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Energy Research and Development Division

FINAL PROJECT REPORT

Development and Demonstration of a Production-Intent Transient Plasma Ignition System for High Efficiency 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.

Development and Demonstration of a Production-Intent Transient Plasma Ignition System for High Efficiency Natural Gas Engines is the final report for the Development and Demonstration of a Production-Intent Transient Plasma Ignition System for High Efficiency Natural Gas Engines project (Contract Number PIR-16-024) conducted by Transient Plasma Systems, Inc. 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

Transient Plasma Systems, Inc. (TPS) developed and demonstrated an advanced transient plasma ignition technology that improves efficiency and competitiveness of heavy-duty natural gas engines. The transient plasma ignition system produces high peak power, low energy, nanosecond duration electrical pulses that generate a highly reactive plasma instead of the thermal spark or arc generated by conventional ignition systems. Before this project, TPS conducted more than 20 single-cylinder engine tests with multiple partners to demonstrate the capability of this advanced ignition technology to extend exhaust gas recirculation (EGR) limits, enabling significant gains in brake thermal efficiency. This project focused on scaling this technology to drive multiple engine cylinders from a common power supply using solid-state components that are capable of compliance with automotive grade requirements. TPS partnered with Argonne National Laboratory to conduct instrumented engine experiments to investigate the scalability of results from past single-cylinder tests to a commercially available, heavy-duty multi-cylinder engine. All engine testing was conducted on the Cummins Westport, Inc. ISX12N, a production on-road natural gas engine available for heavy-duty trucks. Engine testing at Argonne National Laboratory demonstrated a more than 25 percent extension of EGR dilution tolerance with stable engine operation, 30 percent reduction in NOx emissions, greater than 10 percent reduction in CO emissions, and greater than 2 percent relative improvement in efficiency without updated fuel maps. Further optimization with updated fuel maps would enable additional efficiency gains from using the transient plasma ignition system. Transient plasma ignition technology can be integrated with existing natural gas engines to accelerate their adoption over conventional diesel engines, resulting in greenhouse gas and criteria pollutant emission reductions.

Keywords: natural gas vehicles, energy efficient, environmentally friendly, ignition, non-thermal plasma, nanosecond pulsed power, dilute combustion, transient plasma, plasma assisted combustion

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EXECUTIVE SUMMARY

Background

California's transportation sector accounts for 41 percent of the state's greenhouse gas (GHG) emissions. Reducing GHG emissions from vehicles is critical to achieving California's climate change goals and clean air standards. Natural gas, which is largely methane, releases less carbon dioxide (CO_2) and almost no particulate matter (PM) for the same amount of energy as diesel fuel – the fuel used in nearly all heavy-duty trucks, delivery vehicles, buses, trains, ships, boats and barges, farm, construction and heavy-duty military vehicles and equipment. Companies such as Cummins Westport Inc. have developed ultra-low oxides of nitrogen (NO_x) emission natural gas engines for heavy-duty truck – certified to a NO_x emission level that is 90 percent below the existing federal standard. These engines must compete favorably with their diesel alternatives in efficiency, maintainability, and overall operational costs. This project developed a solution to help meet those targets for use in existing or future heavy-duty natural gas vehicles, thereby improving the competitiveness of natural gas vehicles by enabling performance similar to diesel engines.

Project Purpose

Although natural gas engines emit fewer GHG, PM, and NO_x emissions than diesel engines, there is a need to increase natural gas engine efficiency with minimal additional capital or operational costs to improve their market competitiveness with diesel engines. The ignition characteristics of natural gas fuel present challenges for meeting these requirements since high-energy electrical sparks are often used to ignite the high-pressure fuel-air mixture which can lead to premature erosion of the spark plugs. This project advanced transient plasma low-energy ignition technology toward a production system and demonstrated performance on a production natural gas engine. Short, high-voltage electrical pulses produce transient plasma, which consists of low-temperature gas and high-energy electrons. The high-energy electrons enhance ignition and assist with the combustion process. Transient plasma ignition can achieve stable combustion with much lower energy than conventional spark ignition, extending spark plug durability and reducing maintenance costs and associated down time.

Building on previous work on single cylinder research engines, this project demonstrated transient plasma ignition in a production natural gas engine with six cylinders. A successful multi-cylinder engine test proves that the transient plasma ignition technology has matured beyond the component level and can now operate in a relevant environment as a unified system. The project also focused on refining the core transient plasma ignition technology, collecting engine data to allow performance predictions in various engines, and understanding the economics and effectiveness of such a system when integrated into vehicles. The outcome of this research is intended to attract the interest of existing heavy-duty engine manufacturers to help drive a more rapid transition to commercially viable natural gas replacements to diesel.

Transient plasma ignition systems will benefit California's natural gas ratepayers by improving the efficiency, performance and competitiveness of low emission natural gas vehicles. Transient plasma ignition systems can provide these benefits by enabling stable and efficient combustion of dilute natural gas mixtures using low-energy pulses. High dilution levels reduce knock tendencies – premature combustion – by lowering combustion chamber temperatures, but higher ignition energy is required to maintain stable combustion. Mitigating knock enables engine design decisions that can increase fuel efficiency, such as increasing the compression ratio of the pistons.

The potential benefits of changing portions of California's medium and heavy-duty truck fleet from diesel to natural gas using transient plasma ignition include:

- A greater than 20 percent reduction in greenhouse gas emissions with additional reductions possible if using renewable natural gas.
- Reductions in petroleum consumption – 140 million gallons of diesel fuel per year in California at a 10 percent adoption rate.
- A 90 percent reduction in NO_x emissions, including NO_x control at low loads where diesel vehicles tend to have higher emissions.
- Higher engine efficiency – higher boost pressures and compression ratios can be used compared to conventional ignition systems.

Project Approach

The team comprised of Transient Plasma Systems, Inc., responsible for technology development, and Argonne National Laboratory, responsible for laboratory testing on a production engine. Additionally, Cummins Westport Inc. provided the engine and engineering support for setting up and running the demonstration.

The project developed a multi-cylinder ignition system and demonstrated it on a production natural gas engine. To develop the hardware for the first multi-cylinder demonstration of transient plasma ignition, Transient Plasma Systems, Inc. initially developed the control strategy and architecture, followed by detailed circuit designs, prototype circuit boards, connectors, and control software. Transient Plasma Systems, Inc. coordinated with Argonne National Laboratory and Cummins Westport Inc. to plan the engine test so the prototype ignition system could be connected to the engine system and run safely and effectively. Having access to the expertise, personnel and equipment at Argonne National Laboratory was crucial to gathering data on the stability, efficiency and overall performance of the prototype ignition system.

There were unexpected challenges related to implementing new solid-state switching technology to send perfectly timed transient plasma pulses to multiple cylinders. Transient Plasma Systems, Inc. resolved the challenges with troubleshooting techniques, circuit redesigns, and continual system-level testing. Non-technical challenges included managing time and budget to accomplish the objectives in this first-of-its-kind advanced ignition technology full engine test.

While cost was taken into consideration for this single prototype, future cost reductions will be realized via the economies of scale available to an ignition system for the transportation market.

A technical advisory committee was formed and included Professor Martin Gundersen and Dr. Andy Kuthi of the University of Southern California, both experts in pulsed power for a variety of commercial and research applications. The committee advised the research team on technology development, engine integration, and engine testing.

Project Results

This project successfully met the goals of advancing transient plasma ignition technology toward a production system and demonstrating performance on all cylinders of a production natural gas engine. Transient Plasma Systems, Inc. executed pilot studies, evolved previous designs to meet the multi-cylinder operation challenges, and then tested and validated the system prior to a successful engine demonstration at Argonne National Laboratory. During in-house testing of the pulse generator used to produce the transient plasma prior to engine testing, the research team discovered electronic hardware failures. The failures were caused by electromagnetic noise produced by the pulse generator's fast switching of high-voltage power. If enough noise is received by nearby sensitive electronic components, those sensitive components can be damaged. The team mitigated the issue, but the system was limited to achieving about 70 percent of the desired output voltage. Nevertheless, the system performed well when running the heavy-duty commercial natural gas engine during final testing.

The engine demonstration compared conventional spark ignition to transient plasma ignition under standard engine conditions. The transient plasma system performed reliably, resulting in similar performance to standard spark ignition in overall efficiency, stability, and emissions. The benefits of transient plasma ignition were observed when the team pushed the performance of the engine beyond the limits of the standard spark ignition system. Natural gas engines can only tolerate limited air-fuel mixture dilution levels. While the potential efficiency gains from increasing dilution are significant, exceeding the manufacturer's dilution limit leads to unstable operation when using traditional spark ignition. Performance testing demonstrated that transient plasma ignition can increase dilution rates by more than 25 percent without losing engine stability. As a result of operating at the increased dilution enabled by transient plasma ignition, the team observed a 30 percent reduction in NO_x emissions, a greater than 10 percent reduction in CO emissions, and a greater than 2 percent relative improvement in efficiency. These benefits are significant because the fuel map for this production engine was not changed (fuel maps characterize an engine's fuel usage across its entire operating range and normally require updates to optimize the efficiency gains from using an advanced ignition system). Based on previous single cylinder engine tests with transient plasma ignition technology, enabling additional dilution tolerance and updating the fuel map can result in fuel economy gains of more than 20 percent.

Based on this successful demonstration, the work remaining on the path to commercialization includes further refinement of the system architecture to improve system size, weight, and cost.

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

Transient Plasma Systems, Inc. provided the outcomes of this project to industry stakeholders through news releases, presentations at natural gas and engine industry forums such as the Natural Gas Vehicle Technology Forum and Virtual Engine Research Institute and Fuels Initiative Workshop, and teleconferences with known entities such as engine original equipment manufacturers. By partnering with key industry players such as Cummins Westport Inc. and Southern California Gas Company on the project, Transient Plasma Systems, Inc. ensured the potential for continued progress towards commercialization with applications in the natural gas and the gasoline engine markets. Transient Plasma Systems, Inc. plans to target the medium- and heavy-duty engines in transportation and power generation sectors followed by the passenger car market. Public relations efforts have resulted in media coverage across industry and business outlets. Transient Plasma Systems, Inc. plans to share this report with interested regulatory agencies, engine original equipment manufacturers, fuel suppliers and end users to inform them on the potential of transient plasma ignition technology to reduce fuel consumption and greenhouse gas emissions from natural gas engines.

Benefits to California

Transient plasma ignition systems will benefit California's ratepayers by accelerating a transition away from diesel engines in heavy-duty vehicles and substituting in part through low-emission natural gas engines.

Burning natural gas in engines produces 23 percent fewer CO_2 emissions than the combustion of diesel fuel, however, natural gas engines are less efficient than diesel engines, offsetting some of the CO_2 emission reductions. If future natural gas engines are made more efficient, natural gas will be even more favorable from a CO_2 standpoint compared to diesel. Turbocharging and increasing compression ratio are two strategies to improve the efficiency of natural gas engines, however, both necessitate improved ignition systems.

If natural gas engines can be improved to within 10 percent of the efficiency of diesels for Class 8 heavy-duty vehicles, fuel savings will translate to about $6,500 saved and 7,660 pounds of CO_2 emission reductions per year per vehicle. If just 10 percent of the 1,720,000 registered Class 8 vehicles nationwide transitioned to natural gas engines, the annual savings would be $1.1 billion per year and CO_2 emissions would be reduced by 1.3 billion pounds per year. California would see annual fuel cost savings of $82 million and 97 million pounds of CO_2. Additional dollar and CO_2 emissions savings would occur if medium-duty vehicles also transitioned to natural gas, but these additional savings are not estimated here.

In a recent study, researchers found that short-term exposure to air pollution (even at levels generally considered safe by federal regulations and the World Health Organization) significantly increased hospital admissions and associated healthcare costs. Small increases to exposure to ambient fine particulate matter, such as that associated with vehicle traffic and diesel engines, was associated with thousands of additional annual hospital admissions and approximately $100 million of additional annual healthcare costs in the United States. These studies show how vehicle emissions adversely affect the health of Californians. Transient plasma ignition is expected to encourage a more rapid and complete transition away from diesel towards cleaner alternatives, including natural gas engines with very low particulate matter emissions. In addition, transient plasma ignition technology can extend dilute-burn capability, which can reduce NOx emissions by 30 percent or more.

Heavy-duty natural gas vehicles are currently available in limited quantity and are higher priced compared to conventional diesel vehicles. Performance improvements from transient plasma ignition can help accelerate adoption of natural gas vehicles and achieve sufficient cost and volume scales to better compete with diesel.

CHAPTER 1: Introduction

California's transportation sector accounts for 41 percent of the state's greenhouse gas (GHG) emissions. Reducing GHG emissions from vehicles is critical to achieving California's climate change goals and clean air standards. Natural gas, which is largely methane, releases significantly less carbon dioxide (CO_2) and almost no particulate matter (PM) for the same amount of energy as diesel fuel, the fuel used in nearly all heavy duty-trucks, delivery vehicles, buses, trains, ships, boats and barges, farm, construction and heavy-duty military vehicles and equipment. Companies such as Cummins Westport (CWI) have developed ultra-low oxides of nitrogen (NO_x) emission natural gas engines for heavy-duty trucks– certified to a NO_x emission level that is 90 percent below the existing federal standard. These engines need to compete favorably with their diesel alternatives in terms of efficiency, maintenance and overall operational costs. This project developed a solution to help meet those targets for use in existing or future heavy-duty natural gas vehicles, thereby improving the competitiveness of natural gas vehicles by enabling performance similar to diesel engines.

Although natural gas engines emit fewer GHG, PM, and NO_x emissions than diesel engines, there is a need to increase natural gas engine efficiency with minimal additional capital or operational costs to improve competitiveness with diesel. The ignition characteristics of natural gas fuel present challenges for meeting these requirements: today, high energy sparks are often used to ignite the high-pressure fuel-air mixture which can lead to premature erosion of the spark plugs. At a fundamental level, combustion engines burn an air-fuel mixture. The higher the amount of air in that mixture, the more fuel-efficient the engine can be. Most ignition systems struggle to ignite air-fuel mixtures with higher amounts of air and less fuel. Higher energy sparks might help ignite such lean mixtures, but that approach leads to premature erosion of the spark plugs. In transient plasma ignition, though, radicals are produced directly, which is much more efficient, and therefore less energy is needed to achieve ignition even under increasingly dilute conditions.

Transient plasmas can be produced with other methodologies such as radio frequency corona, rather than nanosecond pulses, but the fast-rising voltage in the Transient Plasma Systems, Inc. (TPS) approach creates more radicals by more efficiently transferring energy into the fuel-air mixture. The goal of this project was to advance low-energy transient plasma ignition technology toward a production system and demonstrate performance on a production natural gas engine. The primary focus was on demonstrating ignition in multiple cylinders, as all previous published research was performed with single cylinder engine tests. A successful multi-cylinder engine test proves that the transient plasma ignition technology has matured beyond the component level and is now operating in a relevant environment as a unified system. Additional focus was on refining the core technology, collecting engine data that would allow prediction of the performance in various engines, and understanding the economics and effectiveness of such a system integrated into vehicles. The outcome of this research is intended to attract the interest of existing heavy-duty engine manufacturers to help drive a more rapid transition to commercially viable natural gas replacements to diesel.

This transient plasma ignition (TPI) system will benefit California's natural gas ratepayers by improving the efficiency, performance and competitiveness of low emission natural gas vehicles. TPI can provide these benefits by enabling stable, efficient, dilute-burn combustion of natural gas using low-energy pulses.

The potential benefits of changing large portions of California's medium and heavy-duty truck fleet from diesel to natural gas using transient plasma ignition include:

- A greater than 20 percent reduction in greenhouse gas emissions with additional reductions possible if using renewable natural gas.
- Reductions in petroleum consumption – 140 million gallons of diesel fuel per year in California at a 10 percent adoption rate.
- 90 percent reduction in NOx emissions, including NOx control at low loads where diesel vehicles tend to have higher emissions.
- Higher engine efficiency – higher boost pressures and compression ratios can be used compared to conventional ignition systems.

