a series of frames 16 milliseconds apart for the RFEIS ignitor at a 0.606 equivalence ratio. The first frame shows the RFEIS discharge and the initial phase of combustion surrounding the discharge's four "legs." The next frame shows the four combustion zones and their flame fronts. In the third frame, the four burning zones meet. The final frames then show the end of combustion.

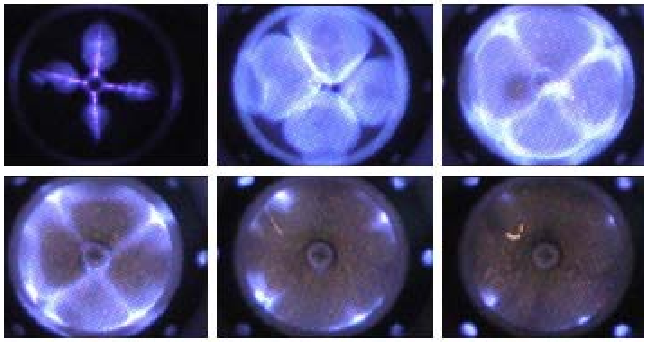

Figure 16. Combustion Sequence for RFEIS
ϕ = 0.606, 16 ms per Frame

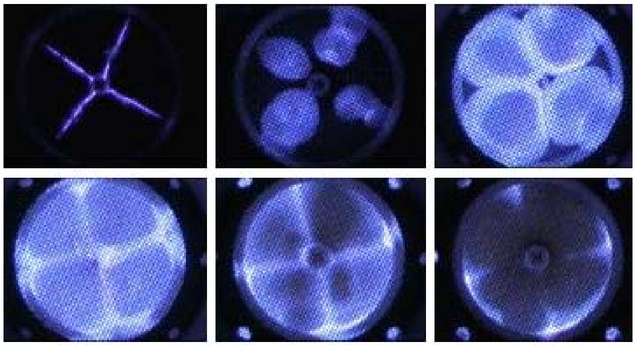

Figure 17. Combustion Sequence for RFEIS
ϕ = 0.571 (Lean Limit), 16 ms per Frame

Figure 17 shows a series of frames for the RFEIS ignitor at its lean misfire limit of 0.571 equivalence ratio (at standard pressure and temperature). In the first frame, very small flame fronts are seen emanating from the four legs of the spark. These four burning zones grow until they collide with each other. The final two frames show the end of combustion, with its burn rate primarily governed by diffusion.

Outcome 4. Durability Development

This outcome corresponds with Objective 3, to demonstrate at least 12 hours of durability of the RFEIS in a hot firing test engine, and was a success. The RFEIS ran in a hot firing test engine for 15 hours. The test engine was a single cylinder, 5 hp gasoline engine driving a high-pressure water pump. The load was controlled by controlling the discharge pressure. The RFEIS was run in the test engine a total of 15 hours at approximately 5 hp.

Outcome 5. Measured NOx Emissions

This outcome corresponds with Objective 4, to demonstrate between 0.1 and 0.5 gm/BHP-hr NOx emissions with RFEIS in a single cylinder engine. The lowest NOx emissions level measured for the RFEIS system while operating with a lean air-fuel ratio was 0.72 gm/BHP-hr, at an equivalence of 0.6. The RFEIS could have run much lower NOx with more ignition retard, but there was not sufficient time to completely map the operating envelope over a broad range of ignition timing and equivalence ratio. The testing time was used to test in an operating envelope where the RFEIS and standard ignition could be compared on an apples-to-apples basis. With cooled EGR, at a stoichiometric air-fuel ratio, the lowest NOx emissions measured with RFEIS was 0.51 gm/BHP-hr at 29.4% EGR. Again, it could have run lower NOx but there was not sufficient time to thoroughly map EGR and ignition timing over the entire operational envelope.

Outcome 6. Stable Engine Operation

This outcome corresponds with Objective 5 and was a success. The RFEIS demonstrated stable engine operation at 90% of the lean limit.

