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Energy Research and Development Division

FINAL PROJECT REPORT

Advanced Plasma Ignition Systems for Class 3-8 Natural Gas Engines

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Natural Gas-Related Transportation.

Advanced Plasma Ignition Systems for Class 3-8 Natural Gas Engines is the final report for the Advanced Plasma Ignition Systems for Class 3-8 Natural Gas Engines project (Grant Number PIR-14-011) conducted by Gas Technology Institute (GTI). The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Gas Technology Institute, Enerpulse, and Ricardo demonstrated that two advanced, high-energy ignition systems are capable of effectively and efficiently igniting homogeneous mixtures of natural gas fuel and air in a heavy-duty natural gas engine. The purpose of testing these ignition systems is to demonstrate pathways to improving natural gas engine dilution tolerance, fuel economy, and emissions without sacrificing gas engine reliability relative to diesel engines. The two ignition systems both build upon the existing, commercially available Enerpulse n-PAC® high-energy ignition spark plugs.

The project team developed an initial design concept for a High Frequency Discharge Ignition System, which produces between two and eight charge-discharge cycles in an engine cylinder to enhance the ignition process. Although bench testing of the prototype system showed promise, further research is needed beyond this project to address challenges related to instability, electrode wear effects, engine optimization, and turbulent effects. The project team developed a second advanced ignition system, the Enerpulse Nano-Plasma C2 Discharge Ignition System, which delivers a single megawatt-level nanosecond pulse to ionize the arc gap followed by a variable energy pulsed power plasma discharge. The engine control unit regulates the spark power and duration, which will allow the engine manufacturer to balance the electrode wear with emissions, power, and fuel consumption through engine calibration. While there were constraints due to the experimental test set up, the C2 system operating in low power mode showed promise of extending a natural gas engine's dilution tolerance, which can improve fuel economy and reduce emissions.

Keywords: California Energy Commission, Gas Technology Institute (GTI), Enerpulse, Plasma, high frequency discharge, natural gas engine, advanced ignition system

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EXECUTIVE SUMMARY

In recent decades, the impacts of climate change have grown in California – as evident by the increased frequency and intensity of heat waves, larger wildfires, and continued sea level rise. As part of the state's response, in 2016, California enacted Senate Bill 32 (Pavley, Chapter 249, Statutes of 2016) establishing a statewide goal to reduce greenhouse gas emissions 40 percent below 1990 levels by 2030. In 2018, then-Governor Edmund G. Brown, Jr. issued Executive Order B-55-18 to set a statewide goal to achieve carbon neutrality by 2045 and negative greenhouse gas emissions afterward.

Emissions reductions in the transportation sector are critical to meeting these statewide goals. The transportation sector the largest source of greenhouse gas emissions in California, accounting for about 40 percent of statewide emissions in 2018. As a complement to transportation electrification and hydrogen fuel cell technology, using natural gas as a transportation fuel in heavy-duty vehicles can lower greenhouse gas emissions and improve air quality as well as reduce petroleum consumption and lower operating costs for businesses and consumers. However, natural gas-fueled engines can face unique challenges preventing wider adoption, including lower efficiency compared to incumbent diesel-fueled engines.

Project Purpose

California sets aggressive oxides of nitrogen (NOx) and greenhouse gas emission targets for the transportation sector's heavy-duty vehicles in order to meet air quality goals. There are methods to achieving these targets including operating natural gas engines at lean air-to-fuel ratios (more air than needed to burn the fuel) or with high levels of exhaust gas recirculation dilution (more air diluting the recirculated exhaust gas). Both approaches, however, create challenging fuel ignition conditions. Blending recirculated exhaust gas with fuel prior to ignition can minimize peak combustion temperature and reduce the production of NOx, but it also dilutes the fuel mixture and makes ignition of the fuel and air charge more difficult when using a conventional spark plug. At some point, combustion becomes unstable and the engine begins to misfire. To address this issue, this project aimed to develop two ignition systems that could improve combustion stability of high dilution natural gas fueled engines.

Project Approach

Initial Design Concept

The project team consisting of Gas Technology Institute, Enerpulse, and Ricardo developed an initial design concept for a high-frequency discharge ignition system. The new system would build upon the commercially available Enerpulse Pulstar Pulse plug's embedded capacitor to create between two and eight charge-discharge cycles in an engine cylinder to enhance the ignition process. Bench testing of a prototype system showed some promise, but the team identified several challenges that needed to be addressed for the approach to be viable. Operation was unstable even in the operating regimes where the system multi-strikes or contains two full-energy spark events. System operation depended heavily on the geometry of the spark plug electrode; thus, electrode wear could affect system performance. Further, the pressures at which the system performs optimally did not necessarily match up with the optimal engine operating conditions. Finally, all testing had been performed in a quiescent chamber, which is a combustion chamber that does not rely on turbulence to thoroughly mix the fuel and air charge. From this testing, it was unclear how the turbulent conditions in a running engine might affect the operation.

The team believed that further research could overcome some of these challenges, but work on a different portion of the project, the Enerpulse Nano-Plasma C2 Discharge Ignition System (C2 System), indicated a more promising approach and the team decided to pursue that approach rather than attempting to overcome problems with the initial concept.

Advanced High Frequency Discharge Ignition System Approach

The alternate advanced ignition system approach uses multiple coils integrated into a single package along with control circuits. The system is triggered by a single engine control unit signal for each cylinder, allowing for easy integration into existing engine platforms. Highlights of the new approach included:

- A single trigger.
- Production of four successive high-energy pulses every time regardless of engine operating conditions.
- Time for the overall event at about 500 microseconds.
- Total energy delivery of 15 millijoules per pulse.
- A passive system easily integrated into existing platforms.
- Development cost the same as the initial concept.
- High component commonality with the C2 System.
- Scalable system that can easily be designed to provide varying numbers of discharges.
- Easily added control circuitry allowing the engine control unit to control the number of discharges to balance performance and plug life.

C2 System Overview

The C2 System is a variable energy, plasma assist ignition system for spark ignited internal combustion engines that builds on the Enerpulse n-PAC technology. The system delivers a single 5 to 20 megawatt, nanosecond pulse that ionizes the arc gap, followed by variable energy pulsed plasma discharge. The engine control unit controls the follow-on discharge by adjusting the total amount of energy by changing discharge amplitude and duration. The system delivers a single 5 to 20 megawatt, nanosecond pulse that chemically changes the arc gap, followed by variable energy pulsed plasma discharge. In other words, the arc gap, a gap that is filled with gas to allow an electric spark to pass between conductors, acquires a negative or positive charge from the aforementioned nanosecond pulse. The variable energy pulsed plasma discharge that follows after the acquisition of negative or positive charges is controlled by the engine control unit, which adjusts the total amount of energy by changing the amount and duration of the discharge. The system compensates for cold starts, stop and start driving, rapid acceleration, highway driving, environmental conditions, and emission feedback by varying the C2 protocols to reach optimum performance and lowest emissions. This type of combustion feedback also improves overall durability and extends electrode life by reducing ignition energy levels when lower energy levels are sufficient. The system energy output level is controlled by a combination of the trigger signal pulse width and a direct current control voltage.

The system is comprised of the following:

1. Non-resistor Pulstar Nano-Plasma Assisted Combustion (n-PAC) spark plug for each cylinder.
2. C2 Ignition Module for each cylinder of the engine.
3. Power Supply to provide the control voltage.

