

DISSERTATION

EMPLOYING EXPERIMENTAL AND COMPUTATIONAL FLUID DYNAMIC METHODS
TO REDUCE METHANE EMISSIONS IN LARGE BORE TWO-STROKE NATURAL GAS
ENGINES BY USING IN-CYLINDER TECHNIQUES

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ABSTRACT

EMPLOYING EXPERIMENTAL AND COMPUTATIONAL FLUID DYNAMIC METHODS TO REDUCE METHANE EMISSIONS IN LARGE BORE TWO-STROKE NATURAL GAS ENGINES BY USING IN-CYLINDER TECHNIQUES

Methane slip from internal combustion engines is an issue that escalates the increase of the average global temperature society is seeing today. Governmental policy has pushed for a reduction of emissions from internal combustion engines to help combat this change in global weather. The purpose of this research was to investigate multiple in-cylinder techniques that were designed to reduce the engine out emissions of a large bore two-stroke natural gas integral compressor engine. Experimental and computational fluid dynamic simulations were used throughout the research. The first technique investigated was using a hydrogen and natural gas blended fuel compared to a solely natural gas fuel. The second technique was designing a pre-combustion chamber that addressed areas of poor or incomplete combustion. Finally, the third technique studied was the injection of a premixed natural gas and air charge into the pre-combustion chamber to improve homogeneity of the pre-combustion chamber. Using hydrogen as a fuel saw reductions in methane emissions of nearly 30%. The optimized prechamber design saw decreases between 22% and 31%, depending on the engines operating conditions. The premixed fuel and air injection did not produce any favorable results. The reductions seen in the first two techniques show that large diminutions in emissions are not only possible, but likely across multiple platforms.

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Chapter 1

Introduction

1.1 Background and Motivation

According to NASA's Goddard Institute for Space Studies (GISS) [1] the average global temperature anomaly in 2024 was 1.28°C (2.3°F) higher than the long-term average (1951-1980) with the last decade being the warmest years recorded. Figure 1.1 shows the temperature anomaly versus year. Data collection began in 1880.

The Intergovernmental Panel on Climate Change (IPCC) studied the effects of rising temperatures and made predictions about how it would impact the world if the upward trend in temperature continues [2]. The panel provides evidence showing that if carbon dioxide levels in the atmosphere continue to increase, a plethora of issues will arise. The number of extreme heat events will increase as frost events and cold spells will drop. Heavy precipitation and pluvial flooding will be widely seen. Colder regions will see a decrease in lake, river, and sea ice, as well as permafrost, hail, snow, glaciers, and ice sheets. The most impacted aspect will be the oceanic and coastal regions; relative sea levels will rise, and coastal flooding, coastal erosion, and marine heatwave events will all become more common. These changes will be seen across the entire globe.

There are multiple factors that contribute to the temperature increase, but two greenhouse gases (GHGs), carbon dioxide (CO₂) and methane (CH₄), contribute the most. Both molecules are referred to as heat-trapping gases, and when released into the atmosphere, they act as insulation to the Earth by absorbing the long-wave radiation from the sun that is reflected from the Earth's surface and emitting it back to the surface. The presence of GHGs, specifically carbon dioxide, in the atmosphere is essential for life on Earth to exist. Without GHGs, Earth's average temperature would be approximately -18°C (0°F) [3] in comparison to the 15°C (59°F) [4] [5]. The excessive accumulation of these gases over time results in an increase in the Earth's surface temperature.

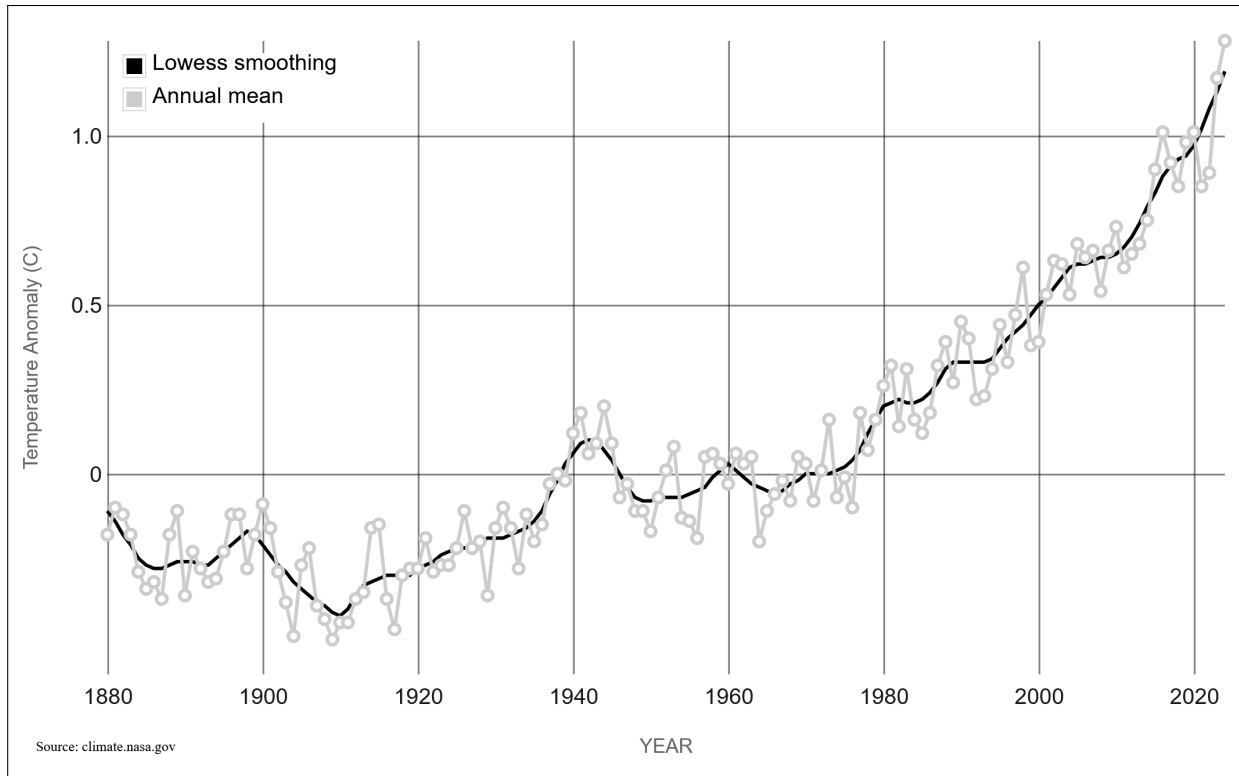


Figure 1.1: Global surface temperature change compared to the long-term average.

According to [6], the growth rate of carbon dioxide trapped in the atmosphere is less than half of what would be expected if all the carbon dioxide released by land use and fossil-fuel burning remained. Carbon dioxide in the atmosphere can remain for centuries [7] until it is either absorbed by the oceans, plants, and soil because of its relatively nonreactive behavior. The absorption from oceans, plants, and soil comprises a large part of the cleanup effort but is not enough to bring levels to net zero.

Methane has a short lifespan compared to carbon dioxide, existing for 7–12 years in the atmosphere where it eventually reacts with oxygen and becomes carbon dioxide. Methane is also a climate super pollutant that traps approximately 28 times the amount of heat that carbon dioxide does [8]. Estimations of around 40% of methane emissions are from natural sources such as wetlands, oceans, wild animals, permafrost, and vegetation, while the remaining 60% is attributed to human activity [9]. The major human-related contributing factors are agriculture and agricultural waste, fossil fuel production and use, and biomass and biofuel burning.