Outcome 7. Test Results of Single Cylinder Engine with Lean Air-Fuel Ratio

This outcome corresponds with Objective 6, to test the standard ignition system in a single cylinder engine and compare it with RFEIS. Comparison tests were conducted in a single cylinder engine with a lean air-fuel ratio. The RFEIS was compared with a typical inductive spark ignition system using a Champion RC78PYP plug gapped at 0.015 inches. The focus of the testing was on the combustion characteristics of lean mixtures with the engine operating at 690 and 1034 kPa (100 and 150 psi) BMEP.

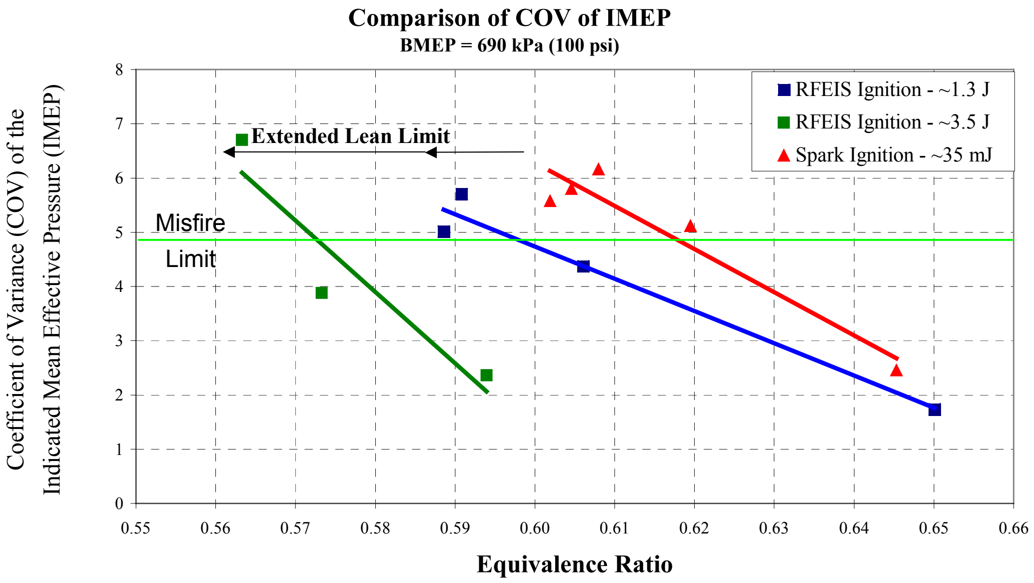

Figure 18. Lean Misfire Limit Comparison at 690 kPa BMEP

The lean limit benefit of the RFEIS was evaluated by comparison with the conventional inductive spark ignition system. For a given system the engine was operated at increasingly leaner conditions until the 5% coefficient of variation (COV) of indicated mean effective pressure (IMEP) limit was reached at maximum brake torque (MBT) timing. The lean misfire limit with conventional spark ignition was found to be at an equivalence ratio of 0.605 at MBT timing. The RFEIS, while operating at ~1.3 J/event, extended the lean misfire limit to an equivalence ratio of 0.590 at MBT timing. At ~3.5 J/event, the RFEIS extended the limit to 0.564 at MBT. The comparison data are shown in Figure 18.

The lean limit was extended as the energy delivered to the mixture increased. Increased ignition energy can affect the BTE and NOx emissions of an engine by decreasing ignition delay, increasing burn rate, and/or improving combustion stability.

Figure 19 displays the NOx/BTE tradeoff for both ignition systems with the engine operating at 690 kPa (100 psi) BMEP, Φ = 0.65, and constant intake air conditions. The outlined data points in the NOx/BTE tradeoff plot show that at a given efficiency the engine produced approximately 20% less NOx emissions on a g/hp-hr basis when operating with the RFEIS.