Project Results

While there were constraints due to the experimental test set up, the C2 System operating in low power mode showed promise of extending the dilution tolerance of an engine, further helping to improve fuel economy and reduce emissions. Results showed that the exhaust gas recirculation dilution tolerance could be extended by as much as 30 percent, from the baseline ignition system at 15.4 percent exhaust gas recirculation to approximately 20 percent. In addition, the lean limit was able to be extended by 3.4 percent from the baseline case. The High Frequency Discharge Ignition System (HFD) is essentially four C2 systems operating in low power mode, firing in rapid succession and delivering four times the energy across the spark gap than one C2 System operating in low power mode. Therefore, it is reasonable to assume that the system would perform significantly better than those of one C2 System operating in low power mode.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The knowledge gained on this project is summarized in this California Energy Commission report. The Southern California Gas Company provided input into the direction of the research for this project, and it is expected that they could support further research and demonstrations in the future. To transfer this technology to a commercial market, companies like Enerpulse, Power Solutions International, Inc. (PSI), and Ricardo have been key partners. The groups that will help share information on this project are the Natural Gas Vehicle Technology Forum and the Advanced Clean Transportation Expo as they will present our information via conferences, workshops, and forums. Our final product will be published through various societies such as the American Society of Mechanical Engineers (ASME), Internal Combustion Engine Division, and the Society of Automotive Engineers (SAE). The companies that would intend to use the product from the research would be Enerpulse and Pulstar, while PSI, Cummins Westport, and Westport Fuel Systems are some of the automotive OEM companies that could be integrating this technology into their natural gas engines.

With Enerpulse bench testing demonstrating a 3.5 to 6.0 percent reduction in fuel consumption in steady state testing on a GM 5.7L Engine, it can also be applied to stationary engines used in power generation and natural gas compression. In addition, since the C2 and High Frequency Discharge Ignition Systems are more capable of 15 to 20 times more ionization than other advanced high-energy systems, they achieve higher levels of EGR leading to much lower NOx emissions. The technologies in this project can also be applied to natural gas engines used in stationary applications such as power generation and gas compression applications.

As for the near-term (beachhead), mid-term, and long-term target markets for the technology, the project team will continue working towards these up to the commercialization phase. Enerpulse is seeking a partnership with a vehicle or engine manufacturer or a large fleet end user as well as exploring research grant opportunities.

Benefits to California

The C2 and High Frequency Discharge Ignition Systems, when fully developed, will enable natural gas engines to approach fuel economy on par with diesel engines with significantly lower emissions. The ability to reduce NOx emissions with these advanced ignition technologies is directly related to the resulting increased ionization of the diluted fuel air mix. This ionization leads to the generation of radical molecules with a greater tendency to react with each other instead of the nitrogen gas present in the combustion chamber.

The energy from the C2 and High Frequency Discharge Ignition Systems is delivered in very short high-energy bursts which produces significantly higher levels of ionization than other spark plug-based ignition systems and testing to date, with the systems running at a fraction of their potential. This has demonstrated the ability to achieve higher levels of exhaust gas recirculation, leading to much lower NOx emissions. Integrating these systems with cooled exhaust gas recirculation and advanced three-way catalyst systems will lead to additional fuel economy along with greenhouse gas and NOx reduction benefits.

While both systems showed promise, additional optimization and testing needs to be performed to determine their full capabilities. In addition, further development work needs to be performed to harden the electronics, reduce manufacturing costs, and reduce packaging size. Enerpulse is performing additional testing while continuing conversations with engine and truck manufacturers to commercialize one or both of the systems. Potential partners include Power Solutions International, Cummins Westport, and Alkane Truck Company. Furthermore, the plasma systems developed in this project are targeted toward the mobile market; however, they can also be applied to stationary engines that are used in power generation and natural gas compression.

CHAPTER 1:
Introduction

The Issue

Current ignition systems using conventional spark plugs have shown limited ability to ignite natural gas fueled engines in either lean air-to-fuel ratios or stoichiometric mixtures[1] with exhaust gas recirculation (EGR) dilution due to the poor energy transfer arising from electrical resistance in the circuit. Some ignition systems use multiple sparks, creating several sparks per ignition cycle. While these systems are much better than those supplied by original equipment manufacturers (OEM), they have yet to improve the ignition of high dilution compressed natural gas fueled engines. With California's extremely low NOx emission targets for natural gas engines used for transportation, these engines must be configured to operate with higher levels of EGR dilution. Without advanced ignition systems, the competitiveness of natural gas engines as an alternative to diesel engines would be constrained and potentially limit their contribution toward meeting California's aggressive NOx and greenhouse gas emission reduction targets.

The blending of recirculated exhaust gas, with its high specific heat, with fuel prior to ignition is a proven way to minimize peak combustion temperature and reduce the production of thermal NOx. However, using EGR dilutes the fuel mixture, making ignition of the fuel and air charge more difficult when using a conventional spark plug. At or above a specific amount of EGR, the combustion becomes unstable and misfire events occur.

The Solution

In this project, the project team of Gas Technology Institute, Enerpulse, and Ricardo successfully addressed these challenges. Enerpulse developed two ignition systems that can improve combustion stability of high dilution natural gas fueled engines built on its existing commercially available high-energy ignition product, the Enerpulse n-PAC® plugs. In both systems, the spark event begins with the capacitive discharge ignition (CDI) power supply charging on the rising edge of the trigger signal. On the falling edge of the trigger signal, the CDI supply is discharged through the CDI coil and current begins flowing to the spark plug. As the voltage at the spark plug rises, the capacitor in the plug is charged. The capacitor discharges during the streamer phase of the spark event when the gap resistance drops to near zero. This discharge lasts just a few nanoseconds.

In the first advanced ignition system developed in this project, the Enerpulse Nano-Plasma C^2 Discharge Ignition System (C2 System), the pulse-forming network discharges into the spark gap creating a larger and longer lasting plasma kernel. The follow-on current is controlled by the length of the trigger signal and the control voltage.

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[1] A stoichiometric mixture is one that contains a ratio in which exactly enough air is provided to completely burn all of the fuel in a combustion process such as in an internal combustion engine.

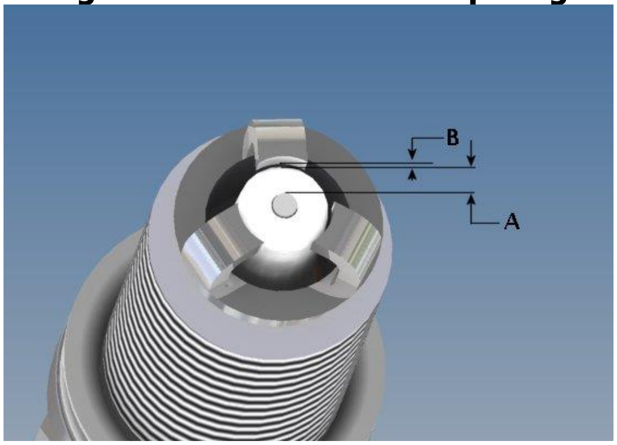
In the second advanced ignition system, the Enerpulse High Frequency Discharge Ignition System (HFD System), approximately 50 microseconds (μS) μS after the first CDI coil is fired, the second coil fires repeating the spark event. This sequence repeats until all four coils have fired.

CHAPTER 2:
High Frequency Discharge Ignition System Overview

Initial Design Concept

The initial design concept for the HFD System called for between two and eight charge-discharge cycles in an engine cylinder using a technology that would build on the commercially-available Enerpulse Pulstar Pulse plug's embedded capacitor. The charge-discharge cycles would result from one cycle of the coil or transformer. This is made possible by the geometry of the plasma plug electrodes, the current discharge of the coil, and the Lorentz effect[2] on the spark. The electrode geometry of the plug is of the semi-surface type (Figure 1). The spark gap is a combination of ceramic and air, the total of which can be four times that of a typical air gap alone. The design capitalizes on the phenomena of electron creep, whereby during the ionization process, the ceramic portion of the gap ionizes at a much lower voltage than the air portion, providing a breakdown voltage similar to that of an air gap 75 percent smaller. The result is a spark channel four times longer than the air gap. This longer spark is then manipulated by the Lorentz effect that curves or bends the spark as it goes to ground providing an even longer spark channel.

Figure 1: Semi-Surface Gap Plug



Source: GTI

The long spark channel cannot be maintained by the coil. The current from the coil pulse is limited and the spark extinguishes depositing its energy into the fuel charge in less than two nanoseconds. However, since the coil is still providing energy, the capacitor re-charges and discharges a number of times during the 100 milliseconds coil discharge cycle. This provides for a series of plasma events that further enhance the ignition process.