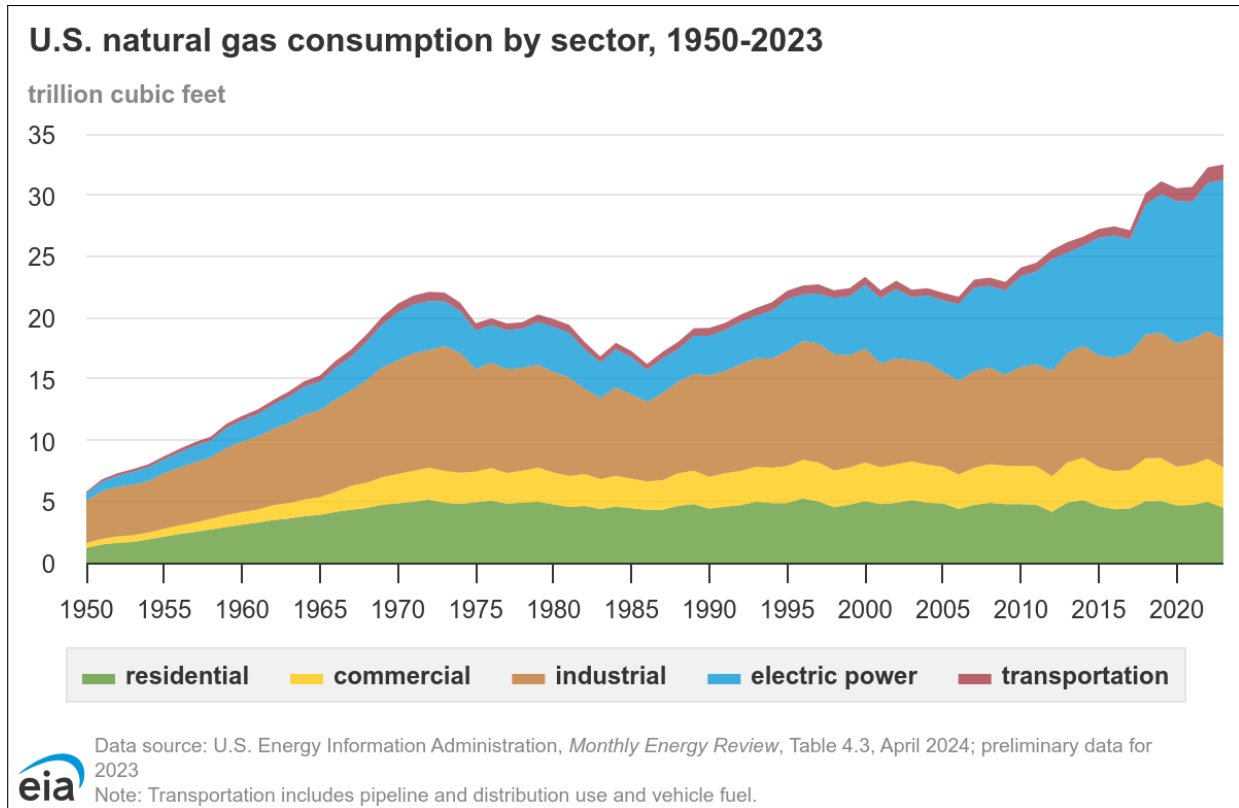


Figure 1.2: U.S. natural gas consumption by sector.

One of the major contributors to methane expulsion into the atmosphere comes from the burning of natural gas for various reasons, including heating, manufacturing, power generation, and transportation. The major constituent of natural gas is methane. In 2023, natural gas production accounted for 38% (39.25 quads) of total energy production in the United States. This is fueled by the continually increasing total demand, as can be seen in Figure 1.2 [10].

The production, transport, and distribution systems for natural gas throughout the U.S. are extensive and complex. Production starts at a natural gas shale, where it is pumped from a source and sent to a processing plant where the gas undergoes several processes. The majority of these processes are separating the natural gas from other constituents such as water, oil, and non-hydrocarbon gases. From the processing plant, the natural gas is sent to underground storage reservoirs for later use or to the consumer with a provider company in between. Figure 1.3 [11] below shows a map of the U.S. gas transportation pipeline system.

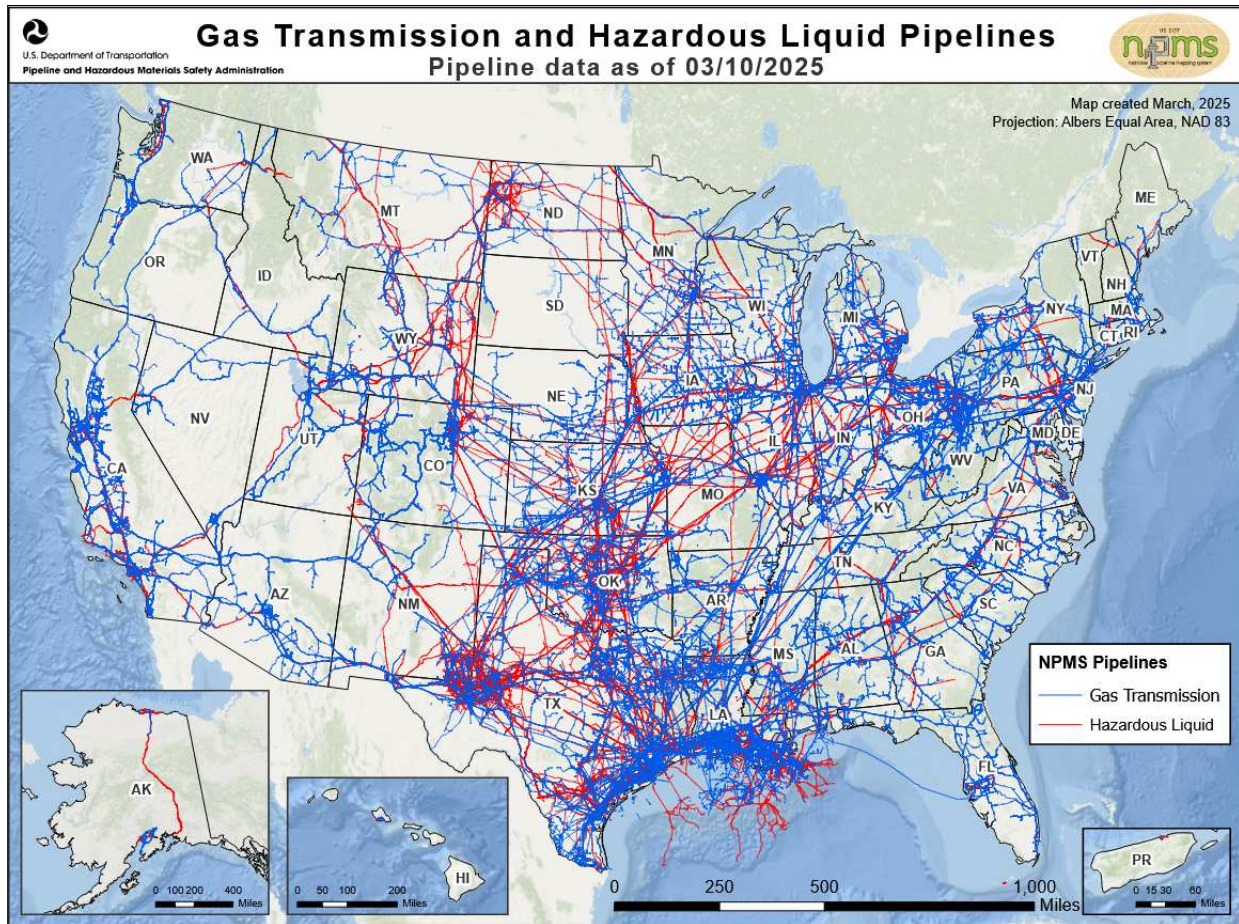


Figure 1.3: Nationwide map of gas transmission pipeline system.