The project goal was to advance transient plasma ignition technology toward a production system and demonstrate performance on a production natural gas engine. The primary focus was on demonstrating ignition in multiple cylinders, as all previous published research was performed on single-cylinder engines or on a single cylinder of a multi-cylinder engine. The project also focused on refining the core technology, collecting engine data that would allow prediction of the performance in various engines, and understanding the economics and effectiveness of such a system integrated into vehicles. The outcome of this research is intended to attract the interest of heavy-duty engine manufacturers to help drive a more rapid transition to beneficial natural gas replacements to diesel.

CHAPTER 2: Project Approach

Multicylinder Transient Plasma Ignition System Development

The project goal was to develop a multicylinder TPI system based on the TPS existing non-thermal plasma ignition technology, and to demonstrate the system's capability to achieve an increase in combustion repeatability at high pressure, high-exhaust gas recirculation (EGR) conditions across a wider operating range than is capable with spark ignition systems. TPS partnered with Argonne National Laboratory and Cummins Westport Inc. (CWI) to implement an instrumented version of Cummins-Westport's production ISX12N six-cylinder natural gas engine at Argonne National Laboratory. TPS worked over the course of this grant to develop the six-cylinder ignition system, while Argonne worked in parallel to instrument the heavy-duty engine received from CWI and baseline its performance with the original equipment manufacturer (OEM) spark ignition system.

Chapter 2 describes the development approach taken by TPS to design and manufacture the initial six-cylinder prototype TPI system, as well as the work conducted by the team at Argonne National Laboratory to implement the engine test setup. TPS performed the following tasks to develop this new system:

1. Conduct pilot studies on natural gas engines and static combustion cells using the existing TPI prototype system previously developed by TPS. These pilot studies developed data to predict performance and optimize design parameters for the production-intent system.
2. Evolve circuit designs based on existing prototypes towards fitting into a compact package with the same form factor of existing technology in production natural gas engines so that it can be used with minimal capital investment. Design efforts focused on cost effective approaches capable of meeting the stringent specifications and regulations for automotive electrical systems.
3. Validate that circuit designs in the compact production intent prototypes can match, or surpass, the performance of existing lab bench ignition systems.

This project accomplished further study and refinement of the core TPI technology and proved its utility when applied to spark-ignited natural gas engines. The collected engine data will enable prediction of the performance in various engines and improve understanding of the economics and effectiveness of such a system when integrated into vehicles.

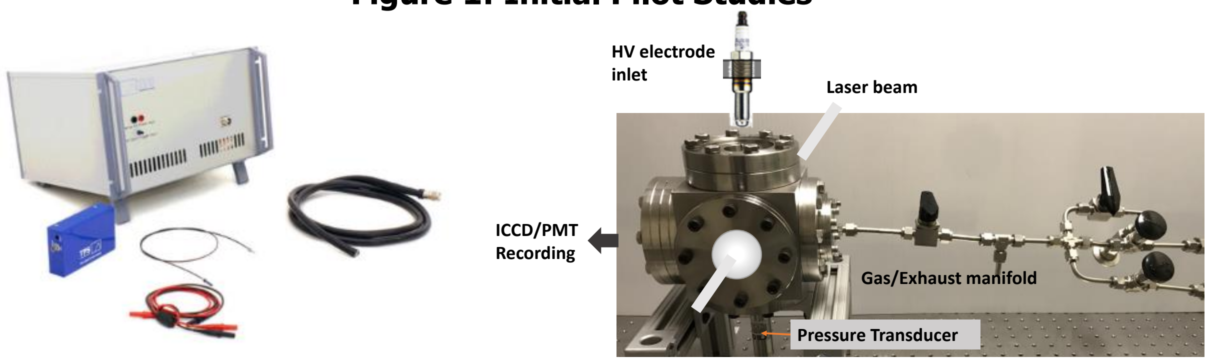
Task 1 – Conduct Pilot Studies

Based on the TPS previous experience conducting single cylinder engine tests and peer-reviewed academic papers,[1] nanosecond pulsed power parameters, including rise time, pulse

[1] Cathey, Charles D., et al., 2007, "Nanosecond plasma ignition for improved performance of an internal combustion engine." *IEEE Transactions on Plasma Science* 35.6: 1664-1668; Gundersen, Martin, et al., 20014, "*Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-mixed E85 SI Engine Operation*," No. SAND2014-1536C. Sandia National Lab (SNL-CA), Livermore, CA (United States); Sevik, James, et al., 2016, "Extending lean and exhaust gas recirculation-dilute operating limits of a

repetition rate/burst rate, pulse duration, and voltage amplitude all impact the combustion process by contributing to the enhancement of reactive species production. A comparison study of nanosecond pulsed atmospheric pressure plasma[2] showed more than three times higher maximum velocity of the streamer head and greater atomic oxygen production by 5-nanosecond (ns) voltage pulses compared with 140-ns voltage pulses at the same amplitude of 8 kilovolts (kV). It is known that the shorter rising time of the external pulsed voltage results in breakdown or initiation of the discharge occurring at a higher reduced electric field E/N (where E is the electric field and N is the number density of the gas). This leads to a higher ionization coefficient as well as a higher drift velocity of the electrons. Hence a shorter rising time of a high voltage pulse is associated with higher electron density and electron temperature, or a right-shifted (towards higher energy) highly non-equilibrium electron energy distribution, particularly during the discharge initiation and formation. This enhances the direct electron impact processes and affects the production of reactive species via heavy particle collisions, charge transfer, dissociative recombination, excitation transfer, associative attachment, and three-body processes, although sustaining the discharge and heavy particle collisions also requires a minimum duration of the external electric fields. The pulse repetition rate (PRR) is another important parameter that not only provides a quantitative "tuning knob" to the total generation of plasma species but also impacts the complete chemistry through the breakdown process and the variation in lifetimes of different excited species.

Figure 1: Initial Pilot Studies



Static cell experiments were conducted using an existing general purpose TPS pulse generator, SSPG-20X, which is capable of producing >20 kV, 10 ns duration pulse onto a 50 Ω coaxial cable. The goal of these tests was to select pulse parameters to drive the design of the multi-cylinder transient plasma ignition system.

Source: Transient Plasma Systems, Inc.

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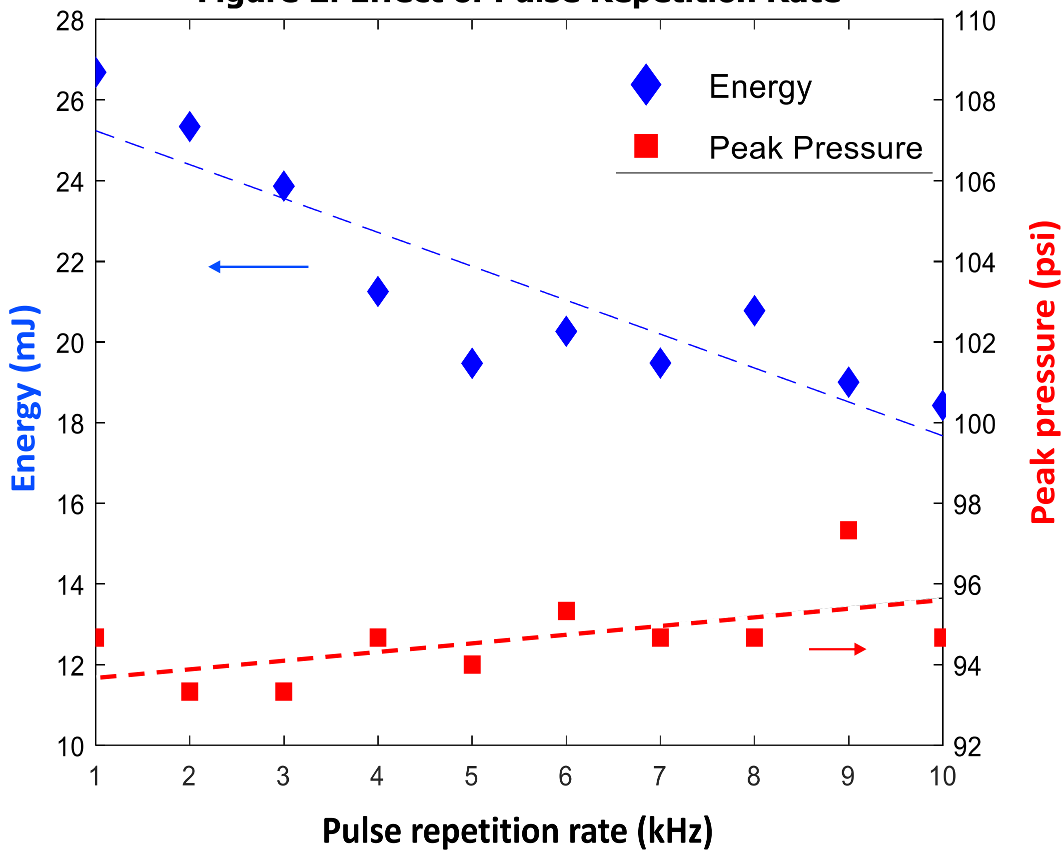
modern gasoline direct-injection engine using a low-energy transient plasma ignition system," *Journal of Engineering for Gas Turbines and Power* 138.11: 112807; Singleton, Dan, et al., 2010, "The role of non-thermal transient plasma for enhanced flame ignition in C2H4–air," *Journal of Physics D: Applied Physics* 44.2: 022001; Singleton, Daniel, et al., 2017, "Demonstration of improved dilution tolerance using a production-intent compact nanosecond pulse ignition system," *International Conference on Ignition Systems for Gasoline Engines (CISGE 2016)*. Springer, Cham; Sjöberg, Magnus, et al., 2014, "Combined effects of multi-pulse transient plasma ignition and intake heating on lean limits of well-mixed E85 DISI engine operation," *SAE International Journal of Engines* 7(4): 1781-1801.

[2] Jiang, C., et al., 2016, "Single-electrode He microplasma jets driven by nanosecond voltage pulses," *Journal of Applied Physics* 119: 083301.

Optimization of nanosecond TPI is a non-trivial task as it involves advanced low-temperature, atmospheric or higher-pressure plasma diagnostic studies for combustion, as well as device and system development in nanosecond pulsed power technology. Since the challenges of fielding plasma diagnostics at the relatively high pressures that are present in the engine at the time of ignition, the focus of this project was guided instead by static cell combustion experiments and by the data collected by TPS during previous single cylinder engine experiments. Figure 2 shows one of the more important findings that came out of the static combustion cell experiments that guided the selection of pulse parameters for the six-cylinder TPI system.

Figure 2: Effect of Pulse Repetition Rate



Multiple-pulsed plasma ignition for combustion in a static stoichiometric methane/air mixture at one atmosphere at various pulse repetition rates (PRRs): total energy deposited in the plasma and the peak pressure of combustion with respect to the PRR. Each ignition event was tested by applying four consecutive pulses at the specified repetition rate.

Source: Transient Plasma Systems, Inc.

In a controlled experiment where a burst of four pulses with a duration of approximately 10 ns was applied to a static stoichiometric methane/air mixture at a pressure of 1 atmosphere, TPS observed that the peak pressure measured during combustion went up, while the total energy deposited in the fuel/air mixture went down. This finding indicates that increasing the repetition rate of the pulse train, or reduces the time between the nanosecond pulses, has potential to improve combustion efficiency at a lower total energy cost. This finding is supported by empirical data that TPS has collected when increasing repetition rate on single-cylinder engine tests. Furthermore, the idea that radical accumulation may occur as the time between discharges is reduced, resulting in increased efficacy, is supported by work independent of TPS conducted at Wright-Patterson Air Force Base.[3]

Outside of this project, TPS was funded by a Department of Energy (DOE) Phase I Small Business Technology Transfer (STTR) grant (DE-SC0017880) in conjunction with Old Dominion University (ODU) to investigate the effect of pulse risetime on combustion. The literature on the effect of risetime effects below 5 ns is scarce, primarily because laboratory equipment that permits risetime adjustment is not available due to the difficulty of tuning this parameter. The literature that does exist, however, suggests that faster rising pulses may generate a larger concentrations of high energy electrons in the plasma, which are known to create beneficial reactive species, such as atomic oxygen and ozone.4 The data that TPS and ODU collected during this effort correlated to rises in peak pressure in static cell experiments; however, due to the difficulty of efficiently producing pulses with risetimes at 1 ns or faster, it was decided not to attempt to implement this feature as part of this effort to demonstrate thermal efficiency gains in the CWI six-cylinder natural gas powered engine as a result of TPI.

Based on these pilot studies, TPS selected the specifications outlined in Table 1 for the six-cylinder system, which is referred to as the transient ignition module (TIM). Based on the results that showed the positive effect of PRR, TPS decided to engineer a system capable of achieving a rate of 100 kHz, an order of magnitude higher than the 10 kHz TPS had previously used for most engine experiments. Due to the technical challenges inherent to achieving multi-cylinder operation, TPS decided to fix the other pulse parameter specifications at values that had previously yielded thermal efficiency gains up to 20 percent in prior engine tests.

Table 1: Target Specifications for Multicylinder Ignition Module

Pulse Parameter	Target Specification
Peak Voltage into 50 Ohm	20 kV
Pulse Duration (FWHM)	10 ns
Pulse Risetime (10-90%)	5-7 ns
Maximum Pulse Energy	75 mJ
Max Pulses per Burst	20
Pulse Repetition Rate	100 kHz

Source: Transient Plasma Systems, Inc.

A more thorough investigation of the effect of pulse risetime and repetition rate on plasma chemistry and combustion efficacy remains an important topic in this application space;

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[3] Lefkowitz, Joseph K., et al., 2015, "Schlieren imaging and pulsed detonation engine testing of ignition by a nanosecond repetitively pulsed discharge," *Combustion and Flame* 162, no. 6: 2496-2507; Lefkowitz, Joseph K., and Timothy Ombrello, 2017, "An exploration of inter-pulse coupling in nanosecond pulsed high frequency discharge ignition," *Combustion and Flame* 180: 136-147.

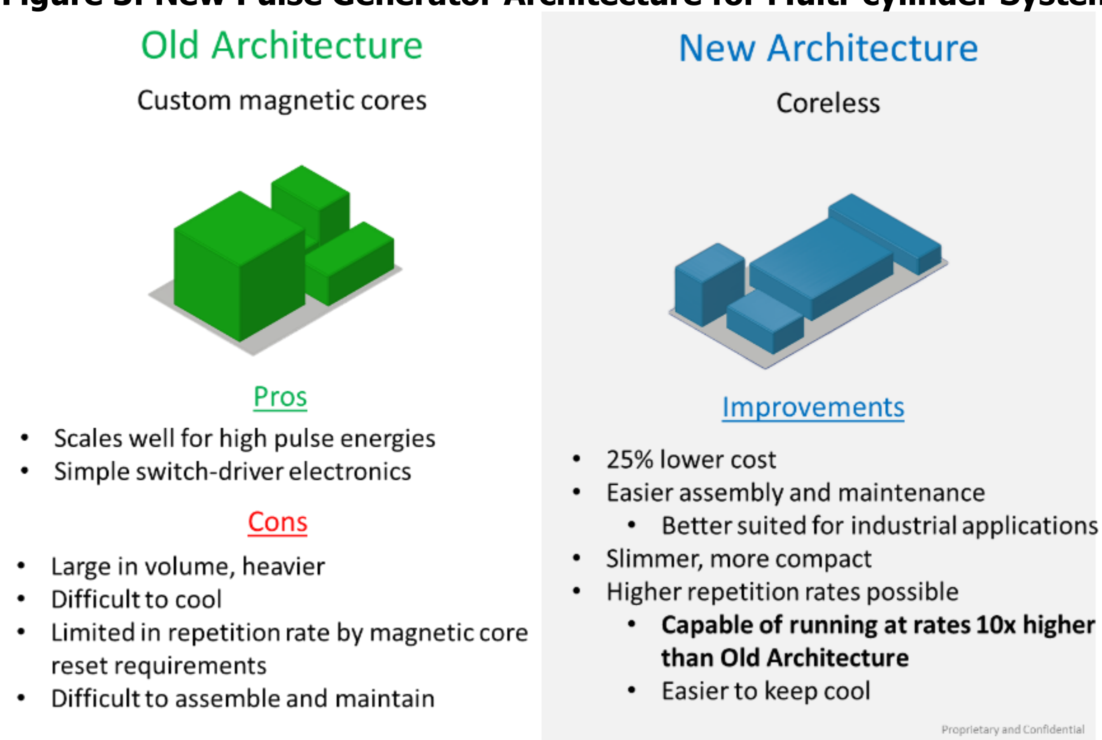
[4] Wang, Douyan, et al., 2010, "Pulsed discharge induced by nanosecond pulsed power in atmospheric air," *IEEE Transactions on Plasma Science* 38, no. 10: 2746-2751.

however, some technical breakthroughs must be made in pulsed power technology and components to realize a practical system with near-term commercial application.