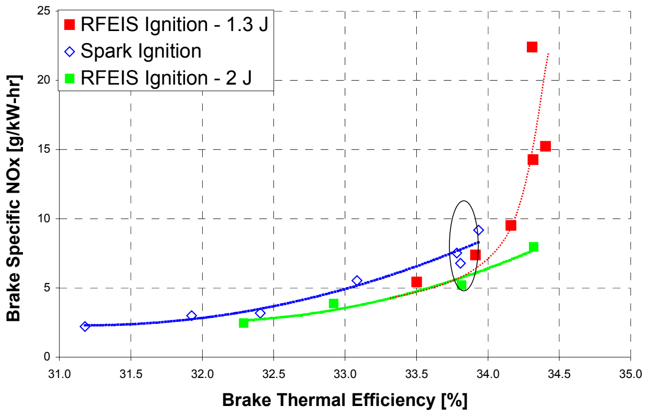

Figure 19. Nox/BTE Tradeoff at ф = 0.65 and 690 kPa BMEP

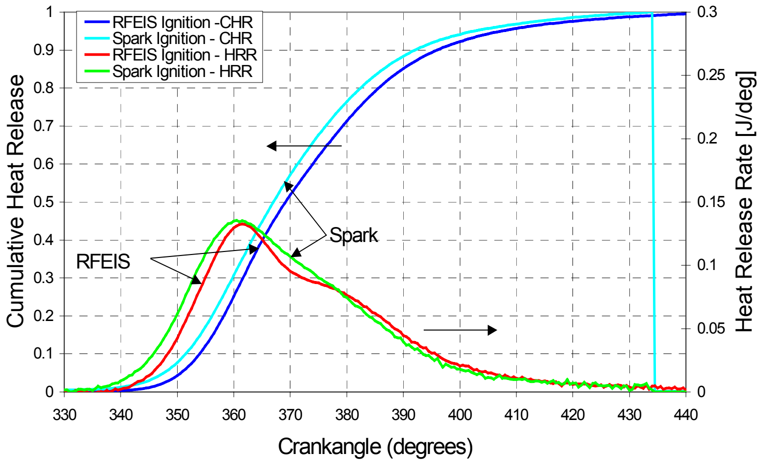

Figure 20. Heat Release Rate Comparison at ф = 0.65 690 kPa BMEP, and Same BTE

The heat release rates for the two outlined points were compared in Figure 20 to reveal insight as to the cause of the trend shift. One hundred consecutive cycles of cylinder pressure data were recorded and averaged, from which the heat release rate was calculated. The cumulative heat release rate has been normalized to show approximately where in the cycle a given percentage of the cylinder mixture has burned. As seen in Figure 20, at MBT timing, the RFEIS combustion event was retarded compared with spark ignition, and the heat release rate profiles were different. NOx emissions decrease while maintaining efficiency due to, in part, the increased initial heat release rate and subsequent continued combustion provided by the RFEIS. Hydrocarbon emissions decreased from 1360 to 1283 ppm and the COV of IMEP decreased from 2.45 to 1.92. This alludes to an improved cycle-to-cycle stability. The improved engine stability may have also contributed to the benefits seen in Figure 19.

Data were also recorded at a 1034 kPa BMEP (150 psi) to emphasize the increase in initial heat release rate with the RFEIS operating at 3.5 J/event. Figure 21 compares the heat release rate between the two ignition systems at the same start of combustion and equivalent engine operating conditions. The heat release rate was accelerated compared with spark ignition at the higher load and leaner mixture, and could be exploited through timing adjustments for further performance benefits. The RFEIS extended the lean limit of the engine by approximately 8%, and has been shown to decrease NOx emissions while maintaining efficiency.