To keep the gas flowing from the wellhead to storage or consumer, compressor stations that utilize reciprocating engines and turbines to power compressors pressurize the gas and create a pressure difference between one point and another, causing flow. The pipes range from small-diameter and low-pressure to large-diameter (1+ meter, 3+ feet) and high-pressure (8+ MPa, 1,200+ psi). Because of pressure losses along the pipeline, compressor stations are needed every 40 to 100 miles to re-pressurize the gas. There are approximately 1,500 transmission stations with 5,500 transmission compression units in the U.S. [12], each requiring a power supply. The engines used to generate power are powered by the natural gas it pumps, which siphons a relatively small amount from the pipeline.

Whether it comes from leakage through the piston rings and crankcase or from incomplete combustion, methane slip from these engines can be a major source. Because of this, the U.S. Envi-

ronmental Protection Agency (EPA) regulates the methane emissions of stationary reciprocating engines using the National Emission Standards for Hazardous Air Pollutants (NESHAP) codified in 40 CFR part 63, Subpart ZZZZ [13].

Another policy titled “Waste Emissions Charge” (WEC) under the Methane Emissions Reduction Program (MERP) was implemented by the EPA that required operators/owners of these engines to pay a fee for any emissions emitted above the outlined threshold. As of May 12, 2025, the WEC will no longer be implemented, as it was disapproved by Congress [14]. Regardless, before the disapproval, this law was in effect and was a large driver in researching methods and solutions to reducing methane slip.

Paired with the WEC is the Greenhouse Gas Reduction Program (GHGRP) Subpart W [15] which requires operators/owners that emit 25,000 metric tons or more of GHGs per year to report GHG data to the EPA. This is an attempt at using data to enforce recognition and accountability.

1.2 Literature Review

1.2.1 Using Hydrogen as a Fuel

A U.S. Department of Energy (DOE) sponsored initiative titled “H2@Scale” [16] aims at advancing the affordability of “hydrogen production, transport, storage, and utilization to enable revenue opportunities across multiple sectors.” A separate initiative titled “HyBlend” [17], also sponsored by the DOE, supports the H2@Scale vision but specifically aims at addressing barriers to blending hydrogen into the U.S. natural gas pipeline system.

With the pipeline compressor station engines siphoning their fuel from the pipeline itself, methane slip from these engines could be reduced since the combustion of hydrogen produces no carbon-based emissions. Although several challenges would arise if the lines were transporting a blend of natural gas and hydrogen, such as increased nitric oxides emissions, reduced energy transmission capacity, increased pressure drop when meeting energy demands, increased required compression power, and excessive combustion dynamics, flame lift-off, and flashback [18], to name a few. Table 1.1 shows a comparison of hydrogen and methane parameters.

Table 1.1: Comparison of Hydrogen and Methane Parameters

Parameter	Hydrogen (H ₂)	Methane (CH ₄)
Gravimetric Energy Density (MJ/kg)	120–142	55–56
Volumetric Energy Density (MJ/L)	8.5–10.1 (liquefied)	23 (liquefied)
Lam Flame Speed S_L (cm/s, $\phi = 1.0$)	210	40
Flame Temperature (K, Air as oxidizer)	2483	2236
Flammability Limits (% volume in air)	4–75	5–15
Ignition Energy (mJ)	0.02	0.28
Combustion Products	H ₂ O	CO ₂ , H ₂
Greenhouse Gas Potential (100 yrs)	0	28–34
Embrittlement Risk	High	Low to moderate

Because hydrogen and methane (the majority constituent of natural gas) are such wildly different fuels, study, and analysis of their behavior in ICEs was required. The following details how the addition of hydrogen to a fuel supply has affected the performance and combustion characteristics of an engine.

Spark Advancement

[19] experimentally tested on a 1976 Toyota 2TC 1.6 L engine using methane and hydrogen blended fuel. He saw that the best efficiency spark advance (BESA) needs to be retarded with the addition of hydrogen in methane (20% by volume) by approximately 3 degrees at any given equivalence ratio to keep the MBT constant in comparison to the purely methane operation case. He saw that from $\phi = 0.6 - 0.75$ the spark advance did not change between equivalence ratios—it held at a constant 40° bTDC. For $\phi > 0.75$, a reduction in spark advancement was required. A sweep of hydrogen-methane blends (by volume) was performed by [20] on a single-cylinder SI CFR engine using methane and hydrogen blended fuels and showed similar results. This is due to the faster flame speed associated with hydrogen, which increases the flame propagation rate.

Thermal Efficiency

[19] also showed that the thermal efficiency increased across all equivalence ratios. It is believed that efficiency improves because the burning gases exhibit a larger temperature increase

during combustion. This implies that there is a larger pressure difference generated, forcing the piston downward with extra force, creating more work being done per unit mass of fuel. Similar results were shown in [21] with a single-cylinder cooperative fuel research (CFR) engine using gasoline and hydrogen fuels—an increase in efficiency across all equivalence ratios with a maximum efficiency located at $\phi = 0.7$. It was noted that as the equivalence ratio increases near stoichiometric, the relative beneficial effects of the addition of hydrogen are diminished. The increase in hydrogen percentage in the fuel starts to affect the power output unfavorably because of the reduction in the lower heating value per unit volume of the fuel blend as hydrogen percentage increases. [19] also compared the average indicated output efficiency against equivalence ratios across the hydrogen/methane blends. They showed that there was a decrease in efficiency with the addition of hydrogen when the spark timing was not retarded.

Lean Limit

Bauer and Forest [22] experimentally tested a single-cylinder CFR engine using methane-hydrogen fuel blends. The lean limit of the engine was found to extend from $\phi = 0.58$ with pure methane operation to $\phi = 0.34$ with a 60%, by volume, methane/hydrogen blend across all operating conditions. Ma and Wang [23] tested a Dongfeng Motor Co. Ltd. in-line 6-cylinder SI 6 L and found similar results using natural gas and hydrogen blends. They found that the COV in indicated mean effective pressure (IMEP) started to increase beyond acceptable levels when excess air ratio (λ)=1.55 using natural gas but λ increased to a value of 2.07 when using a 50% hydrogen, by volume, blend. The extension of the lean limit is supposed to be from a greater mixing of fuel within the cylinder and the reduced energy required to ignite a hydrogen mixed fuel.

Unburned Hydrocarbons

Akansu et al. [24] experimentally tested a Ford 4-stroke cycle 4-cylinder SI engine using methane and hydrogen blended fuels. They found that when the percentage of hydrogen increased, the brake-specific unburned hydrocarbon values decreased. The lowest value is located at $\phi = 0.9$

for both blended and non-blended fuels, with little difference between them. At ϕ values lower than 0.9, brake specific unburned hydrocarbon (BSUHC) levels increased, but the hydrogen blends tend to show decreased values compared to the methane cases, with a maximum reduction of approximately 30% being found with the 30% hydrogen by volume blend. Unburned hydrocarbon (UHC) levels reduce due to the decreased carbon content level and the increase in combustion stability overall.

Nitric Oxides

Nitric oxides (NO_x) levels are a very strong function of spark advancement and peak combustion temperatures [19]. It was found that nitric oxides concentrations increased with the addition of hydrogen in methane due to the faster flame speed than methane alone. This faster flame speed produced a higher flame temperature, which in turn, resulted in a higher nitric oxides concentration. Ma et al. [25] experimentally tested a Dongfeng Motor Co. Ltd. inline 6-cylinder SI 6 L engine using natural gas and a 20/80% hydrogen/natural gas blend. The results showed similar results to [19] – an increase in nitric oxides values with an increase in hydrogen in the fuel at comparable equivalence ratios. But because the addition of hydrogen in the fuel lowers the lean limit of the engine, the engine could operate at an equivalence ratio that produces lower nitric oxides values than natural gas alone.

carbon monoxide and carbon dioxide

Carbon monoxide is a strong function of equivalence ratio and was shown in [19]. carbon monoxide concentration levels (as a dry %) were very low until an equivalence ratio of approximately 0.9 for both the methane and hydrogen-methane mixture. Above the 0.9 equivalence ratio, there is a dramatic increase in the level of carbon monoxide particles, with a slightly less dramatic increase in the case of the hydrogen-methane mixture. This can be explained by accounting for the decrease in carbon content, which had been replaced by hydrogen atoms. Ma and Wang [23] experimentally tested a combustion chamber using methane and hydrogen blends at 30/70% (by volume) hydrogen/methane and 70/30% hydrogen/methane. It was shown that with the increase in

hydrogen percentage, there was a substantial decrease in the carbon monoxide and carbon dioxide output – again, caused by the reduction of carbon content in the fuel. No exact values in ppm or percentage decrease were given.