Task 2 – Evolve Circuit Designs

Since the data from the pilot studies indicated that extending the pulse repetition rate (PRR) had potential to positively impact combustion at reduced peak power from the nanosecond pulse generator, TPS decided to implement a new pulse generating architecture designed to extend PRR capability. Extending PRR is achieved, in part, by eliminating magnetic materials from the pulse forming stage, which had previously been used as part of an inductive adding topology designed to multiply the voltage switched by the primary stage. The time-average flux balance requirement of magnetic materials is a problem for unipolar pulse technology as the time between pulses is reduced because there is less time to reset the cores. By reconfiguring the pulse generating circuitry to rely instead on air-core inductors and the appropriate snub circuits to dissipate reflected energy from cable/electrode mismatch, pushing the repetition rate to 100 kHz is a more straight-forward engineering task. It also reduces cost because the custom-made magnetic cores are no longer required.

Figure 3: New Pulse Generator Architecture for Multi-cylinder System

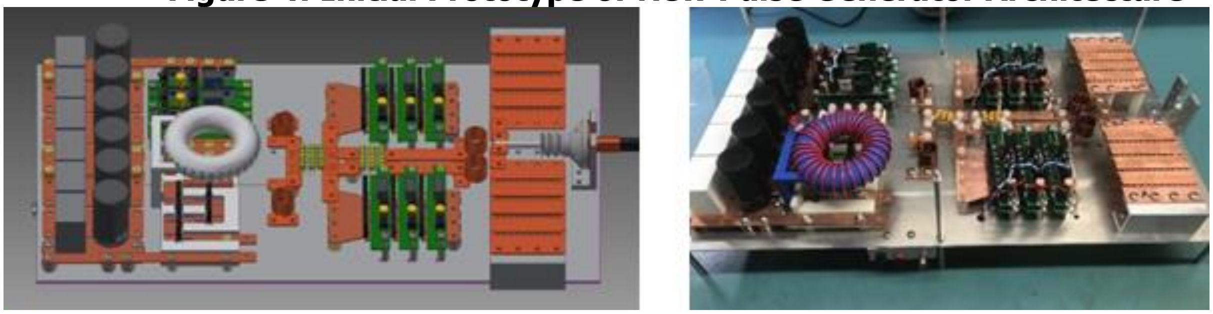


Source: Transient Plasma Systems, Inc.

New High PRR Architecture

An initial prototype of the new high PRR architecture was designed and a brass-board prototype was built, shown in Figure 4, to validate performance against SPICE simulation results. The voltage multiplication achieved by the voltage adding structure was replaced instead by a series-parallel switch array capable of holding off a higher voltage than the primary switches previously used in the inductive adding structure. This higher hold-off enabled the pulse forming circuitry to be charged to a higher voltage, eliminating the need for the voltage multiplication previously provided by the magnetic components. This initial prototype was used to work through a number of issues, included excessive capacitor heating under high load, electro-magnetic interference (EMI) picked up on the twisted pairs that deliver power to the isolated gate-drive electronics, and transient response and power rating for circuitry required to snub reflected energy from load mismatch.

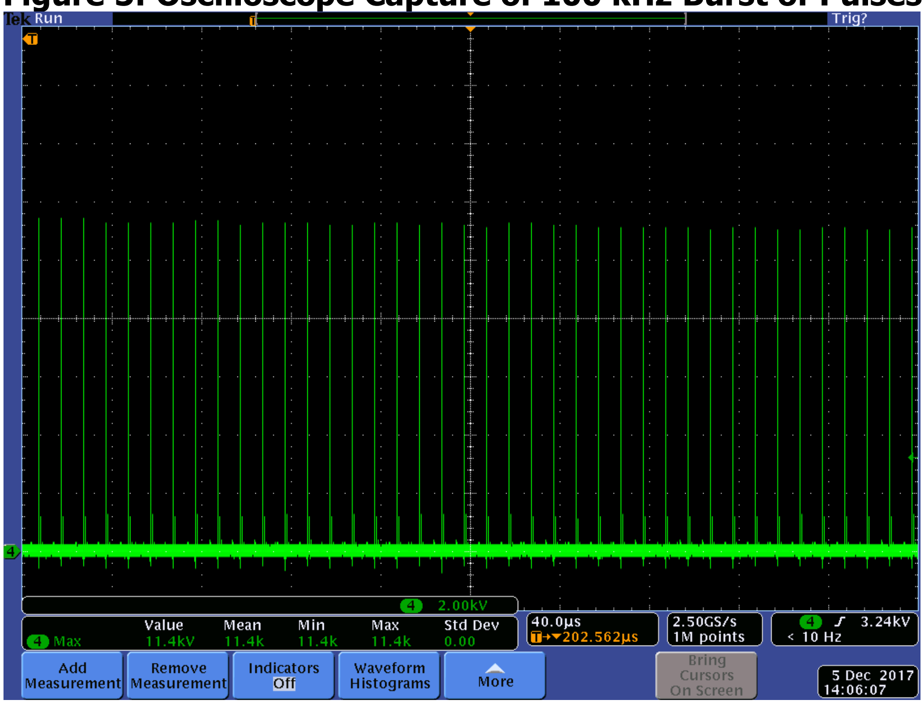
Figure 4: Initial Prototype of New Pulse Generator Architecture



Source: Transient Plasma Systems, Inc.

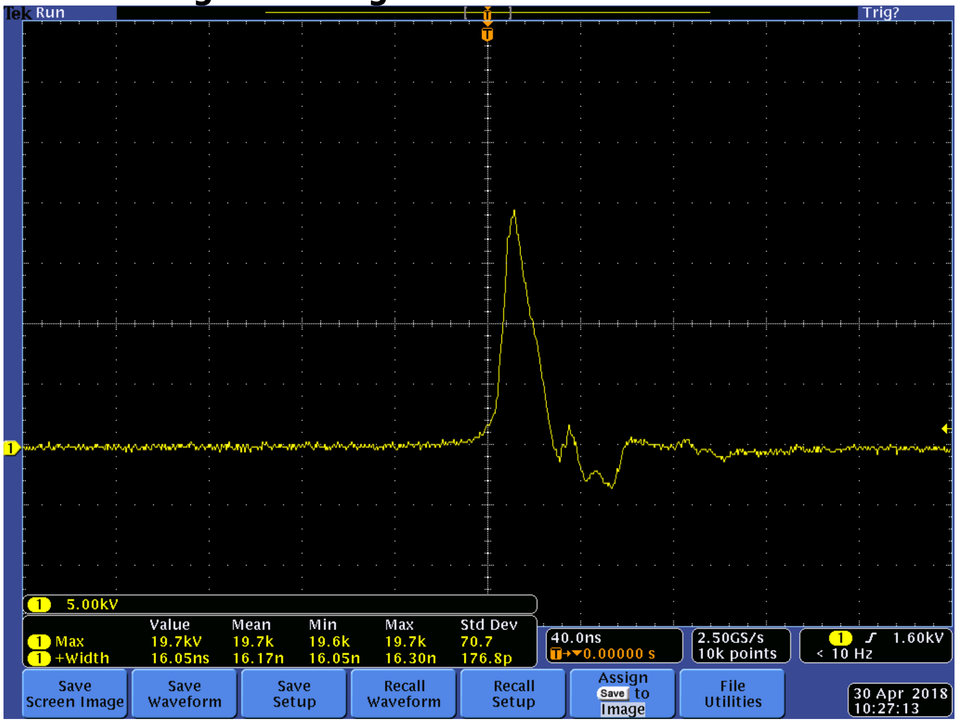
Figure 5 and Figure 6 show an oscilloscope trace capture taken from the prototype system producing a long burst of pulses at 100 kHz into a matched load.

Figure 5: Oscilloscope Capture of 100 kHz Burst of Pulses



Source: Transient Plasma Systems, Inc.

Figure 6: Single Pulse Trace Zoomed In



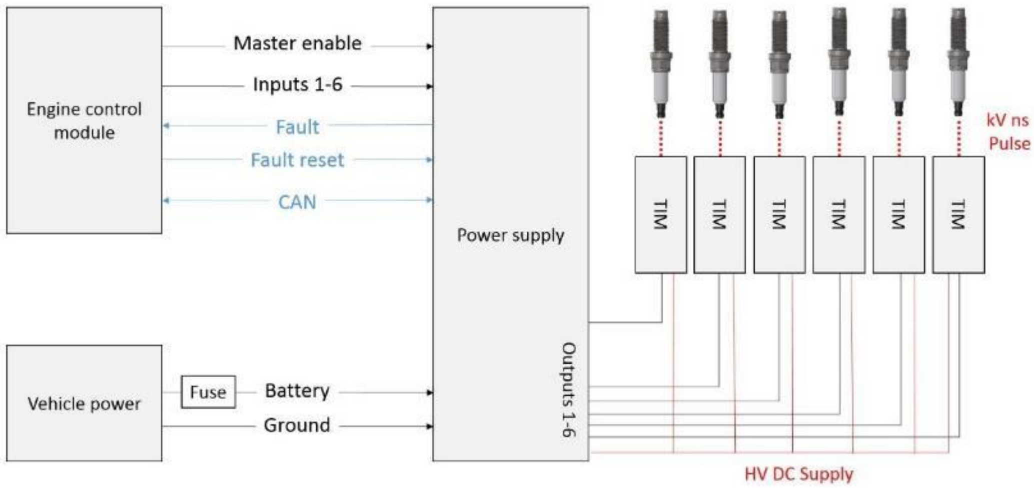
Source: Transient Plasma Systems, Inc.

High Voltage Transmission Gates for Multicylinder Operation

Once the new high PRR system architecture was verified, the primary technical challenge was designing a practical way to drive multiple cylinders. Compared to conventional ignition coil technology, it is much more difficult to implement a single switching supply and gate to sequentially steer the nanosecond duration high voltage pulses to the appropriate igniter. Most modern ignition systems have abandoned the distributor in favor of a coil-on-plug approach, which reduces EMI and can be manufactured at lower costs. This paralleled approach is an attractive path for TPI because it is technically straightforward; however, in an effort to reduce overall cost and size of the ignition module, TPS decided to develop a way to operate the six-cylinder engine off of a common nanosecond power supply with a gating system capable of steering the nanosecond pulses to the appropriate cylinder.

The initial concept and the block diagram for the ignition system architecture using a common nanosecond power supply with a gating system is shown in Figure 7.

Figure 7: Initial Conceptual Block Diagram for Multicylinder Transient Ignition Module



Source: Transient Plasma Systems, Inc.

In this diagram, a pulsed power supply interfaces with vehicle power and the engine control module (ECM), appropriately chops and steps up the DC level fed in from vehicle power, and then switches this energy into one of six TIM modules. Each TIM module compresses and rectifies the energy sent from the power supply to produce a unipolar, nanosecond duration, high voltage pulse. This type of topology is similar at the block diagram level to modern coil-on-plug spark ignition systems that have gained wide commercial adoption. In this case, the coil-on-plug is replaced by a TIM module that is connected directly to the plug, and the insulated gate bipolar transistor (IGBT) module that energizes each coil is replaced by the pulsed power supply. This approach is attractive for two primary reasons:

1. It confines the fast, high voltage signals, which are sources of EMI, to the plug/engine head interface, which is very easy to shield. The shielding prevents the electric and magnetic fields generated by the pulse from interfering with sensors and other electronics.
2. It is feasible to design and build robust, solid-state switches that are compliant with automotive regulations to work as high voltage transmission gates, steering the energy switched by the power supply to the appropriate TIM.

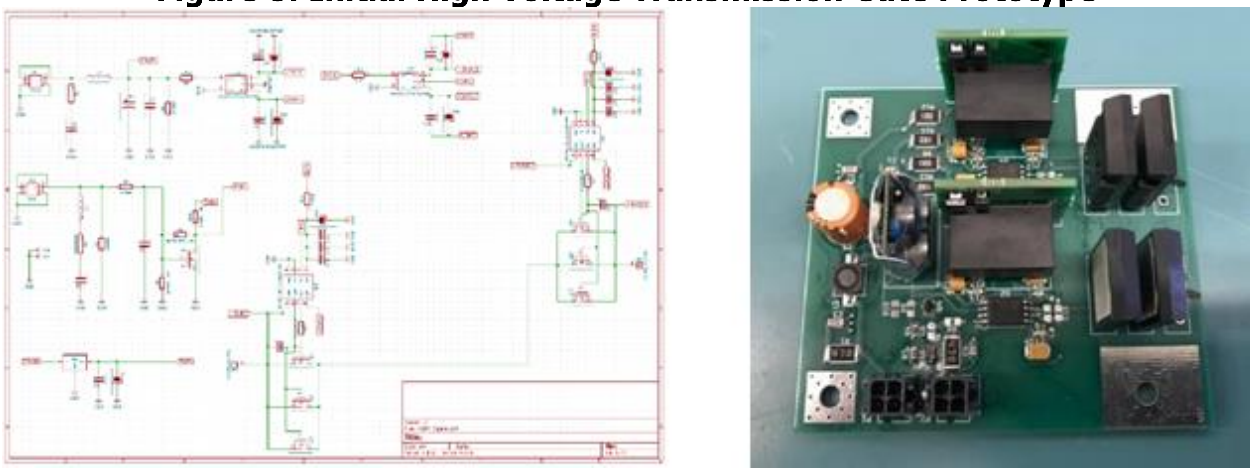
Regarding the second point above, it would not necessarily be impossible to build a solid-state automotive compliant switch to gate the high voltage nanosecond pulse, but it would be sufficiently complex and expensive to make this approach unviable.

The original vision for the high voltage transmission gates was to build a four-quadrant isolated switch based on mature, solid-state devices called IGBTs, which are commonly used in automotive ignition systems and are relatively power dense and inexpensive. Each gate would be modular and be installed at the output of the power supply, enabling the engine control unit (ECU) to switch on the appropriate channel in accordance with the firing sequence.

TPS designed and built an initial prototype (Figure 8) using a 4 kV IGBT manufactured by IXYS that can pulse up to 400 A. Though the turn-on response time of high voltage, high current IGBTs was too long to directly switch the nanosecond pulses, the devices are well suited to work as transmission gates, since they are required only to turn on and off at a rate that matches the engine's RPM. As an example, for an engine that redlines at 3600 RPM, each

IGBT will be required to switch on and off at a maximum frequency of only 30 Hz, well below their multi-kHz rating.