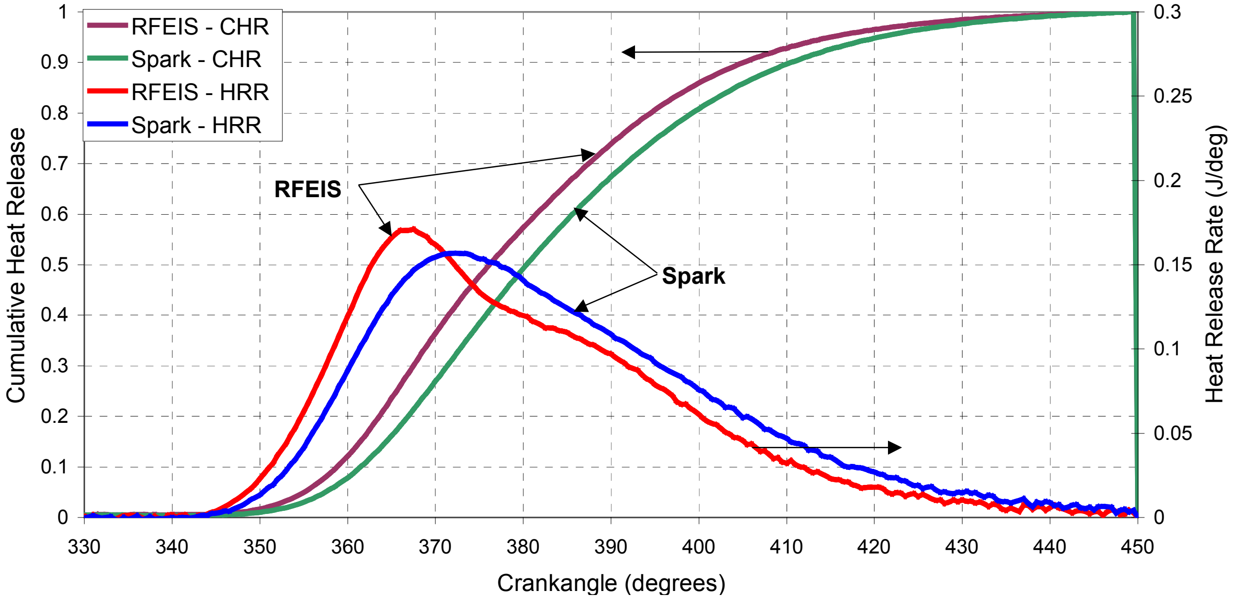

Figure 21. Heat Release Rate Comparison at ϕ=0.62, 1034 kPa BMEP, and Same Start of Combustion

Outcome 8. Test Results of Single Cylinder Engine with EGR

This outcome also corresponds with Objective 6, to test the standard ignition system in a single cylinder engine and compare it with RFEIS.

Tests were conducted comparing the standard ignition system with the RFEIS in a single cylinder engine with EGR at a stoichiometric air-fuel ratio. Unfortunately, there was not enough time in the contract with SwRI to fully explore the advantage of the RFEIS compared with the standard ignition. However, there is enough data to draw some conclusions.

Figure 22 shows the NOx versus efficiency for both the RFEIS and standard ignition. Both indicated and brake efficiencies are presented. The reason for this is that with the test setup we used, varying exhaust backpressure controlled the EGR rate. The higher the exhaust backpressure, the greater the pumping work and lower the brake efficiency.

Comparing the results on an indicated efficiency basis (which does not include pumping work) means the comparison is based only on combustion differences. The results show that at lower EGR rates, NOx efficiency tradeoffs are nearly equivalent, with the RFEIS having a slight benefit. However, at maximum EGR level, the RFEIS improved indicated efficiency from 27.5% to nearly 30% at 0.7 gm/BHP-hr of NOx. This was a >9% improvement in indicated efficiency.