Ignition Delay and Heat Release Rate

Karim et al. [20] continued their hydrogen-methane fuel sweep and compared the ignition delay lag across each fuel blending percentage. They concluded that with an increase in hydrogen percent within the fuel, the ignition delay decreased across all equivalence ratios and the tested spark timings. This reflects the increase of flame kernel growth speed and flame speed of hydrogen. Du et al. [26] experimentally tested a gasoline SI engine using various hydrogen blended percentages (by volume) and a λ sweep. Their results showed an increase in the rate of heat release with an increase in hydrogen percentage. At a λ value of 1.0, the highest rate of heat release (ROHR) was nearly 110 J/°CA, while the purely gasoline fuel was approximately 50 J/°CA. Figure 12 from the paper shows nearly linear correlations for each λ tested. It could also be seen that as λ increased, the ROHR decreased at similar hydrogen percentages. λ equal to 1.0 was nearly 110 J/°CA and $\lambda=1.5$ was slightly above 80 J/°CA, both values being for the highest percentage of hydrogen blended, 11.09% by volume.

Combustion Duration

Mariani et al. [27] experimentally tested a Fiat Panda 1.2 NP L4 SI 1242 cm³ engine using natural gas and hydrogen blends. The combustion duration, defined as the angle between 10% and 90% of heat release, saw a decrease of 16% with a hydrogen/natural gas blend consisting of 15% hydrogen by volume, and a 21% decrease in the 30% hydrogen fuel blend. Both fuels were tested and compared at similar engine operating conditions: 2.5 bar indicated mean effective pressure (IMEP) and 2,400 rpm. This decrease in combustion duration is due to the increased flame speed and increased flame temperature. Di Iorio et al. [28] experimentally tested a 4-stroke single-cylinder 250 cm³ engine using methane and hydrogen blended fuels. Their results were similar to [27]. Reviewing the ROHR, the center of combustion (peak of ROHR) showed advanced crank

angle degree locations with the addition of hydrogen to the base fuel. Purely methane operation gave a location of 24°CA, while the 20% hydrogen (by volume) blend had a location of 19° after top dead center (aTDC), and the 40% blend had a 14 °aTDC location (each value was at the tested 3,000 rpm operating condition).

Cylinder Pressure

Pan et al. [29] numerically evaluated combustion process parameters as well as emission values for a rotary engine using a hydrogen and gasoline fuel mixture. The fuels consisted of 0%, 3%, 6%, and 9% hydrogen mixtures. The spark timing and the equivalence ratio were held constant for each fuel tested. Results showed that as the percentage of hydrogen in the fuel increased, so did the average pressure inside the cylinder. The 9% hydrogen fuel showed a 6-bar increase in pressure over the purely gasoline fueled case. They explain this as being due to the high diffusive velocity of the hydrogen, which creates a more homogeneous mixture, which is advantageous to the flame propagation and combustion process as a whole. This more homogeneous mixture ignites faster and in turn creates a greater pressure inside the cylinder.

Wang et al. [30] experimentally tested natural gas and hydrogen fuel blends on a 0.796 L-cylinder engine. They state that there tends to be a strong correlation between the addition of hydrogen to the base fuel and peak cylinder pressure, maximum rate of pressure rise, and the location of peak pressure. Comparing cycle-by-cycle variations of the indicated mean effective pressures across the pure methane, 23% hydrogen, and 40% hydrogen (by volume), it was shown that there was a decrease as the percentage of hydrogen increased in the fuel. The COV in the case of pure methane shows a wide dispersion compared to the 40% hydrogen case, where the COV is presented as a much tighter concentration. They explain this as misfires and/or partial combustion cycles reducing in frequency as the hydrogen content increases due to the ease of ignition of hydrogen mixed methane versus pure methane.

Flame Temperature

Park et al. [31] numerically evaluated the flame structure of a methane-air flame. Hydrogen was blended at 10, 20, and 30% by mass into the methane fuel. The maximum flame temperature was compared against the global strain rate. The maximum flame temperature showed increases with the addition of hydrogen. A maximum temperature of approximately 2,100 K was found for the 30% hydrogen blend, while 2,000 K was found for the purely methane case. This publication focused on the chemical reactions heavily, and because of this, they explained the increase in flame temperature as the reduction of carbon monoxide and carbon dioxide products, which are the major contributors to radiation heat loss.

The aforementioned research was performed using both numerical and experimental methods on transient engines, cooperative research engines, and combustion chambers. The vast majority of work using ICEs has been completed on 4-stroke small bore engines that do not utilize a pre-combustion chamber. This leaves gaps in the research that need to be filled, such as large bore (190 mm+ bore) 2-stroke slow speed integral compressor engines (stationary power generation). The following proposal seeks to fill those gaps using a Cooper Bessemer GMV-4TF.

1.2.2 Pre-combustion Chamber Characterization

The pre-combustion chamber (PCC) was formally introduced to the world, via patent in 1916 [32], and was a successful attempt at increasing “the thermal efficiency of engines working on the constant volume or explosion cycle.” Since then, refinements to the idea and advancements in technology have added other significant benefits to its use, such as improving ignition stability [33], reducing cycle-to-cycle variability, increasing the engine’s operational limits (e.g., lean combustion), and even being able to control emissions [34]. This literature review covers published material regarding PCC design and optimization through theory, experimental methods, and CFD modeling.

Anderson, et al. [35] published one of the first pieces of research looking at and identifying a PCC's design parameters through theory and experimental means. They formed the idea of a satisfactorily performing PCC as one that appeases the following conditions:

1. Uniform mixing in the PCC, near the spark plug, at the time of ignition.
2. Low cycle-to-cycle variability (CCV) of the flame kernel growth and initial propagation.
3. The discharging flame from the PCC consistently ignites the main combustion chamber over a wide range of AFR's.

It was found that a PCC's measure of homogeneity is based on the Craya-Curtet number, the ratio of the length of the PCC volume to its diameter, and the main combustion chamber's equivalence ratio. The main combustion chamber's geometry is not a factor in the PCC mixing.

Ignition of the PCC was determined to be a function of simply the PCC equivalence ratio and jet velocity at the time of spark, along with the spark energy. The velocities inside the PCC near the spark plug determine the quenching and/or propagation of the flame kernel. The spark energy required to promote combustion is at a minimum value for stoichiometric mixtures and increases as the mixtures become more lean or more rich. Similar results were seen in [36].

Consistent ignition of the main combustion chamber is the most complex part of the criteria. The authors relate ignition of the main chamber's unburned charge "to the total heat release of the unburned charge entrained in the jet mixing zone during the time period available for flame development." In other words, if the heat transfer from the hot PCC gases to the unburned MCC charge is fast enough, before any specific molecule reaches a quenching surface, then a flame will propagate and the MCC charge will ignite.

The authors performed an experimental study of the aforementioned parameters on a 6.5 in (165 mm) bore by 9.0 in (230 mm) stroke single cylinder gas engine under natural aspiration. The engine had a 7.5:1 expansion ratio and used a premixed MCC charge for precise PCC equivalence ratio handling. Two hundred eighty combinations of varying PCC length, PCC diameter, and nozzle diameter were studied.

The experiment resulted in a number of suggested relational values (e.g. $\frac{L}{D} \approx 1.5$, $C_t \leq 0.3$) for optimal PCC performance along with general behavioral connections such as spark energy becoming the controlling factor of ignition when turbulence in the PCC is low, and as the MCC equivalence ratio decreases, the required PCC equivalence ratio to promote MCC combustion increases.