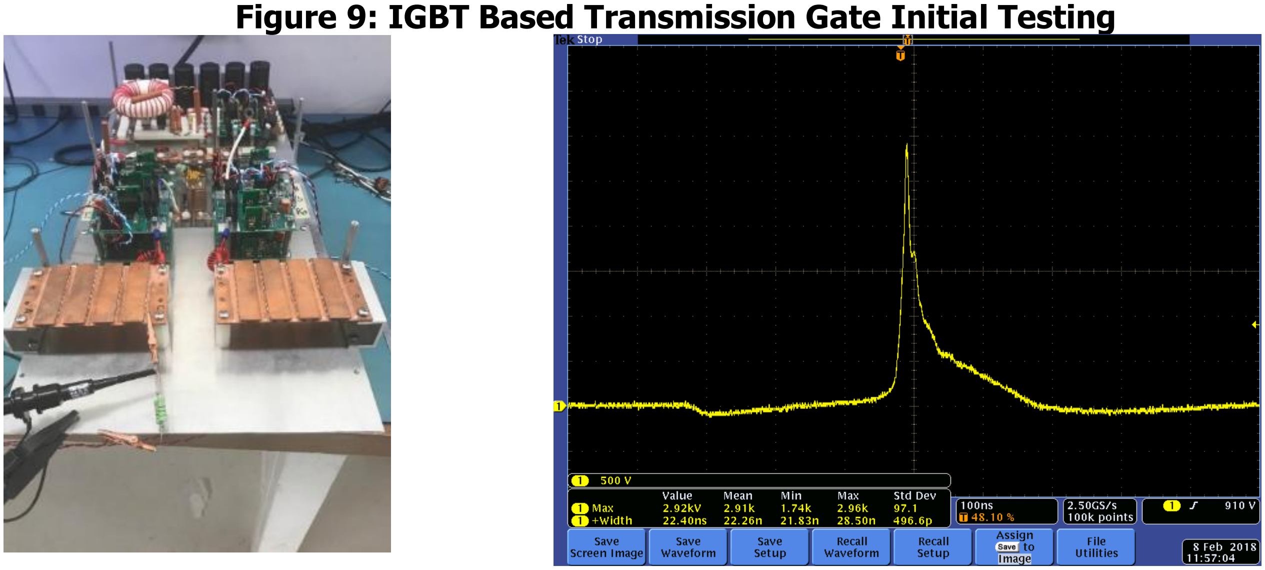
Figure 8: Initial High Voltage Transmission Gate Prototype



Source: Transient Plasma Systems, Inc.

As shown in Figure 9, the initial IGBT based prototype transmission gate was integrated into the brass board high PRR pulse generator for testing. The switching time and blocking capability of the IGBTs worked as expected, but the collector-emitter saturation voltage required across the bipolar transistor that provides blocking and conduction inside of the IGBT to achieve sufficiently high conduction resulted in unacceptably high insertion loss for the nanosecond pulses.

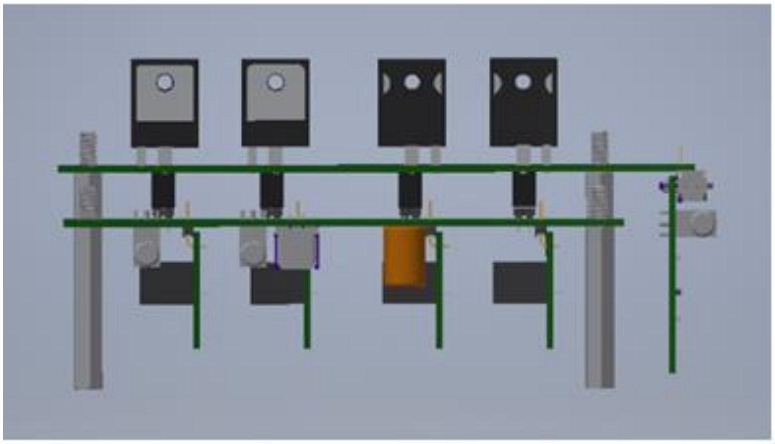
Figure 9: IGBT Based Transmission Gate Initial Testing

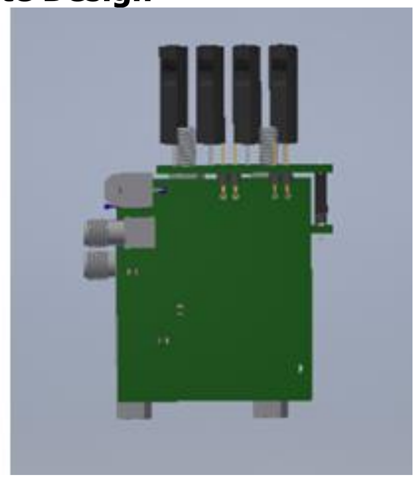


Source: Transient Plasma Systems, Inc.

The transmission gate was redesigned to replace the IGBTs with high voltage metal oxide field effect transistors (MOSFET), which are less power dense than IGBTs, but feature high conductivity at zero terminal voltage because they are field effect devices. Figure 10 shows the CAD model for the redesigned gate based on MOSFETs; each gate required 16 devices. This figure shows the initial design of the MOSFET gate, which included commercially available isolated DC-DC converters to provide power, as well as a shunt IGBT switched path to ground, which was intended to be gated out of phase with the MOSFETs to provide a path for the drain-source capacitance of the MOSFETs to charge when in the blocking state. The IGBT switched path to ground turned out to not be required because the signal bleed through the MOSFET blocking capacitance was sufficiently low at the plug that it did not pose any threat of igniting any exhaust products that may exist in a cylinder.

Figure 10: Revised Transmission Gate Design

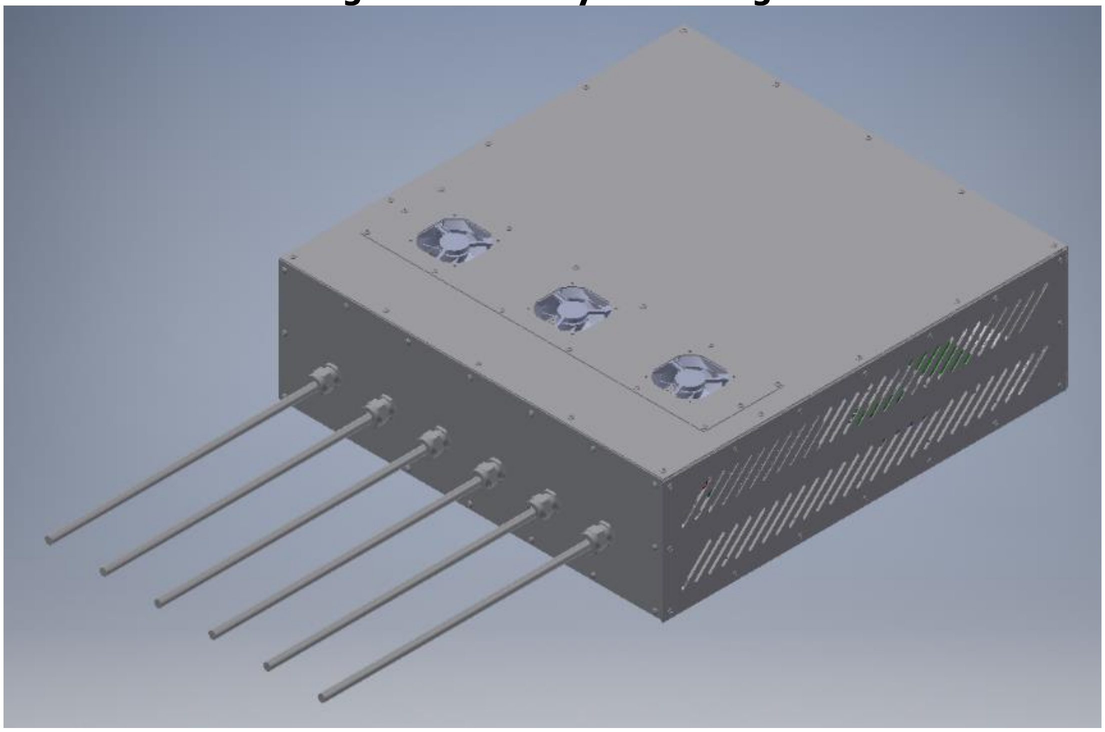




Source: Transient Plasma Systems, Inc.

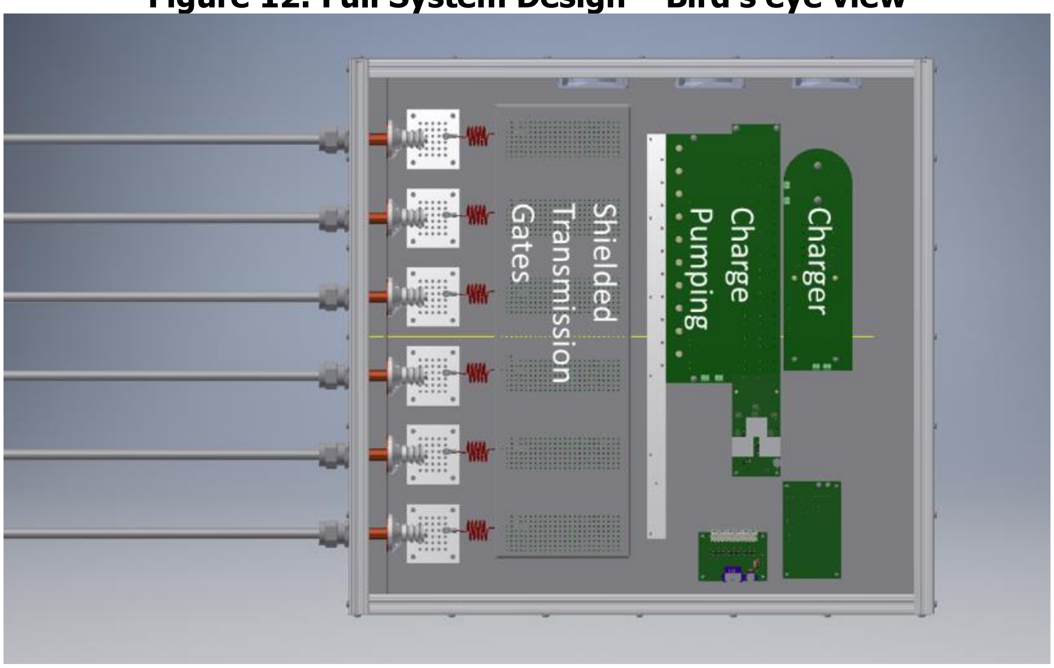
In order to properly test and vet the redesigned transmission gates, TPS designed and built a full multi-cylinder system design to properly test and vet the redesigned transmission gates. CAD models for the system are shown in Figure 11 and Figure 12. TPS made a modification to the block diagram concept illustrated in Figure 3 for practical reasons related to cable length requirements for engine testing. In order to implement individual TIMs directly on each plug, the cable connecting the TIM to the power supply cannot exceed a certain length, and it was determined that this length was too short to provide the reach required when running on the instrumented engine. To head off the possibility of cable length issues, all of the pulse generating electronics were housed inside of the aluminum enclosure shown in Figure 11. Due to the proximity of the transmission gates to the output pulse sharpening circuit, a ventilated shield was pre-emptively designed to mitigate any potential EMI.

Figure 11: Full System Design



Source: Transient Plasma Systems, Inc.

Figure 12: Full System Design – Bird's eye view



Source: Transient Plasma Systems, Inc.

When testing a single channel, a commercial DC-DC isolated converter was not capable of reliably operating in this circuit. It would reliably fail to a short circuit at its input after only minutes of operation, indicating the semiconductor used to switch the primary side of the isolation transformer had failed to a short. This type of failure is likely a result of common-mode swing on the secondary relative to the primary, and the resulting common mode current that flows through the small parasitic capacitance between the primary and secondary turns. Since this part featured the highest isolation voltage and common-mode immunity rating of any commercially available part, the only viable solution was to design a custom converter with higher common mode transient immunity (CMTI). This was achieved by designing the converter to have as little coupling capacitance as possible in both the isolation transformer and the feedback circuitry and by selecting a sufficiently robust primary side MOSFET to switch the transformer. In the end, the circuit design and transformer design were able to achieve less than 6 picofarad (pF) of total coupling capacitance between primary and secondary. This capacitance was owed to a custom designed transformer manufactured at TPS that was hi-pot tested up to 10 kV. For lower voltage applications, the coupling capacitance can be reduced by eliminating the potting compound used to encapsulate the transformer. This more robust isolated power solution was adopted for all switching stages in the transmission gate and pulsed power supply that required isolated power. Figure 13 shows an isolated power and trigger module used in the power supply.

Figure 13: Custom Isolated Power Solution

Source: Transient Plasma Systems, Inc.

Task 3 – Test and Validate

Designing, testing, and validating all of the new isolated power circuitry and retrofitting it into the enclosure took place over the course of 2-3 months. Preliminary testing of the system resulted in minor component changes to the isolated circuitry in the transmission gate's isolated power to further improve CMTI. Single channel testing proceeded positively using a high-pressure load cell (Figure 14) designed to provide a crude representation of load conditions that would be seen when driving the engine.

Figure 14: High Pressure Load Cell

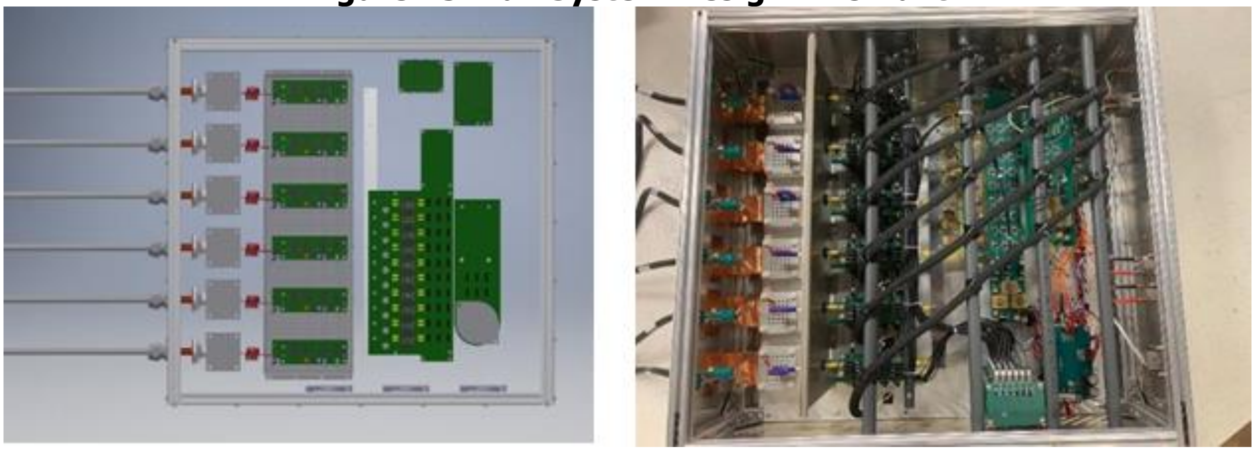
Source: Transient Plasma Systems, Inc.

Each channel was measured and validated to conduct and block bursts of pulses reliably, but when testing shifted to running all six channels in sequence, failures began to occur. The failure mechanism was gate-oxide punch through on the MOSFETs that populated the transmission gates. Trial-and-error testing revealed that this only happened to MOSFETs in the conducting state, not the blocking state.

TPS used an improvised test bed to troubleshoot the failures over several weeks. The MOSFET failure was due to the switching regulator integrated circuit on the isolated power module incorrectly going into a fault detection mode as a result of EMI conducted back on the patch cables that were required to carry the switch-mode voltage to and from the isolation transformers. Due to space constraints, it was necessary to break the DC-DC converter that powered the transmission gates into two separate printed circuit boards, joined by a relatively long twisted pair. In general, this is not advisable for electromagnetic compatibility, but options for retrofitting this solution were limited. After a significant amount of troubleshooting, this EMI issue was solved, and the six-cylinder unit was run extensively into the high-pressure test cell without any failures. The full system design as built is shown in Figure 15.