Bench Testing of Initial High Frequency Discharge Ignition System

A prototype HFD System running on the bench produced between one and six high energy nanosecond arcs over a 500 microsecond period. The bench testing also identified the

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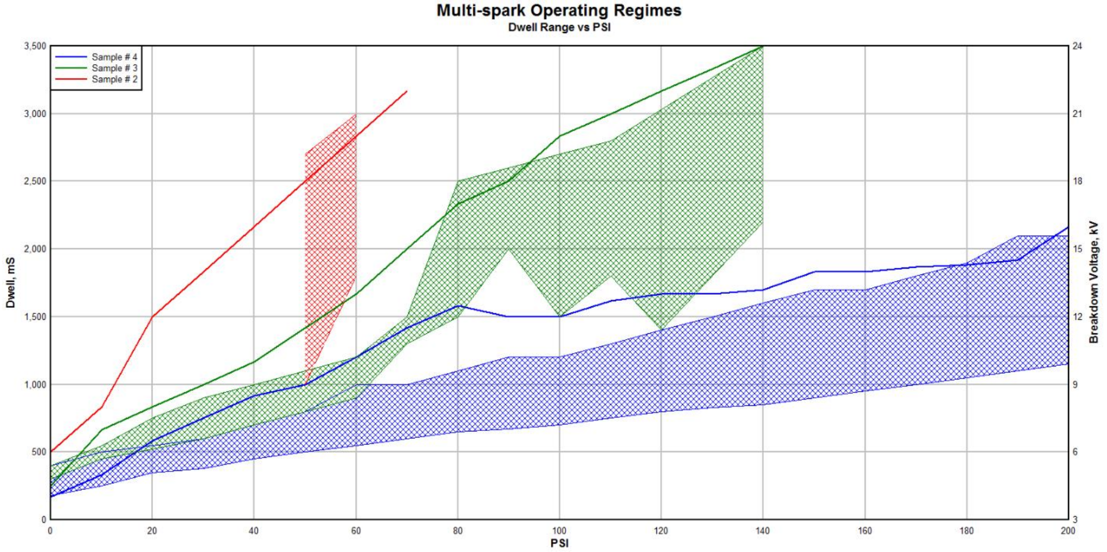
[2] The Lorentz effect is the force acting on moving charged particles in a magnetic field.

pressures at which the HFD would perform a multi-strike. Figure 2 shows the conditions under which three of the spark plug configurations tested will multi-spark.

Figure 2: High Frequency Discharge Ignition System Multi-Spark Conditions for Three Configurations (Samples #2, #, and #4)



Source: GTI

The X-axis is test pressure. The left hand Y-axis is the dwell (that is, on-time) of the coil while the right hand Y-axis is the breakdown voltage. Each sample plug is represented by a different color. The shaded areas are the pressure/dwell operating regimes in which the sample plug sparks multiple times for each trigger event with dwell being read off the left hand Y-axis. The solid lines are the pressure breakdown curves with the voltage being read off the right hand Y-axis. As shown, Sample 2 was one of the least effective candidates because it only multi-strikes between 50 and 60 pounds per square inch (psi) which is well below the time at ignition pressures of the intended engines. Furthermore, the breakdown voltage is very high even at those low pressures. It is interesting that in the narrow range in which it does multi-strike, the dwell range is fairly wide.

Sample 3 had a larger range of pressures at which it would multi-strike and at the appropriate pressures, the dwell range was fairly wide. Unfortunately, the breakdown voltage was excessively high.

Sample 4 was the best performing plug tested to date. The breakdown voltage was under 15 kilovolts (kV) throughout the operating range and when the dwell was adjusted appropriately, it would multi-strike at all test pressures.

While development and testing at this point showed some promise, it was obvious that there were several challenges that needed to be overcome for this approach to be viable, including:

- Operation was sporadic even in the operating regimes in which the system multi-strikes.
- System operation was very dependent on electrode geometry so plug wear (that is, geometry changes) may greatly affect performance.
- Optimal system performance pressures do not necessarily align with optimal engine operating conditions.
- All testing had been performed in a quiescent chamber, so it was not known how the turbulent conditions in a running engine would affect operation.

While further research and development could overcome some of these challenges, the work on Task 3 of the project, the Enerpulse Nano-Plasma C^2 Discharge Ignition System, brought to light another, more promising, approach to the passive HFD System. The decision was made to pursue the advanced approach rather than expend additional resources in attempting to overcome the problems with the initial concept.

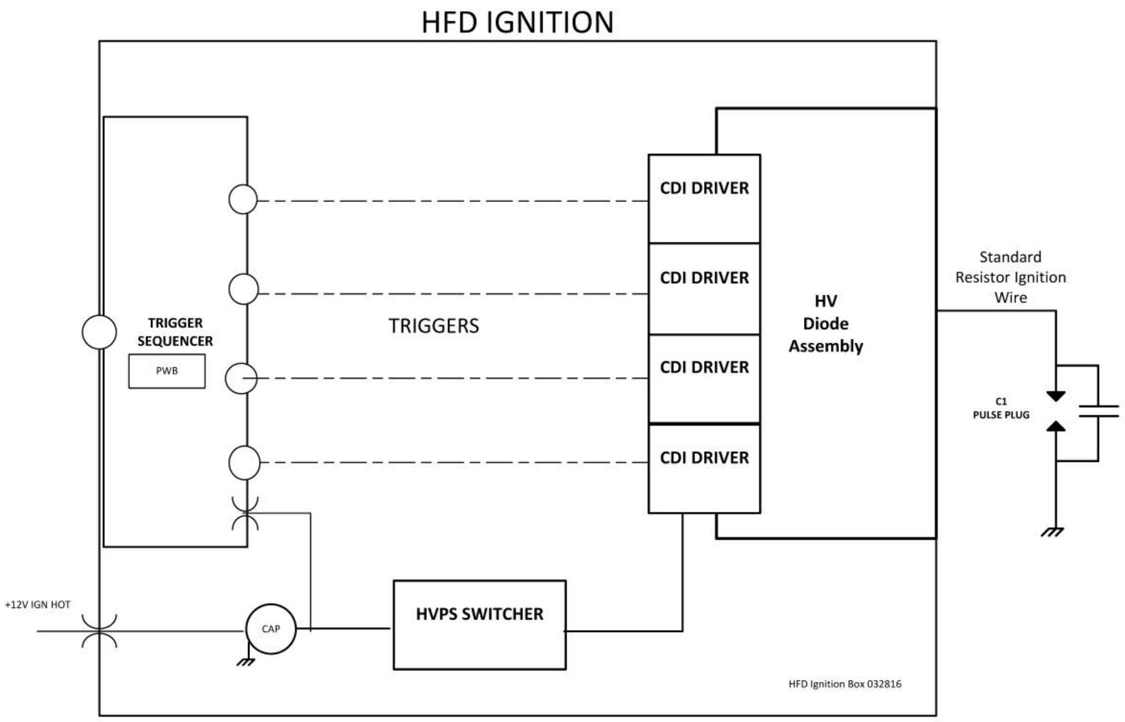
Advanced High Frequency Discharge Ignition System Approach

The advanced approach is to use multiple coils integrated into a single package along with the necessary control circuits. This system is still triggered by a single engine control unit (ECU) signal per cylinder allowing for easy integration into existing platforms. Highlights of the new approach are:

- Single trigger.
- Produces four successive high energy pulses every time regardless of engine operating conditions.
- Overall event takes about 500 microseconds.
- The total energy delivered is 15 milliJoules per pulse.
- Passive system that is easily integrated into existing platforms.
- Cost to develop is the same as the initial concept.
- High component commonality with the C2 System.

Figure 3 shows a block diagram of one channel (cylinder) of the new system. Most of the components are the same as those used in the C2 System. The system is scalable and can easily be designed to provide varying numbers of discharges. Furthermore, easily added control circuitry would allow the ECU to control the number of discharges on a cycle to cycle basis in order to balance performance and plug life.