Let it be noted that the authors state that the size and shape of the PCC volume did not appear to affect the ignition but did not expand that to include the mixing of the PCC. Furthermore, only cylindrical style PCCs with fuel injection entering at the furthest side opposite the nozzle were presented.

Leng et al. [37] studied the impact the number of PCC nozzles and the orifice size had on combustion. Utilizing CFD, they modeled a 7.5 in (190 mm) bore marine SI natural gas engine using multiple PCC configurations. Each configuration varied the number of nozzles (from 4 to 8), the nozzle orifice diameter (1.6 mm to 2.9 mm), and a non-dimensional value β that is a function of the engine's bore, PCC nozzle orifice flow area, and the volume of the PCC.

Results from the simulations showed that, while using a constant β value, higher numbers of nozzles lead to poor radial flame propagation, and lower nozzle counts lead to poor circumferential flame propagation. Poor circumferential flame propagation tended to prolong the combustion duration. The optimal number of PCC nozzles was found to be six.

Regarding the orifice diameter, as the diameters increased, lower pressure differences between the PCC and MCC volumes arose, resulting in a reduction of the gas transfer velocity and effectively reducing radial flame propagation through the MCC, prolonging combustion duration. Smaller diameters led to, again, poor circumferential flame propagation, leading to prolonged combustion duration. The optimal orifice diameter was shown to be 2mm at a β value equal to 0.3. A similar study with similar results was conducted by [38] on a 130mm bore 6-cylinder diesel engine converted to operate using a single cylinder fueled with natural gas.

Simpson et al. [39] experimentally tested five different PCC designs on a GMV-4TF. The designs varied widely and covered PCC volume (micro vs. OEM), PCC fueling (passive vs. active), MCC

fuel injection pressure, nozzle count, and fuel injection style (electronic vs. mechanical). The study was completed with the goal of reducing nitric oxides emissions.

Results showed that, regarding THC emissions, the multi-nozzle design reduced emissions by 43%, the fueled micro PCC reduced emissions by 23%, and the electronically controlled PCC fuel injection reduced emissions by 21%. Note that the multi-nozzle design had the nozzle orientations arbitrarily appointed and was designed to quickly increase the surface area of the flame. An optimization study was also performed but entailed the variance of the PCC fueling techniques (mechanical vs. electronic) only.

This present study aims at filling in the gaps found within the currently published material; using CFD to locate pockets of unburned hydrocarbons within the combustion chamber and then target them by varying the PCC nozzle orientation, diameter, and number of nozzles, with the goal of reducing methane slip. Many groups have experimentally or numerically tested designs such as [40], [41], [42], [43], and [44] but were looking at feasibility and general performance compared to other designs or applying a potential solution to a problem such as flame impingement on the piston as seen in [45]. Some studies were even carried out on non-ICE apparatuses, [46] and [47]. Others have only characterized the PCC through theoretical and experimental analysis, such as [35] and [48]. Because one of the main performance benefits of using a PCC is being able to run under lean conditions and therefore reducing nitric oxides many studies have focused on improving that aspect, such as [49], and [50].

This study applies CFD as a tool to achieve an optimized design and then validates the design through experimental testing. Much of the published material that incorporates experimental and modeling techniques uses experimental data to validate the model. The model is then used to refine or optimize a design or parameter with no further validation completed on the engine.

1.3 Research Questions

This investigation will be split into three separate research techniques, each with an experimental portion. Two of the researched techniques include simulations paired with the experimental. The

investigation will answer questions relating large bore engine methane slip reduction to the (1) use of premixed natural gas and hydrogen fuel blends, (2) varying of PCC design parameters using solely natural gas, and (3) injecting a premixed fuel and air charge into the PCC. To that end, this investigation seeks to address the following research questions:

Hydrogen/Natural Gas Blending

1. How does the addition of hydrogen to a fuel supply affect the combustion stability of a lean-burn, large bore natural gas engine?
2. What are the emissions trade-offs when operating a lean-burn, large bore natural gas engine with varying fuel blend ratios?

Directional PCCs

1. Can combustion efficiency be increased by targeting pockets of unburned methane within the MCC utilizing PCC design?
2. How does PCC geometry affect methane emissions from a lean-burn, large bore natural gas engine?

Premixed Fuel and Air Injection

1. How does premixing the fuel charge injected into the PCC with air affect combustion statistics and emissions?
2. Could this be a viable strategy for reducing engine out emissions?

1.4 Research Objectives

The objectives of this research are to:

1. Quantify how a lean burn large bore engine's combustion characteristics and emissions will vary with the use of a hydrogen/natural gas blended fuel compared to a natural gas-only configuration.

2. Develop and optimize a PCC geometry for methane reduction using CFD.
3. Quantify the feasibility of using CFD to design a PCC that targets pockets of unburned methane within the main combustion chamber.
4. Evaluate the effectiveness and viability of premixing a PCC fuel charge in a direct injection engine regarding combustion stability and emissions.

Chapter 2

Methods and Materials

2.1 Two-Stroke Lean Burn Natural Gas Integral Compressor Engine



Figure 2.1: GMV-4TF engine housed at CSU's Energy Campus inside the Powerhouse.

These studies were performed using a Cooper-Bessemer GMV-4TF natural gas integral compressor engine, which can be seen in Figure 2.1. The engine is a slow speed (300 rpm) 2-stroke cycle engine with a 14 in. (35.6 cm) bore and a 14.375 in. (36.5125 cm) stroke. The engine is rated to make 440 bhp and 7,700 lb-ft of torque when under full load. The GMV uses four combustion cylinders to power two side-mounted compression cylinders—the compression cylinders have been removed in the research engine.

The engine employs a unique articulated rod geometry, designed by Cooper-Bessemer, to connect the power cylinders and the compression cylinder to the crankshaft. The unique configuration results in several differences in performance between the left and right banks of the engine, such as scavenging efficiency, trapped AFR, exhaust and intake port open durations, deviations in PP and LoPP, emissions, and trapped residuals. Details on the geometry and its effects can be read in [51] and a cross-section image can be seen in Figure 2.2.

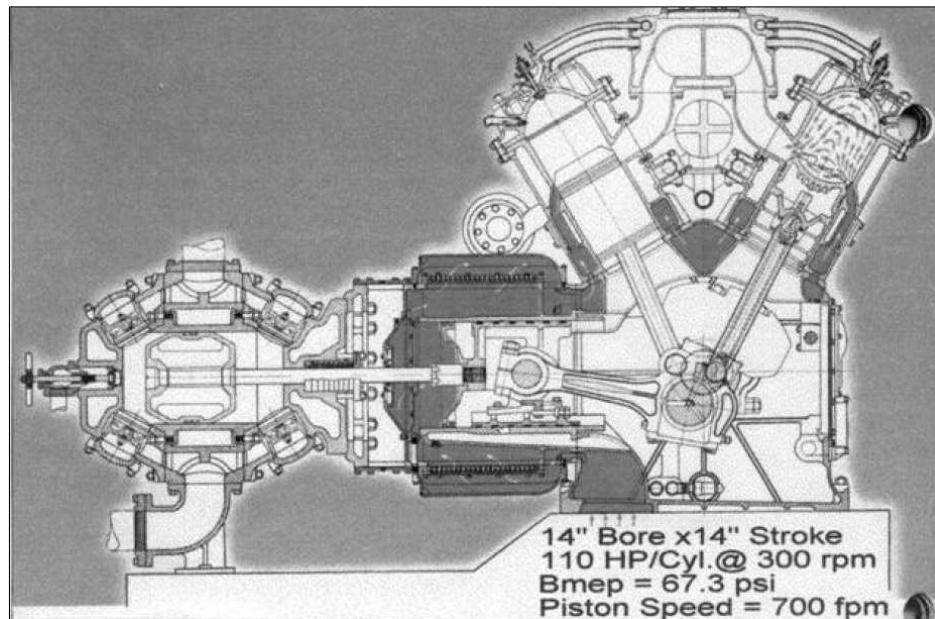


Figure 2.2: Cross-section image of a GMV with the compression cylinders.