Due to budgetary and time constraints, it was not possible to achieve the target output voltage specification of 20 kV onto a 50 Ohm (Ω) cable; the maximum voltage was approximately 14 kV, a roughly 30 percent reduction from the target. There were concerns as to whether this voltage amplitude could produce sufficient electric field to achieve the combustion gains that transient plasma ignition technology had previously shown in single cylinder experiments, but the project proceeded nevertheless in order to demonstrate successful integration of the technology with a production engine as well as the controllability to run as a multi-cylinder system. In the end, the system was able to extend the dilution limit of the CWI ISX12N heavy duty natural gas engine as presented in Chapter 3.

Figure 15: Full System Design – As Built



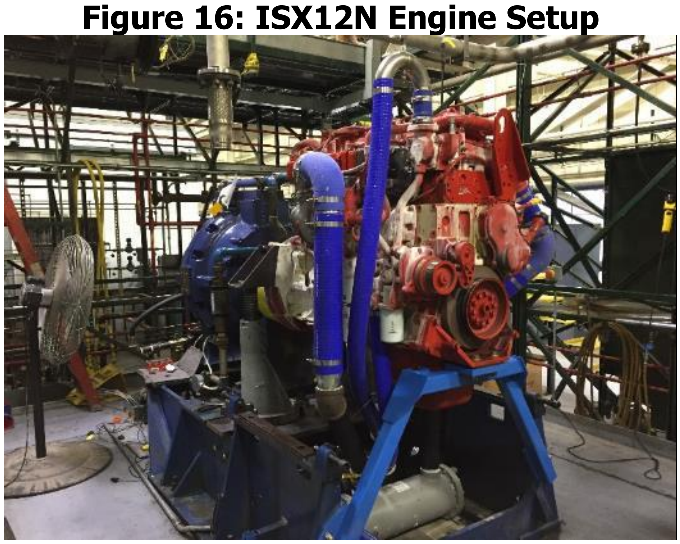
Source: Transient Plasma Systems, Inc.

Engine Test - Experimental Equipment Description

Engine Description

The engine is an ISX12N 11.9 liter, inline six-cylinder natural gas engine manufactured by Cummins Westport, as shown in Figure 16. The engine is rated at 400 hp (298 kW) with a peak torque of 1,966 Nm (1,450 lb-ft.). The engine oil lubrication loop was not modified and the engine holds approximately 45 L (~12 gal) of motor oil. The stock natural gas fuel system is maintained at a fuel pressure in the range from 60-150 psi (4.1-10.3 bar). The engine uses either the stock engine ignition system or the prototype transient plasma ignition system. The engine's fueling, ignition, and exhaust gas recirculation rate is controlled by the stock engine control unit (ECU) via an engine control interface. All rotating parts on the engine are covered to avoid accidental contact.

Figure 16: ISX12N Engine Setup



Source: Argonne National Laboratory

Engine Test Stand

The engine and dynamometer are mounted together on a steel frame, or skid. They are coupled together with a resilient drive coupling. The entire assembly is mounted to an inertia base which is spring/rubber supported for vibration isolation. The inertia system is surrounded by a platform that provides working area and access to the engine. The platform also serves as spill containment for any leaks that may occur.

Dyne Systems Eddy Current Dynamometer and Coupling

The 700HP Dyne Systems Eddy Current dynamometer is shown in Figure 17. The maximum operating speed of the dynamometer is 3,600 RPM, maximum torque is 3,600 ft-lbs and the electrical connection is 140 VDC-16 Amps. The dynamometer is firmly mounted to the bedplate. All rotating parts are covered to prevent accidental contact. All rotating parts have also been balanced to allow operation up to the maximum speed of the dynamometer.

Figure 17: 700 HP Eddy Current Dynamometer

Source: Argonne National Laboratory

The dynamometer is coupled with the engine using a Kop-Flex MAX-C coupling. Engine and dynamometer were aligned within allowable coupling tolerances. An air-starter connected to the dynamometer is used to initially start up the engine. The air starter is controlled with a manual command given to the Digalog system. The starter will not engage until the Digalog system has satisfied all of the predetermined conditions of the engine subsystems and the facility safety systems.

Dynamometer Cooling System

A dynamometer cooling system is set up to control the temperature of the eddy current dynamometer. The system consists of a pump as well as a heat exchanger that dissipates heat from the dynamometer via the dynamometer cooling system to the raw water system. The peak temperature of the dynamometer cooling system is 140°F (60°C). Figure 18 (right) shows a picture of the dynamometer cooling system including pump and heat exchanger.

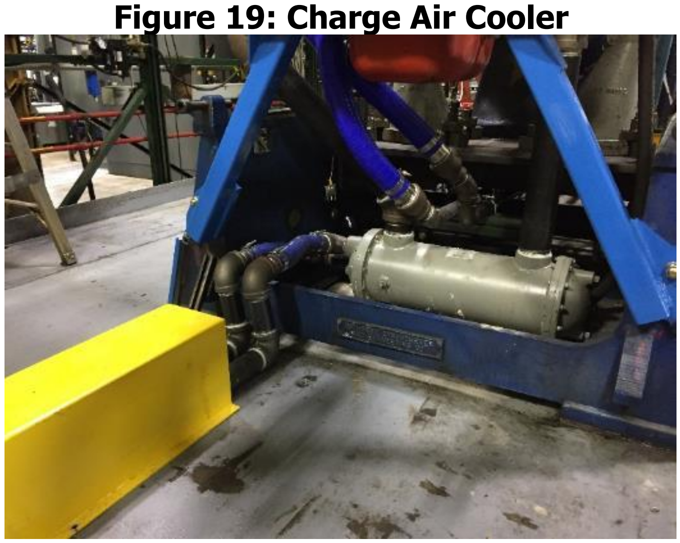
Figure 18: Coolant Heat Exchanger Assembly (left) and Dynamometer Cooling Assembly (right)

Source: Argonne National Laboratory

Engine Air System

The engine combustion air is aspirated from the Hi-Bay and passes through an air filter and laminar flow element before being supplied to the engine. The air then passes through a stock compressor of the turbocharger and is then delivered to the raw water-cooled charge air cooler. The raw water flow through the charge air cooler can be regulated to adjust the temperature of the compressed air. Figure 19 shows the raw water-cooled charge air cooler located underneath the ISX12N engine.

Figure 19: Charge Air Cooler



Source: Argonne National Laboratory

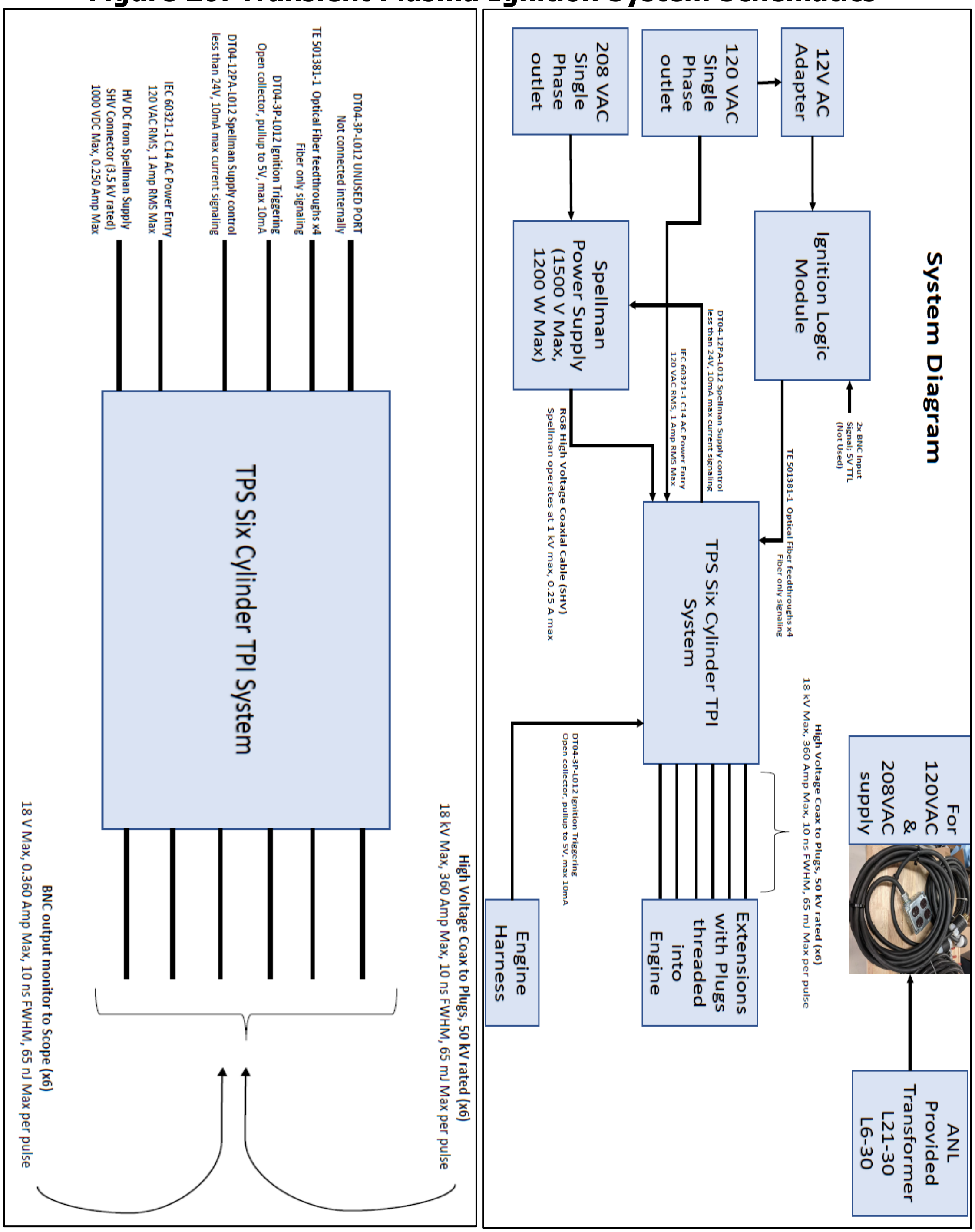
Engine Exhaust System

The engine exhaust is connected to the building exhaust system through an exhaust system consisting of flanges, flexible pipe, an exhaust restriction valve and exhaust pipe. The building exhaust system includes a main muffler mounted to the outside wall of the building to reduce engine exhaust noise. The engine exhaust system has provisions for several exhaust sampling systems. The area around the engine exhaust is hot during engine operation and signs are posted accordingly.

Engine Ignition System

The engine is either operated with the stock engine ignition system or the prototype transient plasma ignition system. The stock engine ignition system is powered as part of the engine control unit using an external 12 VDC power supply. A schematic of the prototype transient plasma ignition system is shown in Figure 20.

Figure 20: Transient Plasma Ignition System Schematics



Source: Transient Plasma Systems, Inc.

The system consists of an external power supply as well as the TPS Six Cylinder TPI System Unit. The power supply is fed with 208 VAC, the TPI system is powered by 120 VAC. Figure 21 shows the TPI system unit installed in the test cell. A wire tray is used to support the coax cables running to the spark plugs installed in the engine.

Figure 21: Prototype Ignition System Installed in the Test Cell

Source: Argonne National Laboratory

Natural Gas Supply System

Natural Gas Supply and Compression System

Natural gas (NG) enters the test building through a hard-plumbed feed line that can be closed off at the point where it penetrates the building wall (Figure 22). The system pressure of the natural gas feed at this point is typically around 5-10 psi.

Figure 22: Main Natural Gas Shut-off Valve

Source: Argonne National Laboratory

The main gas feed is plumbed to two natural gas compressors located inside the high bay. The natural gas compressors increase the feed pressure to up to 160 psi (11 bar) and supply a buffer tank with the compressed gas (Figure 23). The buffer tank is an ASME coded vessel rated to 200 psi at 650F. The buffer tank is equipped with a pressure relief valve that will release natural gas through a hard-plumbed line outside the building. The ASME pressure relief valve is set at 170 psi. The buffer tank is also equipped with a manual valve that can be used to depressurize the tank and system.

Figure 23: Natural Gas Compressors and Buffer Tank

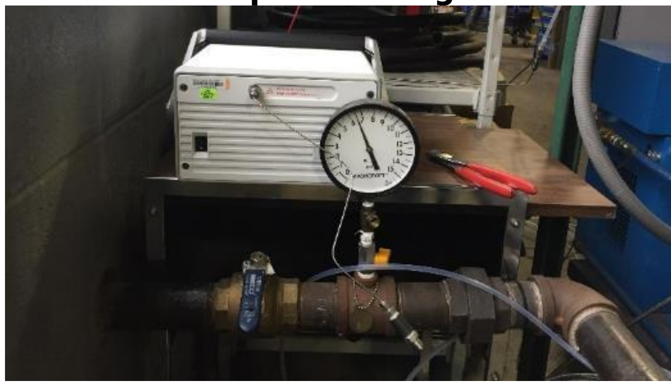
Source: Argonne National Laboratory

From the buffer tank the compressed natural gas is fed to the engine using 1-inch stainless steel tubing and several manually operated shut-off valves. The engine feed also includes a Coriolis flow meter to determine fuel consumption, a coalescing filter as well as a solenoid shut-off valve that is remotely switched by the test cell operator and closes automatically when an emergency stop is triggered. A flexible natural gas rated hose is used to connect the natural gas feed to the fuel system on the engine.

Natural Gas Composition Monitoring using Micro-GC

An Agilent Technologies Model 3000A Micro-GC (Gas Chromatograph) is used to monitor the composition of the natural gas entering the building (Figure 24). The Micro-GC draws small gas samples from the main natural line downstream of the main shut-off valve (NG1). The maximum sample pressure for the Micro-GC is 25 psi (1.72 bar). The recommended sample pressure is ambient to 10 psi (0.69 bar) which is well aligned with the typical natural gas supply pressure of 5-10 psi. Compressed helium at a purity above 99.995 percent is used as a carrier gas and supplied to the Micro-GC through a separate inlet on the back of the unit. The carrier gas inlet pressure is 80 to 82 psi (0.552 to 0.566 bar). Bottled natural gas of known composition is used as calibration gas and fed to the analyzer through the sample inlet port.

Figure 24: Micro-GC Setup Monitoring Natural Gas Quality



Source: Argonne National Laboratory

A gaseous sample is injected into the GC through the heated inlet manifold that regulates the sample temperature and directs it into the flow assembly on a module inside. The sample is drawn by vacuum pump through the injector sample loop and is released onto the column. As the sample gas enters the column, its component gases are separated based on their retention or adsorption property. After column separation, the sample gas enters the Thermal Conductivity Detector (TCD), while the carrier gas also enters the TCD via the reference path and the analytical path. The TCD measures the difference in thermal conductivity between the carrier gas reference and the sample gas components. The Micro-GC samples 30 µL of gas and measures the component concentrations. The evaluation time of the gas is 3-6 minutes. A conservative estimate for the needed flow rate is 3.22 cc/min. Helium gas acts as a carrier, to transport the gas sample through the column. Approximately 15 mL/min of helium gas is vented into the room during operation. The GC is controlled via a control program called Cerity. The measured natural gas composition was very consistent and within expected bounds; the composition and resulting lower heating value of a representative sample is detailed in Appendix A.

Cooling Systems

Three cooling systems connected through heat exchangers are used to provide cooling for different components of the engine setup. The dynamometer cooling system is described above, and the remaining two of those systems are described below.