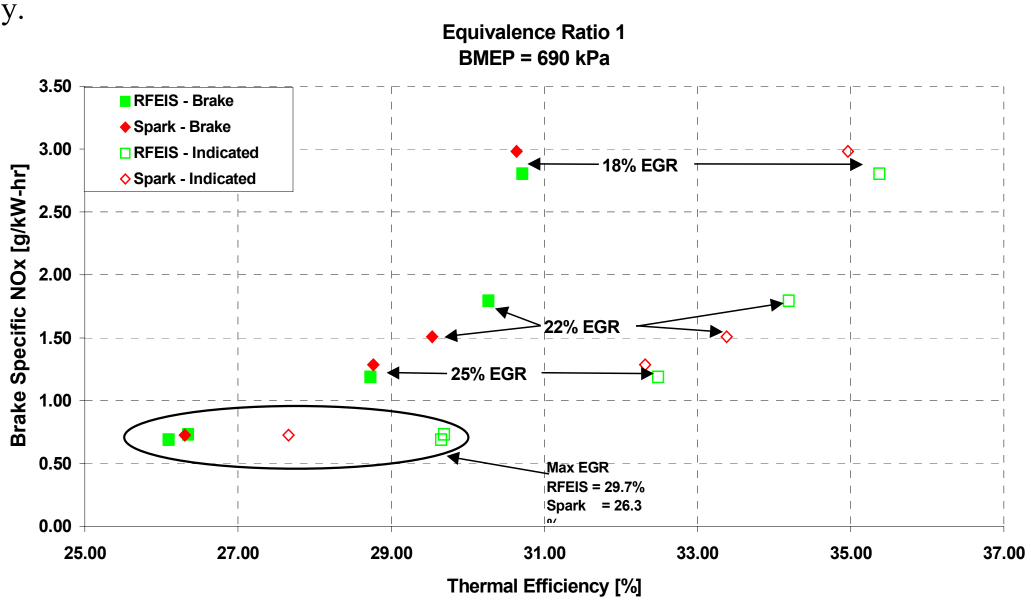

Figure 22. NOx-Efficiency Tradeoff for Stoichiometric A/F Ratio with EGR

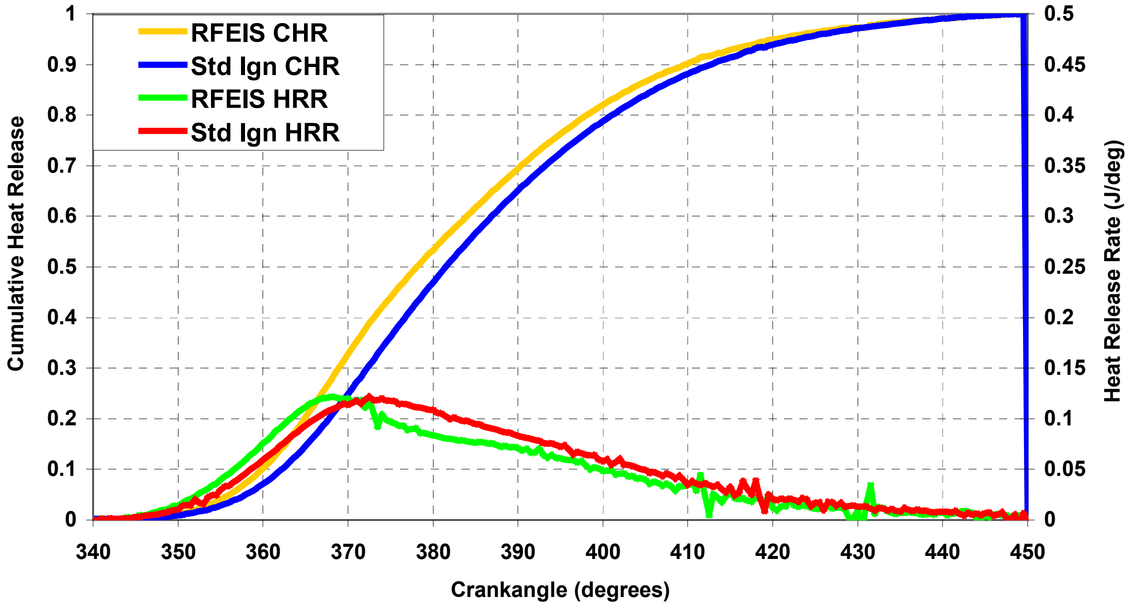

Figure 23. Heat Release Rate Comparison, EGR = 22%, ф = 1, BMEP = 690 kPa

Figure 23 shows the cumulative heat release (CHR) and heat release rate (HRR) for the standard and RFEIS at a stoichiometric air-fuel ratio and 22% EGR. The heat release rate and the cumulative heat release were both faster for the RFEIS ignition. The trend is similar to that seen with the engine running with a lean air-fuel ratio.