Figure 3: Block Diagram of Advanced High Frequency Discharge Ignition System Concept



Source: GTI

CHAPTER 3:
C2 System Overview

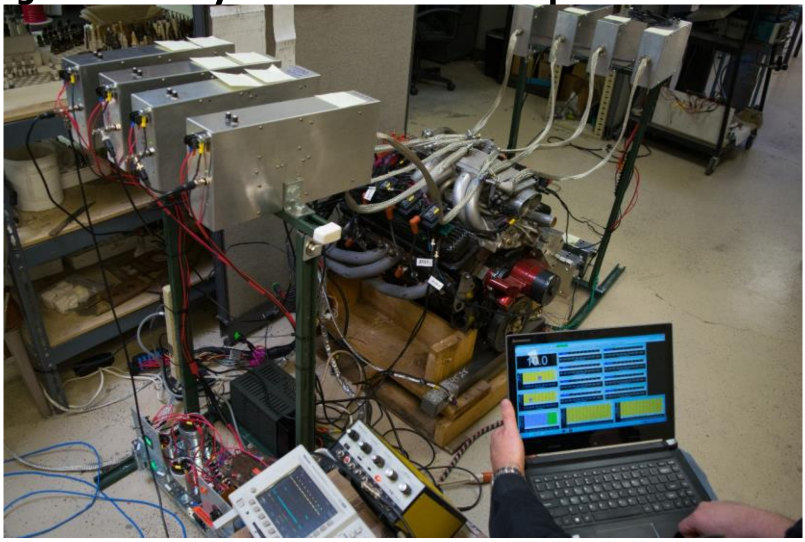
The C2 System is a variable energy, plasma assist ignition system for spark ignited internal combustion engines that builds on the Enerpulse n-PAC technology, delivering a single 5 to 20 megawatt (MW), nanosecond pulse that ionizes the arc gap, followed by variable energy pulsed plasma discharge. The follow-on discharge is controlled by the ECU that makes adjustments to the total amount of energy by changing discharge amplitude and duration. Cold starts, stop-and-start driving, rapid acceleration, highway driving, environmental conditions, and emission feedback are compensated for by varying the C2 protocols to reach optimum performance and lowest emissions. This type of combustion feedback also improves overall durability and extends electrode life by reducing ignition energy levels in operating regimes where lower energy levels are sufficient. The system energy output level is controlled by a combination of the trigger signal pulse width and a direct current (DC) control voltage.

The system is comprised of the following:

- Non-resistor Pulstar Nano-Plasma Assisted Combustion (n-PAC) spark plug for each cylinder.
- C2 ignition module for each cylinder of the engine.
- Power supply to provide the control voltage.

In Figure 4 showing bench testing at Enerpulse, the Pulstar spark plugs are laying on top of the engine and are connected to the eight C2 Modules (the aluminum boxes); the power supply is mounted near the floor below the C2 Module.

Figure 4: C2 System Tested in Enerpulse Laboratory



Source: GTI

Pulstar Nano-Plasma Assisted Combustion Spark Plug

The Enerpulse n-PAC spark plugs have an integrated peaking capacitor in parallel with the spark gap. The insulator in the n-PAC spark plug is much thinner than that of a conventional spark plug and, serves as the dielectric for the opposing plates of the capacitor. The insulator is constructed with higher aluminum oxide content (96 percent+) than a conventional spark plug, providing a higher dielectric constant for the capacitor. The plugs used with the C2 System have no series resistor and rely on aircraft-style, shielded, high-voltage secondary cables for electrical noise suppression.

The capacitor is charged during the rise time of the coil or ionization period of the spark event. The capacitor discharges during the streamer phase of the spark event when the gap resistance drops to near zero. This discharge lasts a few nanoseconds and has a peak power discharge of around 5MW as compared to the 125mW of a conventional ignition/spark plug discharge.

The measured peak current of the spark delivered by a conventional spark plug at 20 kV breakdown voltage is approximately 0.05 A. The measured peak current of an n-PAC spark plug at the same voltage is approximately 1000 A. Calculations of peak power for both plugs, both at a breakdown voltage of ~ 20 kV, are as follows:

$$Peak\ Power\ (Watts) = I^2\ (amps) \times R\ (ohms)$$

$$Conventional\ Ignition:$$

$$Watts = (0.05\ amps)^2\ \times 50\ ohms$$

$$Watts = 0.125\ W\ peak\ power$$

$$Peaking\ Capacitor:$$

$$Watts = (1020\ amps)^2\ \times 5\ ohms$$

$$Watts = 5.2\ MW\ peak\ power$$

The conventional ignition uses a resistance of 50 ohms whereas the pulsed energy ignition uses a resistance of 5 ohms. The resistance of 50 ohms for the conventional spark is taken as the nominal resistance of a long duration low-current spark. The resistance of 5 ohms for the pulsed energy ignition is calculated from Sorensen and Ristic[3] for resistive phase of a spark in the nanosecond regime. Visual demonstrations of the spark discharges for the n-PAC spark plug and the conventional spark plug are shown in Figure 5; such visualizations occur in a pressure vessel at 7 bar and similar spark gaps. Notice the n-PAC spark plug presents a large volume of plasma energy, which is correspondingly missing with the conventional spark plug technology.

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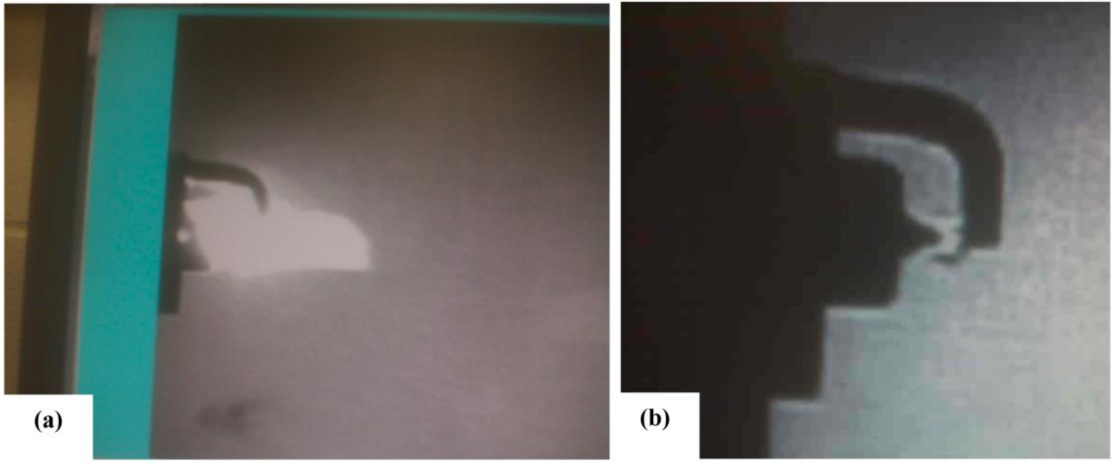
[3] T.P. Sorensen and V.M. Ristic, "Rise Time and Time-Dependent Spark-Gap Resistance in Nitrogen and Helium" J. Appl. Phys. 48, 114 (1977).

Figure 5: Schlieren Images of Spark Discharge / Plasma Kernel from (a) Pulsed Energy Plug and (b) Conventional Spark



Source: GTI

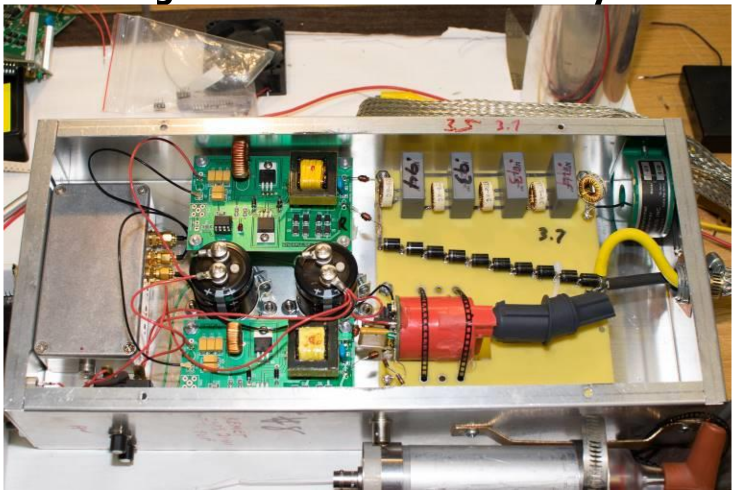
C2 Module

The C2 modules consist of the following main components:

- Logic board
- High voltage power supply for the C2 follow-on current
- High voltage power supply for the CDI
- CDI
- C2 pulse forming network

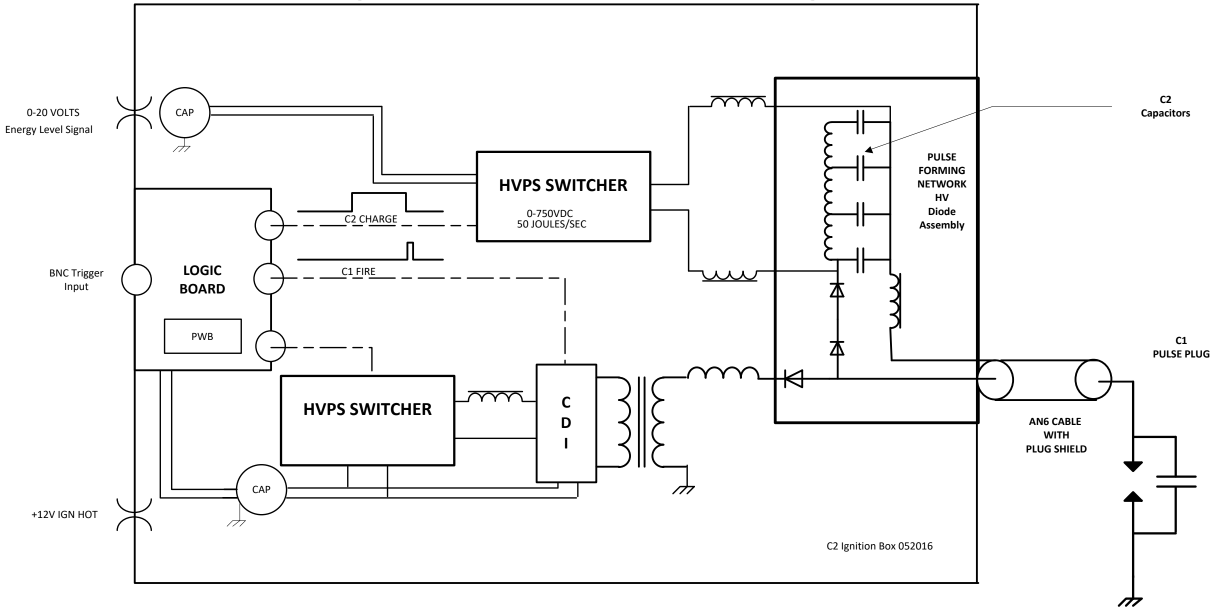
Figure 6 shows an assembled C2 module; Figure 7 shows a block diagram of the module.

Figure 6: C2 Module Assembly



Source: GTI

Figure 7: C2 Module Block Diagram



Source: GTI

CHAPTER 4: Advanced Ignition Testing

Early project concepts outlined testing both systems on a twin turbocharged V8 engine. Due to schedule considerations, Enerpulse's naturally aspirated, non-EGR, 5.7 liter gasoline engine was converted to a supercharged, cooled EGR, port fuel injected, natural gas fueled configuration. Furthermore, Ricardo installed a centrifugal supercharger on the engine in order to best simulate a turbocharger. Among other things, this conversion involved:

- Performing engine simulations to develop an initial calibration.
- Fabricating supercharger mounts.
- Fabricating the exhaust system, EGR valve, and cooler mounts.
- Modifying the intake and exhaust headers to accept the EGR.
- Modifying the cylinder head configuration so the supercharger and cylinder pressure sensor did not interfere with each other.
- Installing new injectors.
- Modifying the fuel rail.

Experimental Setup

A series of steady state tests was performed on an automotive V8 engine, equipped with electronic fuel injection properly sized for natural gas operation. The engine tested was a General Motors (GM) L31-R long block, equipped with a GM tuned port injection manifold with individual fuel injectors for each cylinder. Specifications for the engine are listed in the Table below.

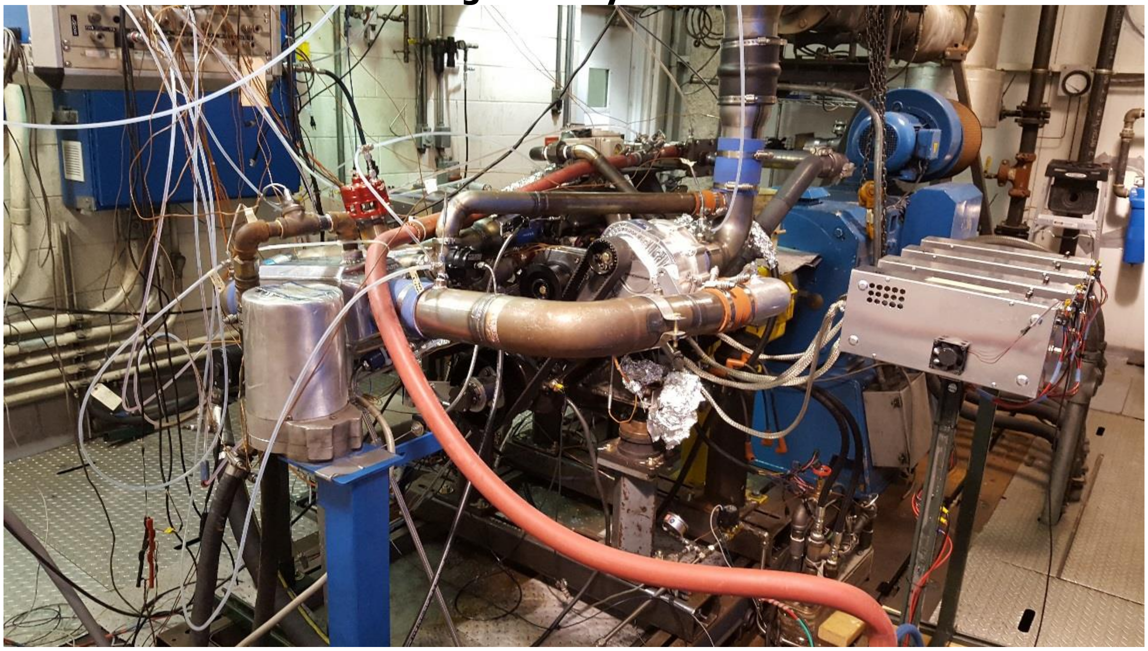
Table 1: V8 Engine Specifications

Specification	Value
Bore [in]	4
Stroke [in]	3.48
Compression Ratio [-]	8
Injection Pressure [kPa]	700

Source: GTI

The experimental test set up is shown in Figure 8. The engine was connected to a Schenk DYNAS HD600 dynamometer with an Alstom AC drive and controlled by a Schenk dynamometer controller. Torque measurements were made by a GIF in-line torque meter. A standard five-gas Horiba MEXA-7100DEGR was used to sample raw exhaust emissions.

Figure 8: Experimental Test Setup of General Motors V8 Engine with Enerpulse C2 Ignition System



Source: GTI

Cylinder pressure measurements were performed only on Cylinder #8, using an Optrand D822D6-Q cylinder pressure transducer. A calibration factor of 25.817bar/V was used within the high speed data acquisition system and thermodynamic pegging was enabled for zero level correction. An AVL INDIMASTER ADVANCED high speed data acquisition system was used to collect crank angle resolved data, running AVL IndiCom V2.5 software.

An AEM Infinity ECU was used to control the engine, controlling both spark timing and fueling. For all operation, the engine was operated in open loop configuration, where the ECU did not receive feedback on the real-time air-to-fuel ratio. Baseline ignition tests were performed with AEM 30-2853 smart coils, capable of delivering up to 118 milliJoules to the spark plug. Five O Motorsports' 2000cc/min peak and hold style fuel injectors were used to deliver the natural gas to the engine. These injectors were sized to be able to adequately deliver natural gas to the engine throughout all operation points.

Pipeline natural gas was used for testing, and delivered to the engine from an external gas compressor at 700kPa. Representative compressed natural gas composition from the Ricardo Burr Ridge test facility is shown in Table 2.