The engine can be configured in numerous ways due to the interchangeability of individual components such as the cylinder head, connecting rod, fueling style, and ignition style. This particular unit has a model “A” cylinder head that equips a centrally mounted fuel injector with an off-center mount for either a traditional spark plug or a PCC for ignition sources.

Two basic fueling configurations are available for the engine with the installed cylinder head: high pressure (HPFI) and low pressure. Figure 2.3 shows the electro-mechanical HPFI setup installed on the number four cylinder of the GMV. There are two major components of the HPFI system: (1) the electric solenoid and (2) the gas admission valve. The solenoid activates in response to the Electronic Fuel Injection (EFI) controller and causes a change in the hydraulic line

pressure. The change in hydraulic line pressure causes the gas admission valve to open and close, allowing fuel to flow into the main combustion chamber. In the image, the green and silver component on the left is the electric solenoid, and the circular green component in the middle is the gas admission valve. The green and shiny silver roller bearing on the right is not used in the HPFI setup. The large braided silver line is the natural gas fuel line. The coiled black cable is the communications cable for the solenoid, and the black tubing is for the hydraulic fluid to transfer between the pump, the solenoid, and the admission valve. The fuel injection pressure for the HPFI system can reach upwards of 800 psi. A detailed report on the functionality and performance of the HPFI system can be seen in [52].

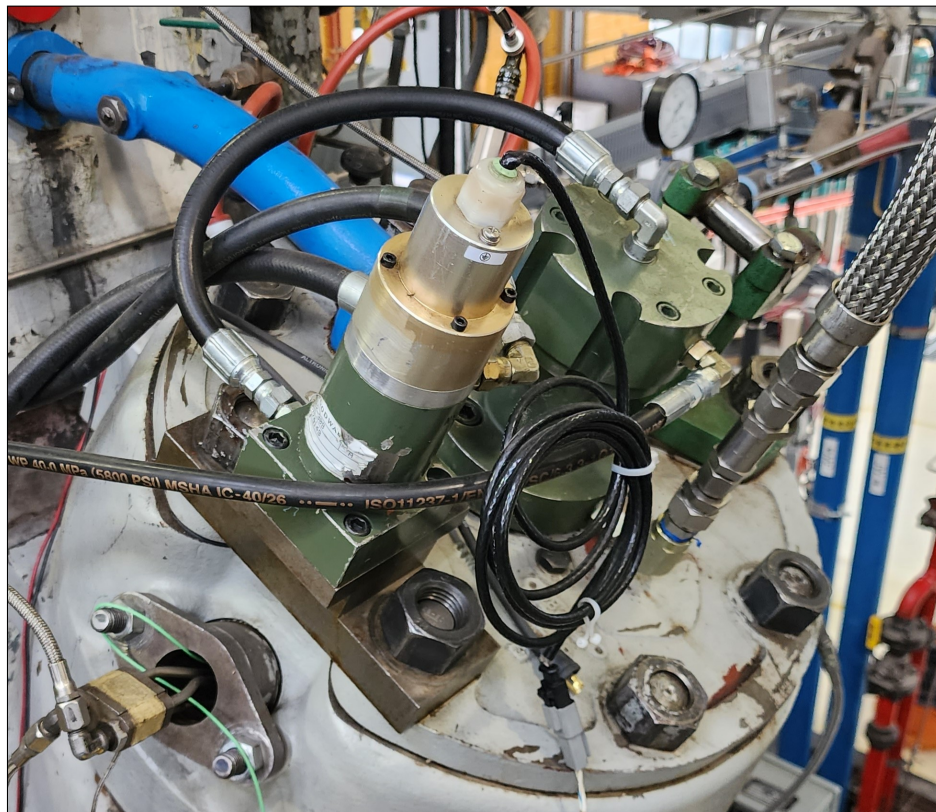


Figure 2.3: The electro-mechanical high pressure fuel injector mounted on cylinder 4 of the GMV

The second fueling configuration is referred to as the mechanical gas admission valve (MGAV) and employs low pressure injection. The fuel injection pressure of this system is close to the gas supply pressure that the Powerhouse receives from the City of Fort Collins, around 20 psi. Figure

2.6 shows the MGAV fueling system installed on the number 4 cylinder of the GMV. In the image, on the right, is the push rod, driven by a camshaft, that causes the rocker arm to pivot around the silver roller bearing previously mentioned, and actuate a valve inside the centrally located fuel header. The red pipe at the top of the image is the fuel supply line with a square adjustment valve on top that can be adjusted to change the fuel flow rate.

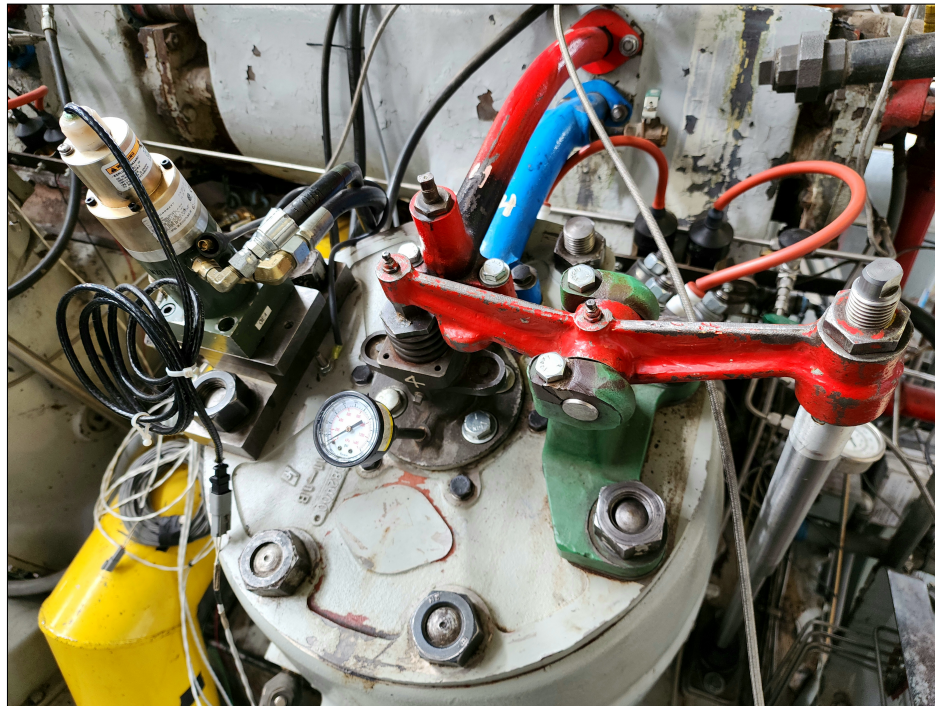


Figure 2.4: The mechanical gas actuated low pressure fuel injector mounted on cylinder 4 of the GMV

As mentioned before, a traditional spark plug can be used to start the combustion process, or a PCC can be used. If the traditional spark plug is to be used, it is inserted into a dummy PCC and is mounted in the same location as when a real PCC is used. The mounting location of the spark plug/PCC can be seen in Figure 2.5. The intake ports are positioned near the bottom of the image where the flat bolted plate is located.