Figure 24 shows coefficient of variation and combustion efficiency versus EGR percent for the RFEIS and standard ignition. The misfire limit is defined where the COV exceeds 5. Where the COV is equal to 5, the RFEIS ignition extended the EGR tolerance from 21.3% to 27.25%.

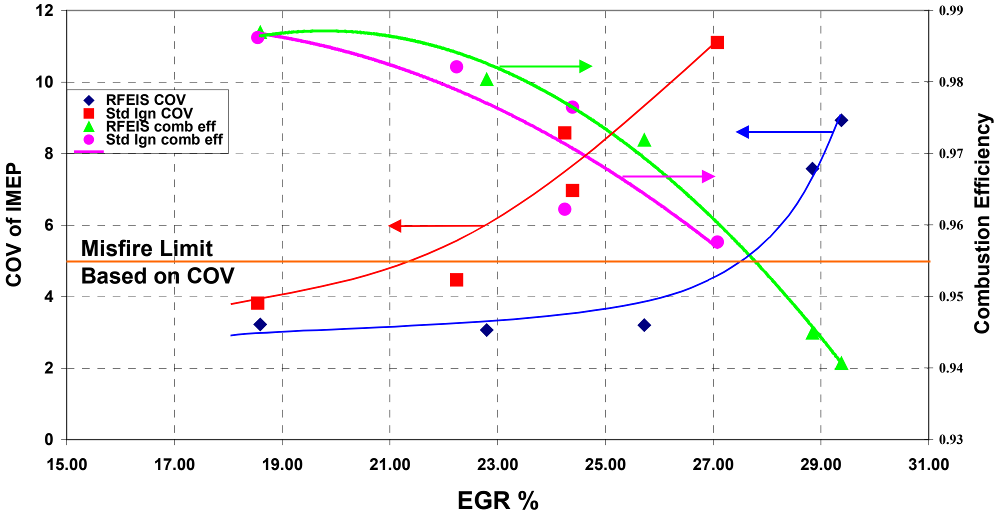

Figure 24. COV of IMEP and Combustion Efficiency vs. EGR Rate

This was a 28% increase in EGR tolerance. This increase in EGR rate will allow an engine to run at a higher knock limited BMEP and at lower NOx levels.