Table 2: Representative Compressed Natural Gas Composition from Ricardo Burr Ridge Test Facility

Composition	Value
Lower Heating Value [BTU/scf]	953
Methane Number	86
Hydrogen to Carbon Ratio [-]	3.89
Oxygen to Carbon Ratio [-]	0.013
Nitrogen to Carbon Ratio [-]	0.007

Source: GTI

Combustion Metrics

Engine stability under dilute conditions was quantified using the coefficient of variance of indicated mean effective pressure (COV_{IMEP}). This is defined as the standard deviation of IMEP divided by the mean IMEP, over the total number of engine cycles collected. The researchers collected 150 engine cycles for each high speed data point. A 3 percent limit was imposed for this testing. In a vehicle application, exceeding 3 percent COV_{IMEP} would signify drivability issues in which the driver would be able to feel engine misfire.

When considering the integrated heat release curve, it can be divided into segments to describe stages of the combustion event. The flame development angle is used to quantify the crank angle duration from the time of spark until some measurable amount of cylinder mass has been burned; the area integrated (AI) 10 percent location was chosen for these tests.[4] The combustion duration is used to quantify the length of the overall combustion event, where the AI-10 and AI-90 percent locations were chosen. AVL Indicom software was used to post process high speed data, with Krieger and Borman used to calculate the AI indexes.[5]

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[4] Heywood, J.B., "Internal Combustion Engine Fundamentals," McGraw-Hill Book

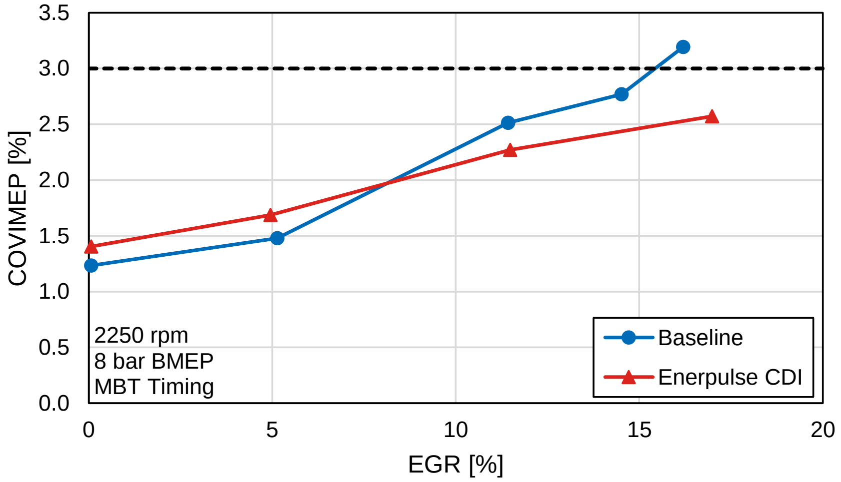
[5] Krieger, R. B., and Borman, G. L., 1967, “The Computation of Apparent Heat Release for Internal Combustion Engines,” ASME Paper No. 66-WA/DGP-4.

CHAPTER 5: Test Results

The HFD System used the same logic board, high voltage power supply, and CDI as the C2 System. In both systems, the spark event begins with the CDI discharge into the Pulstar spark plug. At its lowest power setting, the C2 System uses only the CDI circuit. When not in low power mode, the C2 System supplies a follow-on current immediately after the initial CDI discharge. The HFD System fires additional CDIs sequentially. Therefore, the C2 System running in low power mode is exactly the same as the first stage of the HFD System. The commonality of parts between the C2 System and the HFD System allowed for drawing direct conclusions regarding the HFD system based on the C2 System engine testing. When the C2 System low power mode test results are examined from the perspective of being equivalent to the HFD System running at one-quarter power, they show the promise of both of the systems. The C2 System low power mode tests show significant improvements in combustion stability under EGR dilute conditions.

Figure 9 shows the COV_{IMEP} as a function of an EGR sweep for the baseline and Enerpulse CDI ignition system. The COV_{IMEP} is used to quantify combustion stability and a 3 percent COV_{IMEP} limit was imposed for the testing performed. As seen, the baseline ignition system reached the 3 percent limit at 15.4 percent EGR. Due to the fact that there was only one instrumented cylinder on the engine, data were not able to be collected with the Enerpulse CDI system beyond the combustion stability limit, due to concerns of damaging the engine. However, the data in Figure 9 show that the Enerpulse C2 System in low power mode would have reached the 3 percent limit between 18-20 percent EGR, resulting in up to a 30 percent relative improvement in the dilution tolerance.

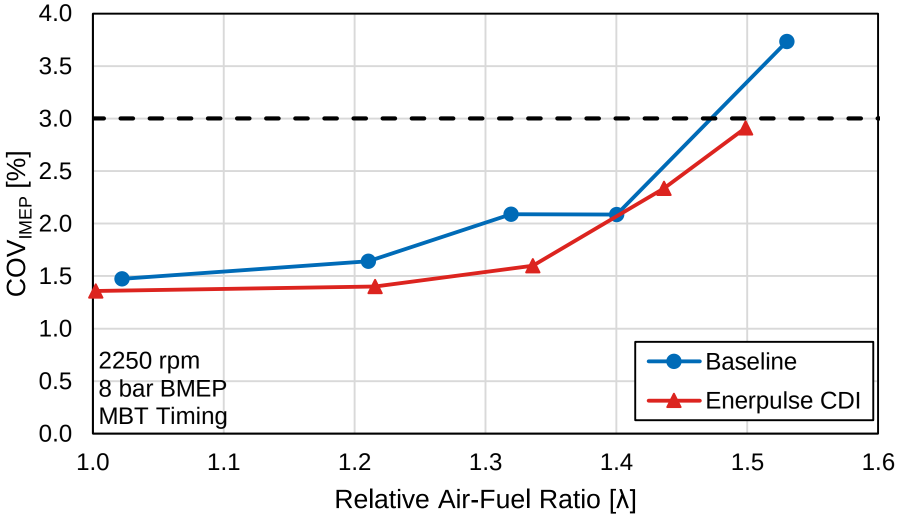
Figure 9: Coefficient of Variance of Indicated Mean Effective Pressure as a function of Exhaust Gas Recirculation Sweep for Baseline and Enerpulse Capacitive Discharge Ignition Systems



Source: GTI

Figure 10 shows the COV_{IMEP} as a function of a lean sweep for the baseline and Enerpulse C2 System running in low power mode. As the baseline ignition system was leaned out, the dilution tolerance limit was reached at $\lambda = 1.45$. While operating with the Enerpulse C2 System running in low power mode, the dilution tolerance limit was not exceeded again due to concerns of the non-instrumented cylinders. However, it is apparent that the dilution tolerance limit would have been met at λ =~1.5, a 3.4 percent improvement over the baseline.

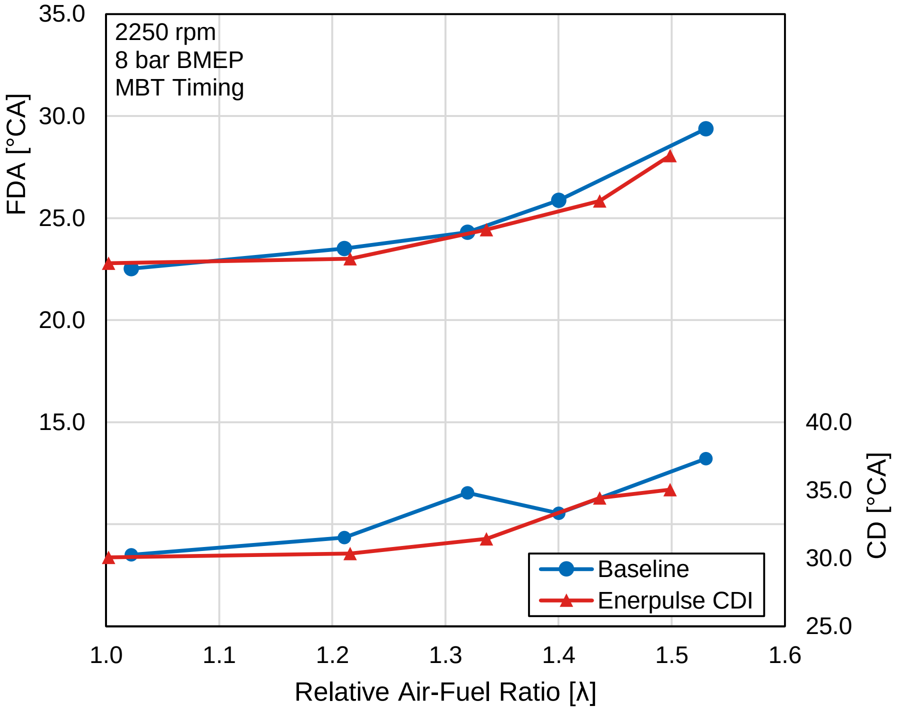
Figure 10: Coefficient of Variance of Indicated Mean Effective Pressure as a function of Lean Sweep for Baseline and Enerpulse Ignition Systems