Main Cooling System

The main cooling system is a raw water (tower water) system that is connected to outside cooling towers and provides the main source for cooling. Typical supply pressure of the raw water system is 5.5 bar (80 psi) with temperatures ranging 57-85°F (14-30°C). Raw water is plumbed to the charge air cooler of the engine using a flow control system to provide cooling for the intake air. The raw water flow rate can be adjusted remotely to control the intake air temperature. Figure 25shows the raw water flow control setup and plumbing to the heat exchanger. The charge air cooler itself is shown in Figure 19.

Figure 25: Raw Water Flow Control Setup and Plumbing to Intake Air Heat Exchanger

Source: Argonne National Laboratory

Engine Cooling System

Engine cooling consists of supply and return lines that provide cooled and pressurized engine coolant at a pressure around 2 bar (30 psi). Engine coolant reaches temperatures of up to 100°C (212°F). Signs are posted to point out hot areas. The system contains a motor driven pump, an electric heater, heat exchanger, and control valve for temperature control, and an expansion tank. The system uses a 50/50 blend of water and propylene glycol with a capacity of approximately 100 gallons (380 L). Raw water is used in a heat exchanger to control the engine coolant temperature. Due to the size of the system, an external coolant pump is used in combination with the stock engine-mounted coolant pump. The pump and heat exchanger setup with coolant reservoir is shown in Figure 18 (left).

Emissions Measurement Systems

AVL AMA i60 Raw Emissions Bench

Emissions measurement probes were installed in the engine exhaust. Small samples of engine exhaust are taken to the emissions measurement equipment. Exhaust from any emissions analyzer is routed into vent lines and transported outside the building.

The gaseous emissions bench is an AVL AMA i60 located inside the engine control room (Figure 26). The AMA i60 bench is equipped with several internal and external electrically heated sample lines (insulated & warm to touch). It is capable of measuring intake carbon dioxide (CO_2), exhaust CO_2, carbon monoxide (CO), total hydrocarbon (THC), methane (CH_4), nitrogen oxide (NO), and oxygen (O_2).

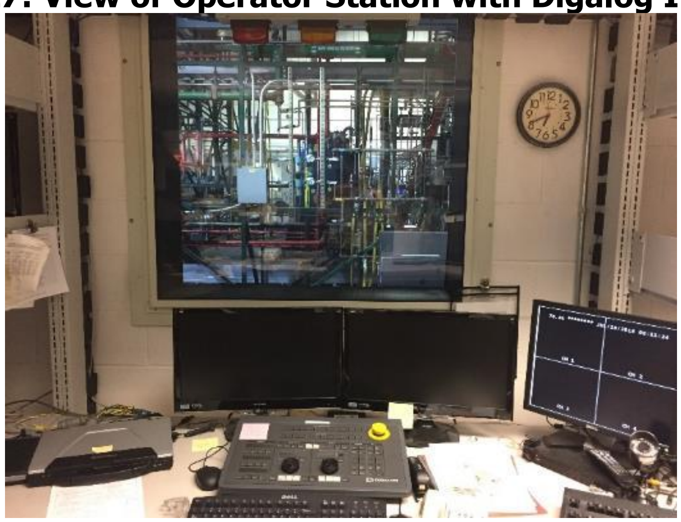
Figure 26: Gaseous Emissions Bench Located Inside the Engine Control Room

Source: Argonne National Laboratory

Dynamometer Controller and Data Acquisition

The dynamometer is controlled through a Digalog interface that allows selection of operating modes as well as manual input of desired dynamometer speed. This interface also continuously performs dynamometer safety checks (Figure 27).

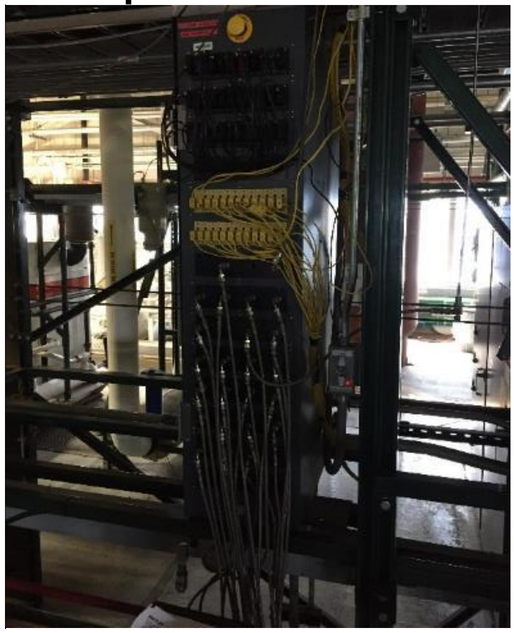
Figure 27: View of Operator Station with Digalog Interface



Source: Argonne National Laboratory

Media pressures are fed to a separate pressure transducer enclosure located adjacent to the engine setup. This enclosure houses up to 23 pressure transducers that convert the physical pressures into electronic signals. The enclosure also houses connectors for thermocouples used to collect temperature measurement. The pressure and temperature signals are then fed into the data acquisition system. A picture of the pressure transducer and thermocouple enclosure is shown in Figure 28.

Figure 28: Thermocouple and Pressure Transducer Enclosure



Source: Argonne National Laboratory

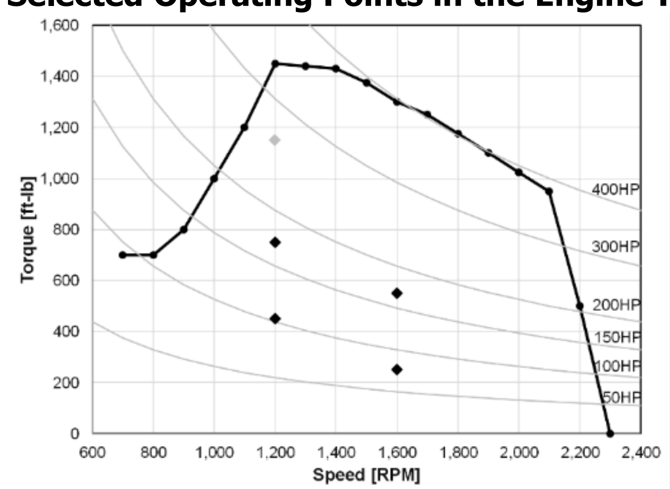
High-speed data acquisition is accomplished using an AVL IndiModul. This system measures in-cylinder pressures from all six cylinders and correlates them to engine crank angle location measured with an AVL 365C crank angle encoder.

CHAPTER 3:
Project Results

Operating Point Selection

The objective of the baseline tests was to establish a data set to compare the performance of the TPI system against and to ensure that the data generated with this particular engine setup is consistent with in-house data provided by CWI. A set of five representative operating conditions was selected for the baseline tests. The operating points were chosen at 1200 and 1600 RPM covering a range of mid-load conditions from 250 to 1,150 ft-lb (339 to 1,558 Nm) of torque (Figure 29). The four data points shown as solid black diamonds in the figure were successfully tested; the fifth intended point shown as a gray diamond was not tested – the internal cylinder pressure at that point (1200 RPM and 1,150 ft-lb of torque) was more than double that of any of the other test points, and the maximum pulse generator output voltage (~70 percent of design value) was insufficient for achieving stable ignition at that test point. In previous tests, TPS had seen that higher output voltages are needed to reliably ignite at the highest cylinder pressures, and there are planned future modifications to the ignition module that will enable those higher output voltages. All operating points selected have a nominal rate of exhaust gas recirculation above 10 percent which was desirable since advanced ignition systems are expected to show performance benefits under dilute operating conditions.

Figure 29: Selected Operating Points in the Engine Torque Map



Selected operating points in the engine torque map. Black diamonds (4) were tested. The gray diamond test point was not achieved during this test.

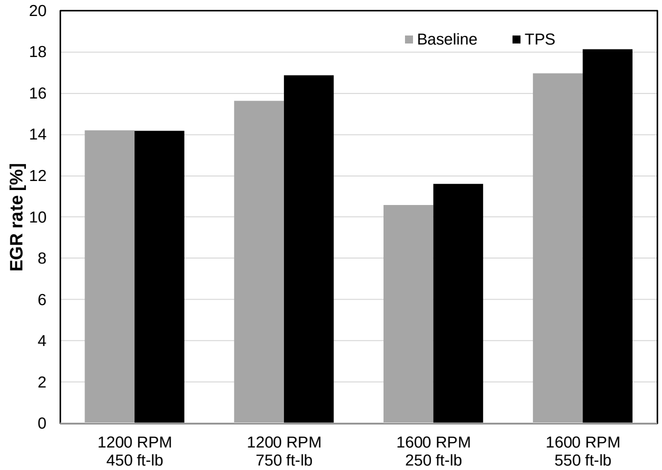
Source: Argonne National Laboratory

Low speed data including pressure, temperatures, and flows rates for each operating point were averaged over 60 sec; high-speed crank angle resolved data was collected for 500 consecutive cycles within the 60 sec interval.

Comparison of Baseline Stock Ignition and Transient Plasma Ignition Results

Engine performance and emissions results for an engine operating stoichiometric with exhaust gas recirculation (EGR) depend on the resulting EGR rates at specific operating conditions. For the initial comparison between the baseline stock ignition system and the transient plasma ignition (TPI) system provided by TPS, stock calibration values were used. Figure 30 compares the resulting EGR rates derived from CO_2 measurements in the engine intake and exhaust showing that the in-cylinder conditions in terms of EGR dilution between the baseline and TPI system were very similar across the range of operating conditions.

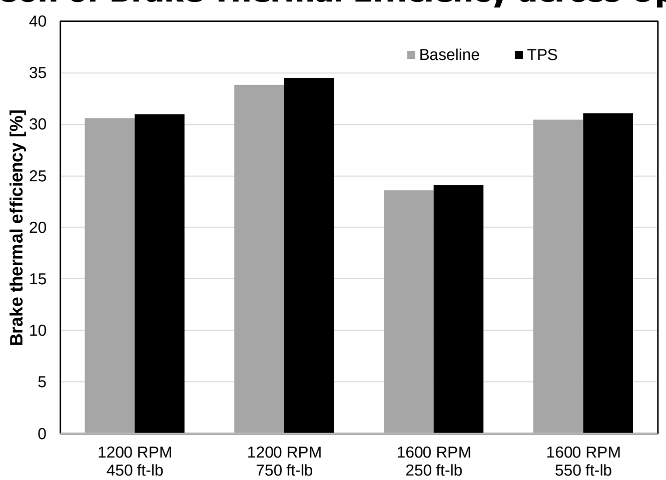
Figure 30: Comparison of EGR Rates across Operating Conditions



Source: Argonne National Laboratory

Figure 31 compares the resulting brake thermal efficiencies for the baseline ignition system and the one provided by TPS across the range of operating conditions. Brake thermal efficiencies are calculated based on measured brake torque as well as natural gas fuel flow and gas composition. As seen in the figure, the resulting engine efficiencies at base calibration are almost identical between the two ignition systems with marginal benefits for the TPS-provided system.

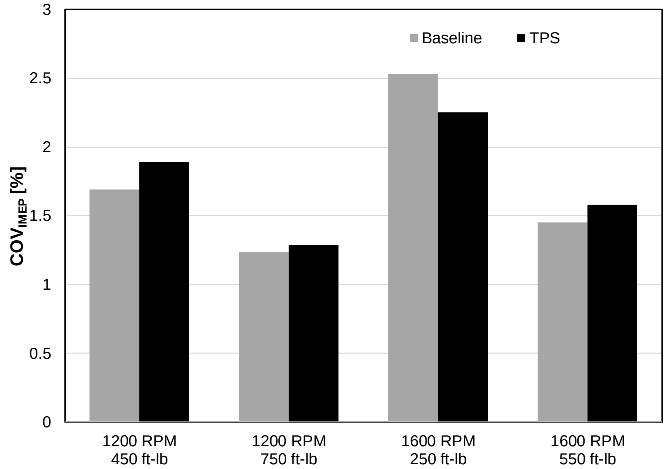
Figure 31: Comparison of Brake Thermal Efficiency across Operating Conditions



Source: Argonne National Laboratory

As a measure of combustion stability, Figure 32 compares the coefficient of variation (COV) of the indicated mean effective pressure (IMEP) of the baseline ignition system relative to the TPI provided by TPS. In general, COV_{IMEP} values below 5 percent are considered stable in terms of combustion stability for research engines. Production engines tune the engine even further to typically achieve COV_{IMEP} values at or below 3 percent. The combustion stability values are quite similar between the two systems and well below the stability limit, as would be expected for the base calibration.

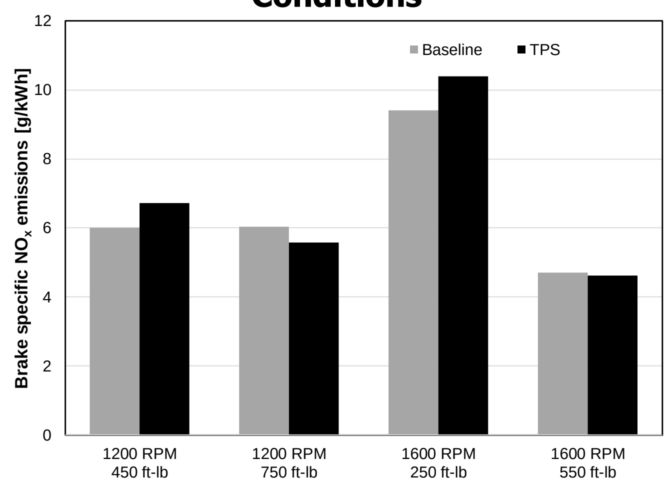
Figure 32: Comparison of Combustion Stability across Operating Conditions



Source: Argonne National Laboratory

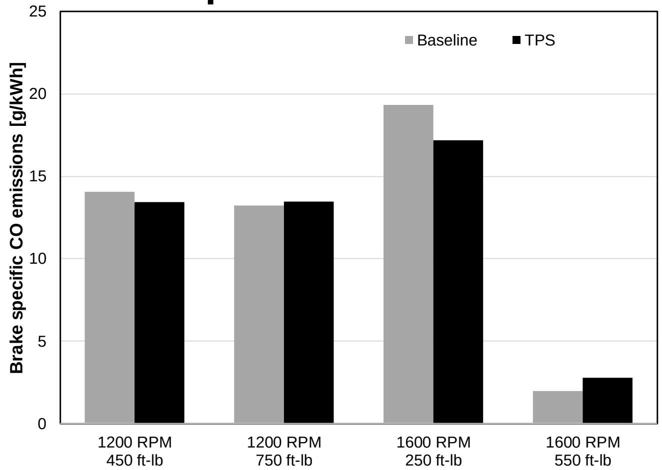
Figure 33 through Figure 36 compare brake specific engine-out emissions including NOx, CO, HC and CH4 emissions. As can be seen from the figures, emissions level between the two ignition systems are consistent across all operating conditions and changes in emissions levels are largely dependent on operating-point specific calibrations rather than differences caused by the ignition systems.