The engine is outfitted with over 100 sensors. Temperatures, pressures, and flow rates for intake air, exhaust mixtures, in-cylinder conditions, fuel supply, and others, can be recorded independently—many at 0.1 CAD intervals. Each cylinder has its own temperature and pressure sensors

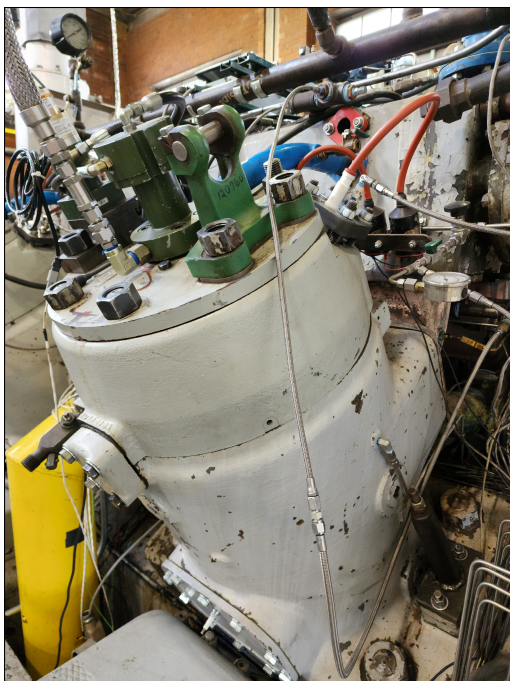


Figure 2.5: Side image of the number 4 cylinder showing the installation location of the spark plug/PCC.



Figure 2.6: The Cooper Bessemer OEM single nozzle pre-combustion chamber.

that give dynamic cycle-by-cycle readings. The temperature and pressure sensors for each intake and exhaust are not dynamic and give an average reading, but a set of dynamic pressure sensors were available to use on a single cylinder of choice—no dynamic temperature sensor is available. The OEM PCCs do not have a mount for pressure or temperature sensors, although a single modified OEM PCC does have a port for a screw-in dynamic pressure sensor and was available for use.

The engine's load is controlled through a coupled water-brake dynamometer and can be seen in Figure 2.7. Little is known about the dyno's specifics, as there were only two of this specific type built by Clark, the engine manufacturer. Both dynos are in use at CSU.

A gas chromatograph (GC) was used to determine the engine's incoming fuel constituents. A constant feed line is supplied to the GC so that any variability in the mixture can be seen over time. The natural gas was supplied via the city of Fort Collins' gas lines—no special fuel mixture was used.

The engine out emissions are determined using a MKS Fourier-transform infrared (FTIR) multi-gas analyzer. A constant feed line is connected from the engine's exhaust to the analyzer so that a continuous averaged measurement can be obtained. The FTIR can be seen in Figure 2.8.



Figure 2.7: The GMV's load is controlled using a water-brake dynamometer.



Figure 2.8: The MKS FTIR used to determine engine out emissions.

Table 2.1 shows the average value, the standard deviation, and the COV in percent of the most important 5-minute averaged engine parameters. The baseline engine data point was taken seven consecutive times to calculate these values. The table shows that the COV for a majority of the parameters falls below 1%, a few fall between 1% and 2%, and only one parameter falls just slightly above 2%. The standard deviations for the given parameters are very low in magnitude compared to the average value. For this work, test results for various hardware configurations and fuel compositions are compared to determine fractional changes in performance and emissions using the same instrumentation and associated calibrations. Thus, inherent instrument and calibration gas uncertainties are the same between cases. For these reasons, the plots throughout this text do not show error bars; in numerous instances, the error bars would be too small to be seen clearly.

Table 2.1: Average values, standard deviations, and coefficients of variance for various 5-minute average performance parameters of the GMV.

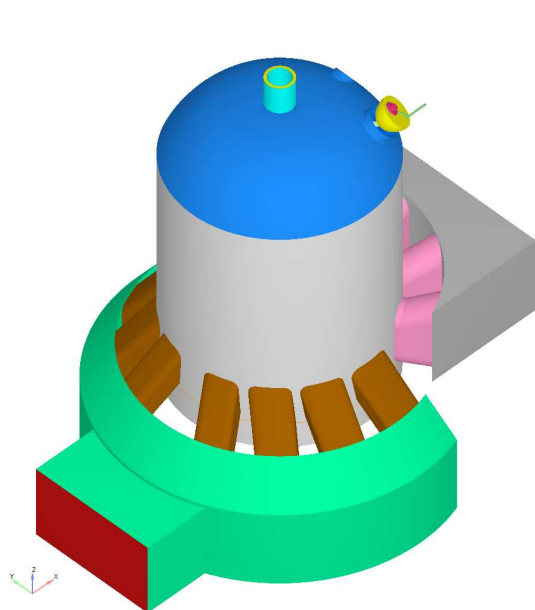
Parameter	Avg. Value	Std. Dev.	COV [%]
Power [bhp]	439.26	0.21	0.05
Load [%]	100.02	0.05	0.05
Fuel Flow [$\frac{lb}{hr}$]	167.43	1.41	0.84
Air Flow [$\frac{lb}{hr}$]	9202.57	6.67	0.07
BSEC [$\frac{BTU}{bhp-hr}$]	6667.32	55.07	0.83
Engine Avg Peak Pressure [psi]	515.36	1.51	0.29
Engine Avg Peak Pres Std Dev [psi]	28.18	0.33	1.18
Engine Avg Peak Pres COV [%]	5.47	0.08	1.40
Engine Avg Peak Loc [$^{\circ}$ aTDC]	18.33	0.05	0.30
Engine Avg IMEP [psi]	73.67	0.11	0.16
Engine Avg IMEP COV [%]	1.75	0.02	1.21
Engine Avg MFB 10% Locations [$^{\circ}$ aTDC]	6.87	0.03	0.50
Engine Avg MFB 50% Locations [$^{\circ}$ aTDC]	14.96	0.07	0.48
Engine Avg MFB 90% Locations [$^{\circ}$ aTDC]	30.02	0.16	0.52
Engine Avg MFB 10% Durations [CAD]	6.07	0.03	0.56
Engine Avg MFB 50% Durations [CAD]	14.16	0.07	0.51
Engine Avg MFB 90% Durations [CAD]	29.22	0.16	0.54
BS THC [$\frac{g}{bhp-hr}$]	5.13	0.05	1.06
BS CH ₄ [$\frac{g}{bhp-hr}$]	3.91	0.05	1.40
BS NO _x [$\frac{g}{bhp-hr}$]	0.60	0.01	2.12
BS CO [$\frac{g}{bhp-hr}$]	1.03	0.02	1.98
BS CO ₂ [$\frac{g}{bhp-hr}$]	463.04	3.79	0.82
BS CO ₂ e [$\frac{g}{bhp-hr}$]	560.85	4.87	0.87

2.2 Engine Modeling Using Computational Fluid Dynamics

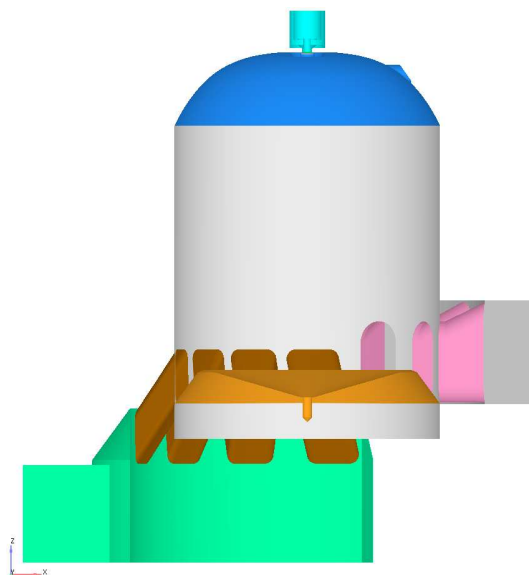
Convergent Science's CONVERGE CFD v3.0 software was used to simulate the engine. Only a single cylinder of the four-cylinder engine was simulated to keep the simulation time and cost reasonable. Figure 2.9 shows the base model geometry used along with its color coded separate boundaries.

The following will detail the various parameter values and conditions used for the baseline model; any changes made to the model for specific testing conditions will be listed in later subsections.