Source: GTI

Figure 11 shows the flame development angle and combustion duration as a function of a lean sweep for the baseline and Enerpulse ignition systems. As the engine was leaned out, the flame development angle began to lengthen for both ignition systems due to the fuel-air mixing becoming harder to ignite. The Enerpulse system started to exhibit a shorter flame development angle for similar or leaner mixtures beginning at λ =1.4. While not as great of a change as the EGR dilution tests, at the leanest mixtures tested the Enerpulse system reduced the flame development angle by 1.3°CA relative to the baseline. At the same time, the combustion duration began to increase with increasing dilution. At the leanest conditions tested, the Enerpulse system reduced the combustion duration by 2.3°CA.

Figure 11: Flame Development Angle and Combustion Duration as function of Lean Sweep for Baseline and Enerpulse Ignition Systems



Source: GTI

While there were constraints due to the experimental test set up, the C2 System operating in low power mode showed promise of extending the dilution tolerance of an engine, further helping to improve fuel economy and reduce engine out emissions. Results indicated the EGR dilution tolerance could be extended as much as 30 percent from the baseline ignition system at 15.4 percent EGR. In addition, the lean limit was able to be extended by 3.4 percent from the baseline case of λ=1.4.

As literature has shown,[6] increasing energy under a dilute condition with COV_{IMEP} in the range of 3-5 percent allows for engine stability to be brought under the stability limit. The HFD System is essentially four C2 Systems in low-power mode firing in rapid succession delivering four times the energy across the spark gap than the C2 System operating in low power mode. Therefore, it is reasonable to assume that the HFD System would produce test results significantly better than those of the C2 System operating in low power mode.

The Enerpulse C2 System allows for a follow-on current to be applied to the spark plug gap. This is a user controlled parameter and is capable of delivering up to 1 joule of energy depending on the settings. For the data shown in Figure 12 and Figure 13, the C2 System was operated at 15V and dwell was increased up to 20ms, which coincides with ~0.5 joule of energy delivered to the spark plug.

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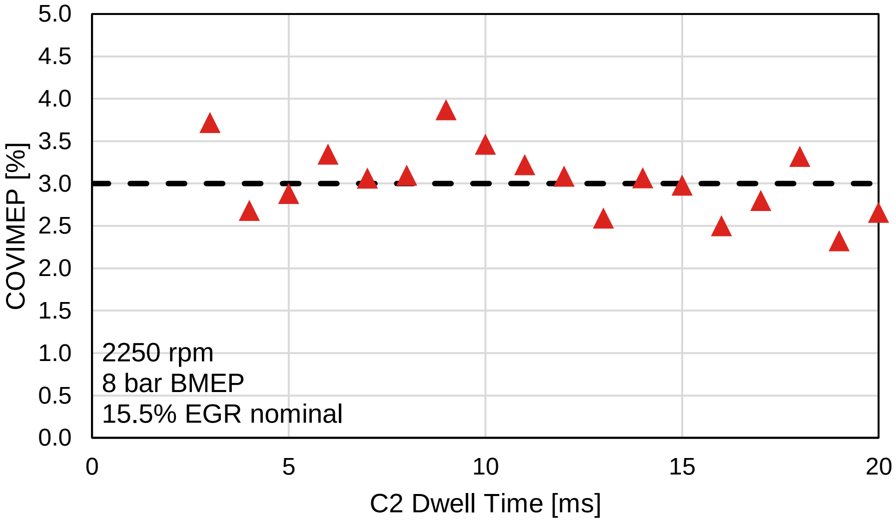
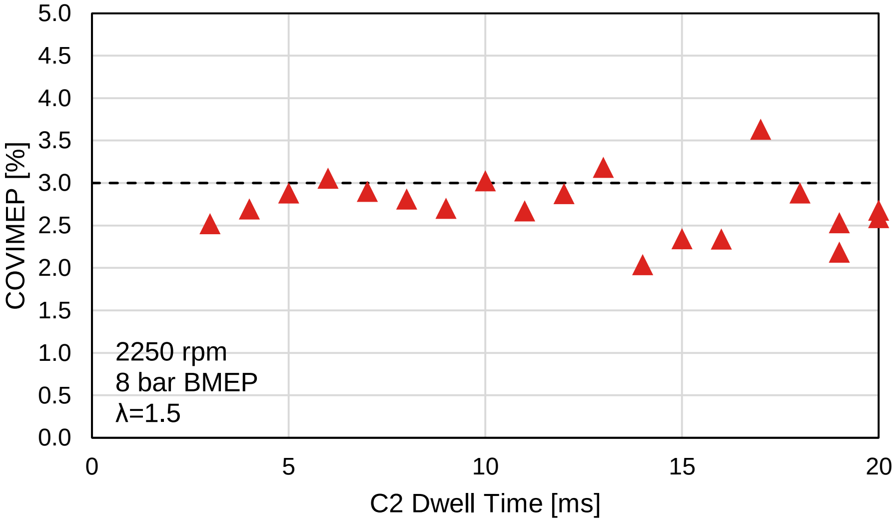
[6] Scarcelli, R., Zhang, A., Sevik, J. "Advanced Ignition Systems for Gasoline Direct Injection (GDI) Engines." 2017 Department of Energy Annual Merit Review.

Figure 12: C2 Energy Sweep at Exhaust Gas Recirculation Dilute Condition



Source: GTI

Figure 13: C2 Energy Sweep at Lean Condition



Source: GTI

For the data collected, there is not a distinct trend in the engine stability as dwell time (energy) was increased regardless of the dilution. Literature has shown[7] that increasing energy under a dilute condition with COV_{IMEP} in the range of 3-5% allows for engine stability to be brought under the stability limit. At the same time, once that energy threshold is met, adding additional energy does not add any benefit; meaning the stability level stays constant.

While literature has shown increasing energy is beneficial to engine stability, this unfortunately, was not observed in Figure 12 and Figure 13. After testing was completed, the Enerpulse C2 equipment was analyzed in the Enerpulse laboratory. It was determined that the box used for Cylinder #8 had a defective inductor and therefore caused the follow-on current

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[7] Scarcelli, R., Zhang, A., Sevik, J. "Advanced Ignition Systems for Gasoline Direct Injection (GDI) Engines." 2017 Department of Energy Annual Merit Review. https://energy.gov/sites/prod/files/2017/06/f34/acs084_scarcelli_2017_o.pdf.