Figure 33: Comparison of Brake Specific NOx Emissions across Operating Conditions



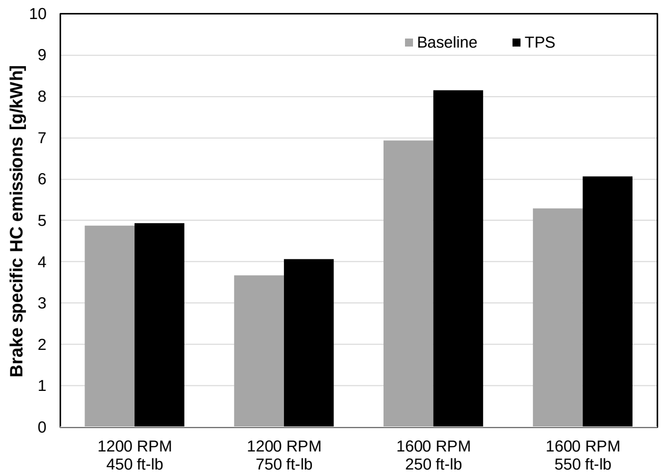
Source: Argonne National Laboratory

Figure 34: Comparison of Brake Specific CO Emissions across Operating Conditions



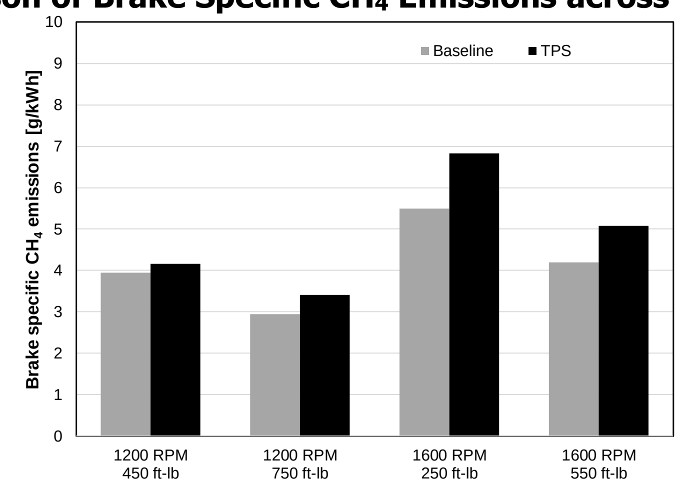
Source: Argonne National Laboratory

Figure 35: Comparison of Brake Specific Hydrocarbon Emissions across Operating Conditions



Source: Argonne National Laboratory

Figure 36: Comparison of Brake Specific CH_4 Emissions across Operating Conditions



Source: Argonne National Laboratory

Transient Plasma Ignition System Performance Opportunities

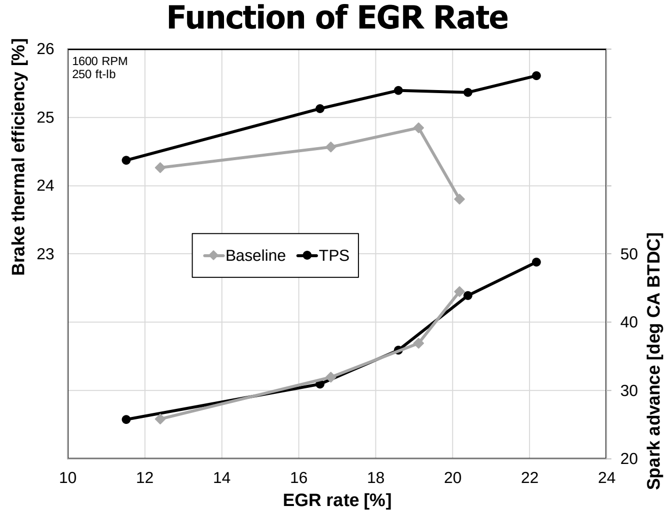
Objective

The objective of the performance opportunity testing was to determine if the TPI system was able to provide combustion benefits compared to the stock ignition system under challenging operating conditions. These challenging operating conditions were achieved by deviating from the stock engine calibration and increasing EGR ratios significantly beyond stock levels. As a result of the increased EGR levels, combustion duration increases, and combustion is expected to become unstable. If the TPI system can maintain combustion stability at increased EGR levels compared to the stock ignition system, then the engine can achieve efficiency benefits as well as emissions improvements—increasing EGR not only lowers the peak in-cylinder temperature resulting in less NOx production, but also opens the throttle thereby reducing associated pumping losses and improving overall engine efficiency.

Results

Figure 37 shows the influence of increasing EGR rates on attainable brake thermal efficiencies with spark timing reported for references at an engine speed of 1600 RPM and a load of 250 ft-lb. With increasing EGR levels, combustion duration increases requiring more spark advance to maintain consistent combustion phasing. As seen in the figure, consistent spark timing advance for both the baseline and TPI system provide by TPS was required to offset for the slower combustion duration with increasing EGR levels. Increasing EGR levels initially result in increased brake thermal efficiencies for both ignition systems. However, the brake thermal efficiency for the stock ignition system drops off sharply beyond 19 percent EGR while the ignition system from TPS maintains improved brake thermal efficiencies beyond 22 percent EGR levels. The stock calibration at this operating condition runs at an EGR level of around 12 percent. Assuming that the same safety margin to unstable combustion was to be maintained, the TPI system could be run at or above 15 percent EGR resulting in an absolute efficiency improvement of at least 0.5 percent (or more than 2 percent relative) compared to the stock ignition system.

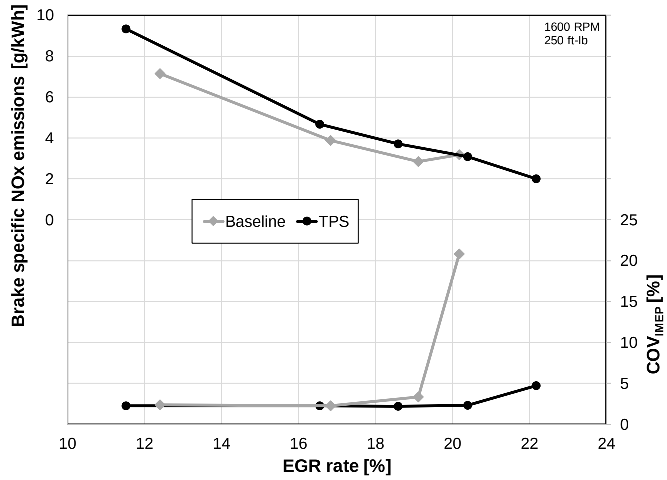
Figure 37: Comparison of Brake Thermal Efficiency and Spark Advance as a Function of EGR Rate



Source: Argonne National Laboratory

Figure 38 compares the resulting brake specific NOx emissions as well as combustion stability for the same EGR sweep. The sudden drop-off in brake thermal efficiency with the baseline stock ignition system coincides with a sharp increase in COV_{IMEP} beyond 19 percent EGR which is the result of engine misfires. The TPI system maintains a COV_{IMEP} below 5 percent beyond 22 percent EGR (although infrequent misfires were observed at that condition). As expected, NOx emissions drop with increasing EGR rates with absolute levels consistent between the two ignition systems. A 30 percent reduction in NOx emissions could be achieved with the TPI system by increasing the EGR levels due to the improved combustion stability and EGR dilution tolerance.

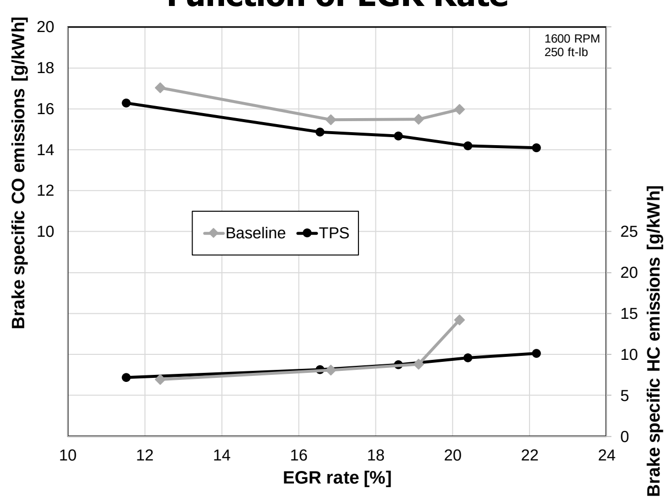
Figure 38: Comparison of Brake Specific NOx Emissions and Combustion Stability as a Function of EGR Rate



Source: Argonne National Laboratory

Figure 39 shows the brake specific CO and HC emissions for the EGR sweep. Results are consistent between the two ignition systems with a noticeable increase in both CO and HC emissions for the baseline stock ignition system beyond 19 percent EGR which is consistent with engine misfires. Applying the same logic as before, CO emissions could be reduced by more than 10 percent with the TPI system by increasing the EGR levels due to the improved combustion stability and EGR dilution tolerance.

Figure 39: Comparison of Brake Specific CO and Hydrocarbon Emissions as a Function of EGR Rate



Source: Argonne National Laboratory

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Stakeholder Engagement

The TPS market transfer plans for achieving industry adoption of this technology involves gaining interest and engagement of all stakeholders in the heavy-duty engine market. A key aspect of the plan was to ensure awareness of the goals and intent of this project among the stakeholders in the market, in particular, the engine manufacturers. TPS shared the news (https://transientplasmasystems.com/blog/2017/06/14/cec/) about being awarded the project by the CEC on the company website and has provided an update on the project whenever it has had an opportunity to speak with external audiences. For example, TPS shared project updates to industry stakeholders at the Natural Gas Vehicle Technology Forum, held in Downey, California in 2018 as well as at their subsequent gathering in Salisbury, North Carolina in 2019. Similarly, TPS provided a project update at the Virtual Engine Research Institute and Fuels Initiative (VERIFI) at Argonne National Laboratory in July 2019 to a technical audience representing vehicle and engine OEMs. Additionally, TPS engaged with engine manufacturers about the project and discussed the potential of the technology in helping mitigate greenhouse gas emissions.

Engagement with stakeholders was further underlined by the support of Cummins Westport Inc. (CWI), a leading OEM for heavy-duty on-road natural gas engines, who provided a current in-production on-road engine for the testing of the TPI system. Additionally, by engaging Argonne National Laboratory, TPS now has a partner who could support the project with combustion expertise and provide exposure to other industry stakeholders given the laboratory's global reputation in combustion research. Another critical industry partner was Southern California Gas Company, a natural gas utility representing a key stakeholder in California's natural gas value chain.

The successful completion of the testing was publicly announced by TPS via a press release. This press release was also sent to the engine OEMs that have previously engaged with TPS. The press release received good coverage and was picked up by several news and industry outlets. A sample is reported below including OEM Off Highway, Modern Work Truck Solutions, Oil & Gas 360, and Next Gen Transportation. This coverage will help gain visibility and knowledge of the work performed and should help future adoption by the industry.

- Press Release
- Total pickup: 105
- Total potential audience: 48M
- Notable syndications:
    - OEM Off-Highway
    - Green Car Congress
    - NGTNews
    - Modern Work Truck Solutions

- Autoblog
- The Street
- Yahoo! Finance
- VB Profiles (Part of VentureBeat)
- MarketsInsider
- Oil & Gas 360
- Energy Daily
- The Association of Energy Engineers

The encouraging test results were shared via teleconference meetings with all the organizations involved in the project including CWI, CEC, SoCalGas and Argonne National Laboratory. The test results will also be made public via this report which can enable independent review by industry stakeholders building awareness of the capabilities of the TPI technology. The successful testing was a critical milestone in validating the viability of TPI technology by the first ever demonstration of operation on a multi-cylinder in-production on-road engine under on-road conditions. The test results confirmed the improvement in fuel efficiency and lower greenhouse gas emissions under dilute burn conditions. The validation of these benefits will encourage fleet providers, transportation services and heavy-duty engine manufacturers to test the technology and explore avenues to accelerate adoption. Additionally, regulatory agencies can investigate inclusion of transient plasma ignition as a solution to drive cleaner emissions standards.

Strategy for Commercializing Transient Plasma Ignition Technology

While the light commercial vehicle market represents the largest opportunity for TPS, it is also the most demanding in its need for durability, cost and size. Spark plugs in natural gas engines degrade faster due to increased input energy typically needed to achieve stable combustion under dilute conditions. The increased energy reduces the lifetime of the spark plugs, which requires more frequent maintenance intervals and higher costs from the replacement plugs and related downtime. The distinguishing feature of transient plasma ignition is the ability to achieve stable combustion under extremely lean conditions with much lower energy, thereby providing a solution to the plug durability problem.

Development of a production prototype ready for the light commercial vehicle market will need significantly more resources and a longer time horizon. TPS would like to first successfully penetrate the medium- to heavy-duty natural gas engine market for trucks and stationary power generation by developing a production-ready prototype. TPS can leverage that success to expand to the light commercial vehicle market which makes up a large portion of the New Ignition Systems market shown in Figure 40.

Figure 40: Global Market Sizes for New Ignition

Source: Transient Plasma Systems, Inc.

As compared to the light commercial vehicle market, the heavy-duty natural gas engine market is poised to adopt TPI technology more quickly and is more tolerant to development costs and has lower sensitivity to price as an adoption hurdle during the market introduction period. TPS estimates the ignition system cost for this market can be ten times higher than for gasoline passenger cars (greater than $500/system wholesale price).

Other reasons for targeting heavy-duty natural gas engines before moving to the gasoline engine market include:

- The targeted market segment is characterized by current needs to lower emissions while improving fuel efficiency for which no established, cost effective, and reliable alternative exists.
- Marketing and sales efforts can be well focused by both customer and internal calendar, containing the required effort and cost. TPS plans to focus 2020 efforts towards developing TPI further from a durability and cost perspective.
- Development activity will be largely funded through a strategic partnership, reducing capital requirements.
- The research and development activity will expand and leverage the intellectual property assets of TPS.
- The light commercial vehicle market is anticipated to develop more slowly, allowing TPS to leverage the technology, expertise, and credentials realized from the natural gas heavy-duty engine market to effectively penetrate new commercial opportunities, including passenger car and aftermarket ignition systems.

CHAPTER 5: Conclusions and Recommendations

Conclusions

TPS developed what is believed to be the first solid state, multi-channel transient plasma ignition system and demonstrated its capability to improve break thermal efficiency and reduce emissions by extending the dilution limit of a CWI ISX12N six-cylinder natural gas engine. The engine, which was donated by CWI, was set up and instrumented at Argonne National Laboratory, where TPS delivered the six-cylinder transient plasma ignition system and supported testing. TPS demonstrated a stable increase in dilution by more than 25 percent with stable engine operation, 30 percent reduction in NOx emissions, greater than 10 percent reduction in CO emissions, and greater than 2 percent relative improvement in efficiency. This is significant because the fuel map was not changed, which is normally how one would take advantage of an advanced ignition system. The gains were therefore likely achieved through stronger ignition alone; that is, transient plasma can improve ignition directly by providing a more volumetric ignition event (compared to a highly-localized traditional spark) as well as a faster-moving flame front. Given the number of technical challenges encountered in developing a gated, six-cylinder transient plasma ignition system, these results are particularly encouraging because the peak voltage generated by the system during testing at Argonne was limited to 70 percent of the peak voltage that TPS has delivered in previous engine tests.

Based on the results from these previous single cylinder tests, TPS expects that with increased voltage, the dilution limit could be further extended while maintaining acceptable COV, potentially resulting in higher thermal efficiency gains and further emissions reductions. TPS identified the electronic component that exhibited susceptibility to EMI issues, which limited the peak voltage for this test to 70 percent of the target. Follow-on work will involve redesigning the multi-channel TPI system to replace this controller integrated circuit with a more robust discrete transistor design. This redesigned, more robust multi-channel system will be tested in conjunction with Argonne National Laboratory and TPS engine test partners in 2020.

Recommendations

Based on the results of engine testing, TPS recommends continued hardware development to realize a more robust multi-cylinder TPI system capable of running at the higher voltages of previous single cylinder ignition tests, which have shown to be capable of extending the lean limit to a fuel-air equivalence ratio of 0.480 with COV_{IMEP} <5 percent with heated intake air and >20 percent fuel-economy improvement while delivering <20 mJ per cycle.[5] TPS is funded by Kairos Ventures to develop this system and has been awarded grants from the National Renewable Energy Laboratory and the Department of Energy. The first award funds, in part, the development of active sensing techniques to maintain plasma ignition, while avoiding sparking. The second award, in part, funds the extensive testing required to collect data

[5] Sjöberg, Magnus, et al., 2014, "Combined effects of multi-pulse transient plasma ignition and intake heating on lean limits of well-mixed E85 DISI engine operation," *SAE International Journal of Engines* 7(4): 1781-1801.

across engine operating conditions that will inform decision making of the real-time spark avoidance hardware. Data collected by TPS and its engine testing partners from more than 25 instrumented engine tests at facilities around the world over the last five years clearly shows that this technology can facilitate significant emission reduction and efficiency gains of 20 percent. Based on the consistency of these results, TPS is committed to working with knowledgeable partners to bring this technology to market.