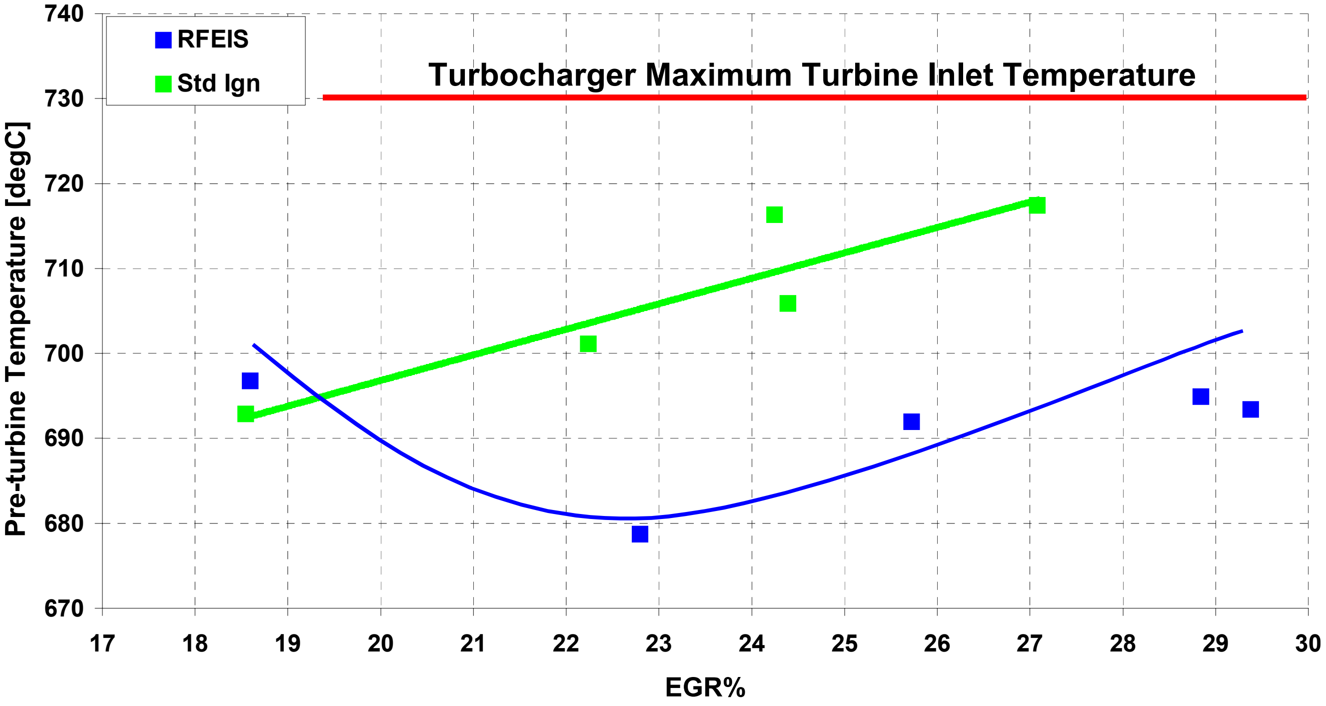

Figure 25. Pre-Turbine Temperature vs. EGR

One problem with cooled EGR engines is that at high EGR rates, the turbine inlet temperature exceeds the limits of the turbocharger. Figure 25 shows the pre-turbine inlet temperature for the standard and RFEIS ignition systems. The RFEIS reduced turbine inlet temperature up to 25 deg Celsius. This was due to the faster combustion rate with the RFEIS ignition.

Outcome 9. Projected Capital and Life Cycle Costs

This outcome corresponds with Objective 7, to verify the projected capital cost of \$8.00/kWe and life cycle cost of \$.25/MWe-hr, and was a success.

The industry target for the ignition system is an initial cost of approximately \$4.00/kWe, life cycle cost of \$0.25/MWe-hr and a repair cost of \$0.15/MWe-hr. Based on these numbers, the total life cycle cost for a 2-megawatt generator with a life of 80,000 hours is \$72,000.00. The initial cost of the RFEIS is expected to be around \$8.00/kWe and the repair costs, to be around \$0.15/MWe-hr. This adds up to a total life cycle cost of \$40,000.00, or a savings of almost 45% per engine. The life cycle cost of RFEIS is low because it is designed to last 80,000 hours.

Conclusions

Combustion Test Chamber

- RFEIS initiated a multi-zone flame front; the standard ignition initiated a single zone.
- RFEIS extended the lean limit by 30% (propane).
- At $\Phi = 0.8$, RFEIS reduced the ignition delay by 45% and reduced the rise time by 60%.