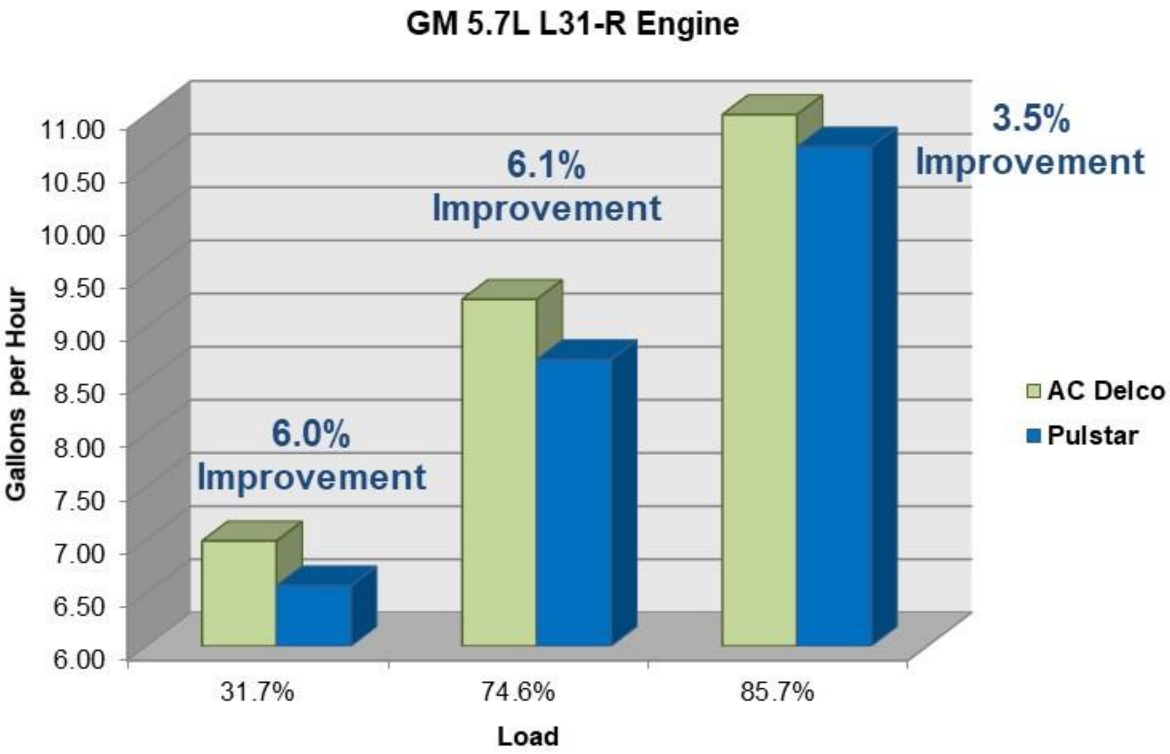
to drop out intermittently at higher energy levels. This means the system was varying between low power mode and follow-on current mode for a given dwell time, helping to explain why there is no distinct trend in the data. While some trends are shown of decreasing combustion instability for increasing energy levels, nothing conclusive can be drawn because of the defect in the test system.

CHAPTER 6: Conclusions

Projected Future Benefits

The use of n-PAC® plasma ignition on which these systems are based has shown great benefits in testing and real-world application. In a test performed by Roush Engineering, a GM 6.0L engine running on CNG had a 2.7 percent reduction in fuel use through the use of n-PAC® plasma ignition in an FTP 75 test. As seen in Figure 14, Enerpulse engine bench testing has demonstrated from 3.5 percent to 6.0 percent reduction in fuel consumption in steady state testing on a GM 5.7 liter engine.

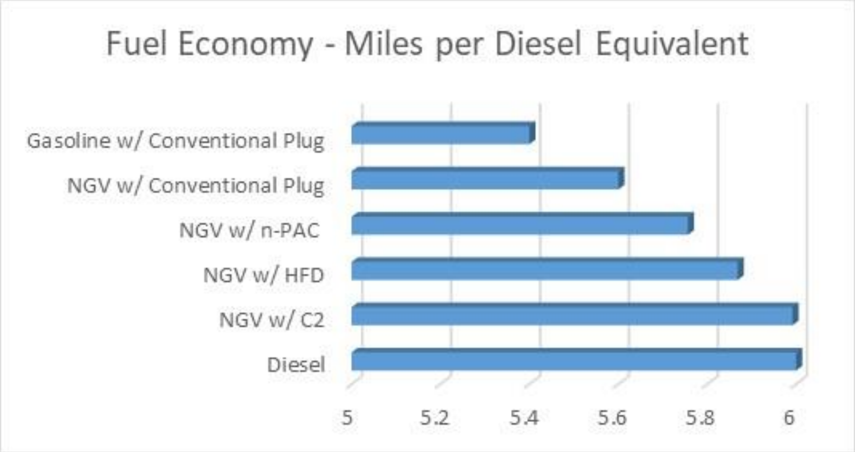
Figure 14: Fuel Economy Improvement from Pulstar Plugs



Source: GTI

The C2 and HFD Systems, when fully developed, will enable natural gas engines to approach fuel economy on par with diesel engines with significantly lower emissions. Fuel economy performance targets for both the HFD and C2 Systems are presented in Figure 15.

Figure 15: Fuel Economy Performance Targets of Proposed Technologies Relative to Competing Ignition Systems



Note: Assumptions are: fuel economy estimates (McBride, Bob, Inputs and Methods for the 2013 Transportation Energy Demand Forecast, California Energy Commission Workshop, presentation on Medium and Heavy-Duty Vehicle Movement in California, June 26, 2013) are 6 MPG for diesel, 5.4 MPG for gasoline and 5.6 MPG for natural gas using a conventional spark plug. A 2.8 percent increase with a natural gas engine using the current commercial n-PAC® technology will result in 5.76 MPG. A 20 percent improvement in lean burn capability with a natural gas engine using high frequency discharge ignition will result in 5.87 MPG while 5.99 MPG with a compressed natural gas engine using C2 ignition can be realized with a 30 percent improvement in lean burn capability.

Source: GTI

The ability to reduce NOx emissions with HFD and C2 Systems is directly related to the resulting increased ionization of the fuel mix. This ionization leads to the generation of radical molecules with a greater tendency to react with each other instead of the N_2 present in the combustion chamber.

Thanks to the close-coupled peaking capacitor in the Pulstar spark plug, the energy from the C2 and HFD Systems is delivered in very short high-energy bursts. This produces significantly higher levels of ionization than other spark plug based ignition systems, and testing to date, with the systems running at a fraction of their potential, has demonstrated the ability to achieve higher levels of EGR leading to much lower NOx emissions. When HFD and C2 are integrated with cooled EGR and advanced three-way catalyst systems, additional fuel economy, greenhouse gas, and NOx benefits can be realized.

While both systems showed promise, additional optimization and testing needs to be performed to determine their full capabilities. In addition, further development work needs to be performed to harden the electronics, reduce manufacturing costs, and reduce packaging size. Enerpulse is performing additional testing while continuing conversations with engine and truck manufacturers to commercialize one or both of the systems. Potential partners include Power Solutions International, Cummins Westport, and Alkane Truck. Furthermore, the plasma systems developed in this project are targeted toward the mobile market; however, they can also be applied to stationary engines that are used in power generation and natural gas compression.

As technology advances, automotive manufacturers will continue fuel economy improvements as well as reduce the overall vehicle emission signature. For United States automotive manufacturers, it is most common to use EGR in a spark-ignited engine in order to maintain compliance while using a traditional three way catalyst after-treatment system. As EGR rates begin to increase, the limit of traditional spark ignition systems begin to be approached. Advanced ignition systems serve as a means to enable high EGR rates, reducing emissions and improving fuel economy.

Recommendations

While there were constraints due to the experimental test system, the Enerpulse system showed promise of extending the dilution tolerance of an engine, further helping to improve fuel economy and reduce engine out emissions. Results indicated that even with the systems operating at partial power, the EGR dilution tolerance could be extended as much as 30 percent, from the baseline ignition system at 15.4 percent EGR. In addition, the lean limit was able to be extended by 3.4 percent from the baseline case of λ =1.4. Further improvements are probable with the systems operating consistently at full power.

Recommendations for further testing, beyond the scope of this project, include improving the internal circuitry of the Enerpulse system to improve durability. Another area of interest is to provide multiple spark plug designs for testing, in order to form the flame kernel over a larger volume. Enerpulse will be seeking a partnership with a vehicle or engine manufacturer or a large fleet end user as well as exploring research grant opportunities.

LIST OF ACRONYMS

Term	Definition
AI	Area integrated
CDI	Capacitive discharge ignition
COV_{IMEP}	Coefficient of variation of indicated mean effective pressure
DC	Direct current
ECU	Engine control unit
EGR	Exhaust gas recirculation
EPIC	Electric Program Investment Charge
GM	General Motors
GTI	Gas Technology Institute
HFD	High frequency discharge ignition
kV	Kilovolt
mJ	Millijoules
MW	Megawatt
MPG	Miles per gallon
NOx	Nitrogen oxides
Psi	Pounds per square inch