CHAPTER 6: Benefits to Ratepayers

Transient plasma ignition systems will benefit California's ratepayers by accelerating a transition away from diesel heavy-duty engines, with substitutes including lower emission natural gas engines.

For a given energy content of fuel, combustion of natural gas generates 23 percent fewer CO_2 emissions than combustion of diesel fuel. However, current natural gas engines are less efficient than modern diesels, offsetting some of the difference in CO_2 emissions. For example, the California Low Carbon Fuel Standard Program applies an approximate 10 percent efficiency deficit to natural gas engines relative to their diesel counterparts. If future natural gas engines are made more efficient, natural gas will be even more favorable from a CO_2 standpoint compared to diesel. Turbocharging and increasing compression ratio are two strategies to improve the efficiency of natural gas engines, however, both necessitate improved ignition systems.

If natural gas engines can be improved to within 10 percent of the efficiency of diesels for Class 8 vehicles, it will translate into about $6,500 saved and 7,660 pounds of CO_2 emission reductions per year per vehicle. This calculation is based on diesel at $4.04 per gallon and natural gas at $2.69 per diesel gallon equivalent for a heavy-duty truck traveling 65,000 miles per year at 5.8 miles per gallon on diesel fuel. If just 10 percent of the 1,720,000 registered Class 8 vehicles nationwide transitioned to natural gas engines, the annual savings would be $1.1 billion per year and CO_2 emissions would be reduced by 1.3 billion pounds per year. California alone would see annual fuel savings of $82 million and 97 million pounds of CO_2. Additional dollar and CO_2 emissions savings would occur in if medium-duty vehicles also transitioned to natural gas, but these additional savings are not estimated here.

In a recent study,[6] researchers found that short-term exposure to air pollution (even at levels generally considered safe by federal regulations and the World Health Organization) significantly increased hospital admissions and associated healthcare costs. Small increases to exposure to ambient fine particulate matter, such as that associated with vehicle traffic and diesel engines, was associated with thousands of additional annual hospital admissions and approximately $100 million of additional annual healthcare costs in the United States. These studies show how vehicle emissions adversely affect the health of Californians. Transient plasma ignition is expected to significantly reduce particulate matter from heavy-duty engines by encouraging a more rapid and complete transition away from diesel towards cleaner natural gas. In addition, TPI can be used to extend dilute-burn capability, which can reduce NOx production by more than 50 percent. NOx emissions were shown to be reduced below 20 ppm when TPI was used to extend the lean burn capability to a fuel-air equivalence ratio of 0.50 in an experimental single-cylinder spark ignition engine fueled with E85 at Sandia National Labs.

Heavy-duty natural gas vehicles are currently available in limited quantity and hence are higher priced compared to conventional diesel vehicles. Performance improvements from

[6] Yaguang, Wei, et al. 2019, "Short term exposure to fine particulate matter and hospital admission risks and costs in the Medicare population: time stratified, case crossover study," *BMJ* 2019; 367 : l6258.

transient plasma ignition can help accelerate adoption of natural gas vehicles and achieve sufficient cost and volume scales to better compete with diesel.

This research sets the stage for follow-on projects. Developing a new ignition system for production engines must be done in well-established, manufacturer-defined stages, and can take a significant amount of time. Demonstrating transient plasma ignition technology on a multi-cylinder engine is a key milestone along the roadmap of developing a production ignition system. With the technology risk now reduced to an acceptable level, the next steps can start to shift towards reducing the cost, size, and weight of the system while continuing to find ways to improve the technical performance.

LIST OF ACRONYMS

Term	Definition
CAD	Computer aided design
CH_4	Methane
CMTI	Common mode transient immunity
CO	Carbon monoxide
CO_2	Carbon dioxide
COV	Coefficient of variation
CWI	Cummins Westport Inc.
DOE	Department of Energy
ECM	Engine control module
ECU	Engine control unit
EGR	Exhaust gas recirculation
EMI	Electromagnetic interference
ft-lb	Foot-pounds
FWHM	Full width at half maximum
GC	Gas chromatograph
hp	Horsepower
IGBT	Insulated gate bipolar transistor
IMEP	Indicated mean effective pressure
kV	Kilovolt
MOSFET	Metal oxide semiconductor field effect transistor
NG	Natural gas
NOx	Oxides of nitrogen
ns	Nanosecond
ODU	Old Dominion University
OEM	Original equipment manufacturer
PM	Particulate matter
PRR	Pulse repetition rate
rpm	Revolutions per minute
STTR	Small Business Technology Transfer

Term	Definition
TCD	Thermal conductivity detector
THC	Total hydrocarbon
TIM	Transient ignition module
TPI	Transient plasma ignition
TPS	Transient Plasma Systems, Inc.

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APPENDIX A:
Natural Gas Composition

The measured natural gas composition of the fuel used for the engine testing is detailed in Table A-1, Table A-2, Table A-3, and Table A-4.

Table A-1: Natural Gas Fuel Property Derivation Input Data

			NG Fuel Property Derivation					
			Input Data			Processed: 01/27/20 13:55		
Mole Fractions from ASTM D-1945 @ 60°F & 1 atm			ASTM D-3588					
Natural Gas Constituents	Chemical Formula	Mole Fraction	Specific Gravity	Net Heat Val B.t.u./cu.ft.	ASTM D-1945 Data Source			
Methane	**CH4**	0.96203653	0.58206302	928.972385	*name the source of data*			<--- enter data into italics cell
Ethane	**C2H6**	*0.028644*						
Propane	**C3H8**	*0.002785*		*Cylinder: description*				
I-Butane	**C4H10**	*0.0001066*		*description*				
N-Butane	**C4H10**	*0.0002043*		*description*				
I-Pentane	**C5H12**	*5.077E-05*		*description*				
N-Pentane	**C5H12**	*4.341E-05*						
Hexanes	**C6H14**	*0*	§86.113-94 (e) Natural gas fuel. (1) Natural gas fuel having the following specifications					
Heptanes	**C7H16**	*0*	will be used for exhaust testing of natural gas-fueled vehicles.					
Octanes	**C8H18**	*0*	Methane		min, mole pct.	89.0	Pass	
Nonanes	**C9H20**	*0*	Ethane		max. mole pct	4.5	Pass	
Hydrogen	**H2**	*0*	C3, and higher		max. mole pct	2.3	Pass	
Helium	**He2**	*0*	C6, and higher		max. mole pct	0.2	Pass	
Nitrogen	**N2**	0.0061579	Oxygen		max. mole pct	0.6	Pass	
Oxygen	**O2**	*0*	Inert gases: Sum of CO2 ar		max. mole pct	4.0	Pass	
Carbon Dioxide	**CO2**	*0.0055137*	Odorant					

Source: Transient Plasma Systems, Inc.

Table A-2: Natural Gas Specific Gravity, Ratio's and Weight Fraction

					NG Fuel Property Derivation								
					Specific Gravity, Ratio's and Weight Fraction Determination							Processed: 01/27/20 13:55	
Component	Chemical Formula	Constituent Mole % of Fuel	1.008 # H Atoms per molecule	4.003 # He Atoms per molecule	12.011 # C Atoms per molecule	14.007 # N Atoms per molecule	15.999999 # O Atoms per molecule	Gram Molecular Weights	Mole % X Mole weight	Mole % X # H Atoms	Mole % X # C Atoms	Mole % X # C Atoms X C g mole wght	
Methane	**CH4**	*96.2037%*	4	0	1	0	0	16.043	15.43395205	3.8481461	0.9620365	11.55502076	
Ethane	**C2H6**	*2.8644%*	6	0	2	0	0	30.07	0.861324479	0.1718639	0.057288	0.688085688	
Propane	**C3H8**	*0.2785%*	8	0	3	0	0	44.097	0.12280794	0.0222796	0.0083549	0.100350103	
I-Butane	**C4H10**	*0.0107%*	10	0	4	0	0	58.124	0.006193112	0.0010655	0.0004262	0.005119088	
N-Butane	**C4H10**	*0.0204%*	10	0	4	0	0	58.124	0.011876477	0.0020433	0.0008173	0.009816831	
I-Pentane	**C5H12**	*0.0051%*	12	0	5	0	0	72.151	0.003663106	0.0006092	0.0002539	0.003048992	
N-Pentane	**C5H12**	*0.0043%*	12	0	5	0	0	72.151	0.003132075	0.0005209	0.0002171	0.002606988	
Hexanes	**C6H14**	*0.0000%*	14	0	6	0	0	86.178	0	0	0	0	
Heptanes	**C7H16**	*0.0000%*	16	0	7	0	0	100.205	0	0	0	0	
Octanes	**C8H18**	*0.0000%*	18	0	8	0	0	114.232	0	0	0	0	
Nonanes	**C9H20**	*0.0000%*	20	0	9	0	0	128.259	0	0	0	0	
Hydrogen	**H2**	*0.0000%*	2	0	0	0	0	2.016	0			0	
Helium	**He2**	*0.0000%*	0	2	0	0	0	4.003	0			0	
Nitrogen	**N2**	*0.6158%*	0	0	0	2	0	28.014	0.172507411			0	
Oxygen	**O2**	*0.0000%*	0	1	0	0	2	32	0			0	
Carbon Dioxide	**CO2**	*0.5514%*	0	0	1	0	2	44.009	0.242651983		0.0055137	0.066224931	
Sum of All Constituents		100.55%							16.85810863				
Sum Carbon Bearing Constituents		99.94%										12.43027338	
Sum of HC Constituents		99.39%								4.0465286	1.0293938	12.36404845	
Sum of Non-CH4 HC Constituents		3.18%								0.1983824	0.0673572		

Source: Transient Plasma Systems, Inc.

Table A-3: Natural Gas Property Derivation Intermediate Calculations

	NG Fuel Property Derivation			
	Intermediate Calculations			Processed: 01/27/20 13:55
THC Hydrogen	(Mole % HCi)(H atoms per HCi) =	4.04652856	x - HC Hydrogen	
THC Carbon	(Mole % HCi)(C atoms per HCi) =	1.02939376	y - HC Carbon	
THC H/C Ratio	H/C THC = THC Hydrogen / THC Carbon	3.93098221		
D hc	D hc = 1.1771 X (12.011 + H/C thc X 1.008)	18.802 = 1.1771 X (12.011 + 3.931 X 1.008)		
NMHC Hydrogen	(Mole % NMHCi)(H atoms per NMHCi) =	0.19838244	All non-Methane Hydrocarbons	
NMHC Carbon	(Mole % NMHCi)(C atoms per NMHCi) =	0.06735723	All non-Methane Hydrocarbons	
NMHC H/C Ratio	H/C NMHC = NMHC Hydrogen / NMHC Carbo	2.9452286		
D nmhc	D nmhc = 1.1771 X (12.011 + H/C nmhc X 1.0	17.633 = 1.1771 X (12.011 + 2.945 X 1.008)		
CWF nmhc	CWF nmhc = 12.011 / (12.011 + H/C nmhc X 1	0.802 = 12.011 X (12.011 + 2.945 X 1.008)		
Grams C per gram mole	(Mole % Xi)(C atoms per Xi)(MW C) =	12.4302734	Total Carbon Weight	
NG gram mole weight	(Mole % Xi)(MW Xi) =	16.8581086	Total Fuel Weight	
CWF ng	g C/ g NG fuel =	0.73734685		
HC gr of C per gr mole of	(Mole % HCi)(C atoms per HCi)(MW C) =	12.3640485	Total HC Carbon Weight	
NG gram mole weight	(Mole % Xi)(MW Xi) =	16.8581086	Total Fuel Weight	
CWF hc/ng	CWF hc/ng =	0.73341848		
Grams CO2 per gr mole	(Mole % CO2)(MW CO2)	0.24265198	CO2 Weight	
NG gram mole weight	(Mole % Xi)(MW Xi) =	16.8581086	Total Fuel Weight	
WF co2		0.01439378		
Specific Gravity	per ASTM D-3588	0.58206302		
D ng grams / cu ft	D ng grams/cu ft = Sp Grav X 28.316847 X 1.2	19.856 = 0.582 X 28.316847 X 1.2047		
D ng lbs / 100 cu ft	D ng lbs/100 cu ft = 100 X D ng gr per cu ft / 45	4.377 = 100 X 19.856 /453.6		
NHV B.t.u./cu ft	per ASTM D-3588	928.972385		@ 60°F and 1 atm
NHV B.t.u./pound	NHV = 453.6 X Sp Grav / (NHV X 28.316847X1	21221.7911		@ 68°F and 1 atm

Source: Transient Plasma Systems, Inc.

Table A-4: Natural Gas Fuel Property – ASTM Fuel Analysis

NG Fuel Property Derivation Report

Part 1 - ASTM Fuel Analysis

Processed: 01/27/20 13:55

Mole Fractions from ASTM D-1945 @ 60°F & 1 atm			ASTM D-3588				
Natural Gas Constituents	Chemical Formula	Mole Fraction	Specific Gravity	Net Heat Val B.t.u./cu. ft.	ASTM D-1945 Data Source		
Methane	CH4	0.9620365	0.582063	928.97239	name the source of data		
Ethane	C2H6	0.0286440					
Propane	C3H8	0.0027850		Cylinder: description			
I-Butane	C4H10	0.0001066		description			
N-Butane	C4H10	0.0002043		description			
I-Pentane	C5H12	0.0000508		description			
N-Pentane	C5H12	0.0000434					
Hexanes	C6H14	0.0000000	§86.113-94 (e) Natural gas fuel. (1) Natural gas fuel having the following specifications				
Heptanes	C7H16	0.0000000	will be used for exhaust testing of natural gas-fueled vehicles.				
Octanes	C8H18	0.0000000	Methane		min, mole pct.	89.0	Pass
Nonanes	C9H20	0.0000000	Ethane		max. mole pct	4.5	Pass
Hydrogen	H2	0.0000000	C3, and higher		max. mole pct	2.3	Pass
Helium	He2	0.0000000	C6, and higher		max. mole pct	0.2	Pass
Nitrogen	N2	0.0061579	Oxygen		max. mole pct	0.6	Pass
Oxygen	O2	0.0000000	Inert gases: Sum of CO2 ar		max. mole pct	4.0	Pass
Carbon Dioxide	CO2	0.0055137	Odorant				

Part 2 - NG Test Processor Input

Natural Gas Properties	THC H/C Ratio	NMHC H/C Ratio	CWF ng	CWF hc/ng	WF CO2	Net HV B.t.u./lb	ASTM D-3588 Spec Grav
	3.931	2.945	0.737	0.733	0.014	21222	0.582

* The above data are to be entered onto the NG Vehicle Test Analysis Input Data Sheet

** Net (Lower) Heating Value is at 68°F and 760 mm Hg

Part 3 - NG Test Processor Calculations

Natural Gas Properties	THC H/C Ratio	D hc grams/cu ft		NMHC H/C Ratio	D nmhc gr/cu ft	CWF nmhc	
	3.931	18.802		2.945	17.633	0.802	

Natural Gas Properties	CWF ng	CWF hc/ng	WF co2	Specific Gravity	D ng grams/cu ft	D ng lbs/100 cuft	Net HV B.t.u./lb
	0.737	0.733	0.014	0.582	19.854	4.377	21222

Send comments to courtois.william@epamail.epa.gov | This is not official EPA Certification Guidance. | US-EPA-OAR-OMS-TSD-WMC

Source: Transient Plasma Systems, Inc.