Single Cylinder Lean Tests

- RFEIS ran a total of 40 hours at up to 13.8 bar (200 psi) BMEP.
- RFEIS extended the lean misfire limit by 8% compared with the standard ignition.
- At $\Phi = 0.60$ and equivalent BTE, RFEIS decreased NOx emissions by 20% (0.5 gm/kW-hr)
- At $\Phi = 0.62$, RFEIS decreased the initial (0-10%) cumulative heat release time by 17%, the 10-50% time by 8%, and the 50-90% time by 4%.
- The fast initial burn rate with the RFEIS was offset by a relatively slow end of burn. This indicates that in-cylinder turbulence is still required to speed up the end of the burn to further extend the lean misfire limit.
- The amount of corona energy per discharge and the electrode configuration significantly affected the heat release rate.

Single Cylinder EGR Tests

- RFEIS extended the EGR misfire limit by 28% compared with the standard ignition.
- At 0.75 gm/kW-hr NOx, the RFEIS improved the indicated BTE by 7.2% (2 BTE points) over the standard ignition.
- At EGR rates above 22%, the RFEIS reduced the turbine inlet temperature by 25 deg C.
- At 22% EGR, RFEIS decreased the initial (0-10%) cumulative heat release time by 13%, the 10-50% time by 6%. The 50-90% time was 1% slower compared with the standard ignition.

Recommendations

While the RFEIS shows promise, much work remains to be done. We make the following recommendations:

- Conduct an analysis of fluid dynamics to determine optimum chamber geometry, corona discharge shape and intake port swirl.
- Test the developed system on a single cylinder test engine with sufficient data to demonstrate the NOx emissions goal.
- Run a series of knock limit tests. The RFEIS multi-zone flame front should significantly improve knock limited BMEP.
- Demonstrate durability in a field test.

The Project Development Status Questionnaire following this report describes our plans to bring the RFEIS to market. It references Appendix 2, our application to be considered for venture capital, submitted to the National Renewable Energy Laboratory Industry Growth Forum, which includes details about our business, our product, the market and other factors pertinent to our commercialization plans.

Public Benefits to California

Based on results obtained to date, there is reason to believe that RFEIS may be the technology that will allow reciprocating gas engines to meet California's electrical generation needs and the goals of engine manufacturers for 50% efficiency and NOx levels of no more than 0.1 gm/BHP-hr by 2010.

Reduced NOx emissions is one very real benefit the RFEIS offers to the state of California. In terms of distributed generation and based on data from the Commission/EPRI [7], none of the reciprocating engines can meet the Air Resources Board's (ARB) 2007 NOx emissions standard of 0.07 lb/MW-hr. However, an engine with the RFEIS, operating stoichiometric with EGR, and with a three-way catalyst is able to meet this standard, which translates into NOx emissions' reduction of 85%. At present, the ARB has not set such a low emissions level for any but the South Coast Air Quality District, but if this standard is expanded to other districts, further and widespread NOx emissions' reduction can be realized.

In terms of truck engines, the 2007 emissions levels are almost impossible to achieve with current diesel technology. The gasoline fueled, cooled EGR technology with RFEIS will reduce NOx emissions from the current 2gm/BHP-hr for diesels to as low as the 0.015 gm/BHP-hr demonstrated in the ARICE program, at the same horsepower level as the current diesel.

Initial cost savings is another important benefit. RFEIS allows a 25% uprate over a standard ignition because of the extended knock limit with EGR, an advantage that will significantly reduce the initial cost of engines in both the industrial and transportation sectors.

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[7] EPRI Draft Consultant Report, “Assessment of California CHP Market and Policy Options for Increased Penetration,” prepared for CEC Public Interest Energy Research Program, Electric Power Research Institute, Palo Alto, California, April 2005.

Glossary

Φ	Equivalence Ratio
ARES	Advanced Reciprocating Engine Systems
ARICE	Advanced Reciprocating Internal Combustion Engine
BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
BTDC	Before Top Dead Center
COV	Coefficient of Variance
EGR	Exhaust Gas Recirculation
IMEP	Indicated Mean Effective Pressure
MBT	Maximum Brake Torque
mj	Millijoules
NTSC	National Television System Committee
psi	Pounds Per Square Inch
RPECS	Rapid Prototype Engine Control System
SwRI	Southwest Research Institute