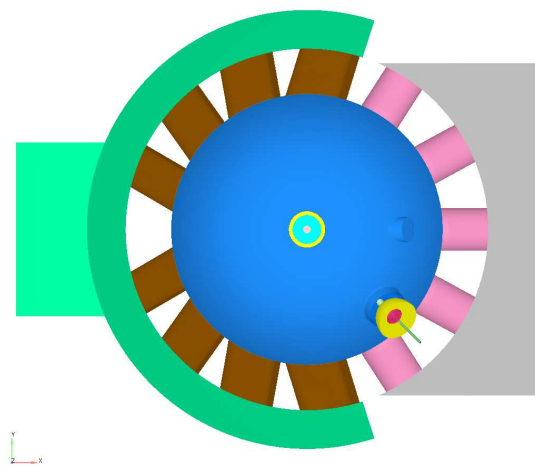
The Simulation and Analysis of Gas-phase Emulsions (SAGE) detailed chemistry solver was applied to the model to simulate chemical kinetics. The solver was coupled with a NUIGMech1.1 derived chemical kinetics mechanism named RT-NUIGMech1.1 that employs 164 species and 1,157 reactions.



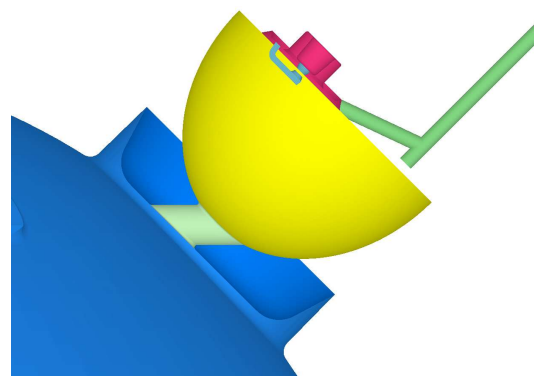
(a) Isometric view of the single-cylinder model.



(b) Side cutaway view of the single-cylinder model to show ports and piston profile.



(c) Top view of the single-cylinder model.



(d) Side cutaway view of the PCC showing the spark plug location and OEM nozzle orientation.

Figure 2.9: Converge 3D model used for the baseline model.

Because the model is physically large (14 inch bore), the Reynolds-Averaged Navier-Stokes (RANS) transport equations were used. The Re-Normalization Group (RNG $\kappa - \varepsilon$) methods by Yakhot et al. [53] were used to model small-scale turbulence. Converge's default values for both the SAGE and RNG $\kappa - \varepsilon$ models were applied. In an attempt at saving more computational compute time, the combustion solver was turned on 1 crank-angle degree (CAD) before the time of spark. The spark was modeled as a stationary spherical energy source of 0.0456 Joules that lasted for 0.4 CAD.

The mesh for the model was created in CONVERGE at computation time. The base mesh size was 8 mm and adaptive mesh refinement (AMR) and fixed-embedding were employed. A temporal file (by CAD) was used to limit the maximum number of cells at given points in the simulation with the largest number of cells produced being 8 million. The model was discretized into six major regions: intake, exhaust, injector, cylinder, prechamber, and PCC gasoline. AMR for velocity, temperature, and species were applied to each region at particular CAD's. AMR details can be seen in Appendix A.1 and fixed embedding details can be seen in Appendix A.2.

Table 2.2 shows a detailed list of model parameters and their initial/given values. Table 2.3 shows the initial species mass fraction compositions in the MCC, PCC, and exhaust regions. The initial conditions were determined from previous simulations and experimental data.

Table 2.2: CFD base model initial conditions and engine parameter values

Parameter	Value
Cylinder Bore	0.3556 m
Stroke	0.372 m
Engine Speed	300 rpm
Compression Ratio	10
MCC fuel injection timing	-115° to -95 °aTDC
MCC fuel injection pressure	varied
PCC fuel injection timing	-223° to -104 °aTDC
PCC fuel injection pressure	varied
Intake pressure (approximate)	130,203 Pa
Intake temperature	316 K
Exhaust pressure (approximate)	125,011 Pa
Exhaust temperature	618 K
Intake port open/close	-235°/-122 °aTDC
Exhaust port open/close	-249°/-108 °aTDC

Table 2.3: CFD model initial species mass fraction composition in each region

Species	MCC/PCC	Exhaust
CH ₄	0.00106	0.00053
C ₂ H ₄	2e-5	1e-5
C ₂ H ₆	0.00024	0.00012
C ₃ H ₈	8e-5	4e-5
CO	0.0004	0.002
N ₂	0.74376	0.7634
CO ₂	0.07436	0.00951
H ₂ O	0.05574	0.00712
NO	0.00013	7e-5
NO ₂	5e-5	2e-5
O ₂	0.12415	0.2189

2.2.1 Directional Pre-combustion Chambers Setup

Four novel prechamber nozzle designs and configurations were simulated and compared against the OEM prechamber design. The purpose of the design variations was an attempt at decreasing the amount of unburned methane at the end of the combustion cycle.

The baseline CFD case setup was used for each design. Every aspect and parameter of the case is identical apart from the prechamber nozzle geometry. The nozzle flow area for each design was

identical to the OEM design, as was the volume of the prechamber itself. The only factors changed were the number of nozzles, the direction of the nozzles, the nozzle diameters, and in one case, the shape of a nozzle.

The OEM prechamber design consists of a single nozzle of 0.32" diameter. The nozzle is aimed such that it is perpendicular to the cylinder's axis of symmetry. Figure 2.10 shows a 3D CAD model of the design from a bottom view for a straight-on look at the nozzle and a cylinder top-down view as if the prechamber was installed on the cylinder head. The thin circle in the top-down view depicts the cylinder walls and crevice volume where unburned methane is found after combustion. The red arrow indicates where the nozzle is pointing—in this case, the nozzle is aimed high, across the cylinder, towards the opposite cylinder wall.

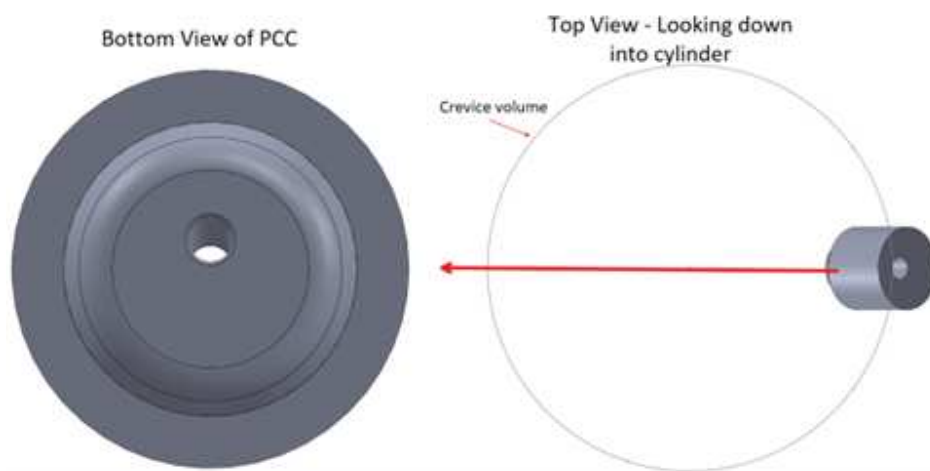


Figure 2.10: OEM PCC design. The thin circle in the top-down view depicts the cylinder walls and the area where unburned methane is found after combustion. The red arrow indicates where the nozzle is pointing.

The first prechamber design is a 5-nozzle design. Each nozzle is circular and has the same diameter of 0.1". For this design, each nozzle was positioned in such a way that the flame-jets are equally spaced around the cylinder with respect to the crevice volume. The motivation for this design was equal flame propagation around the crevice volume. Figure 2.11 shows the same bottom view and top-down view of the 5-nozzle design.

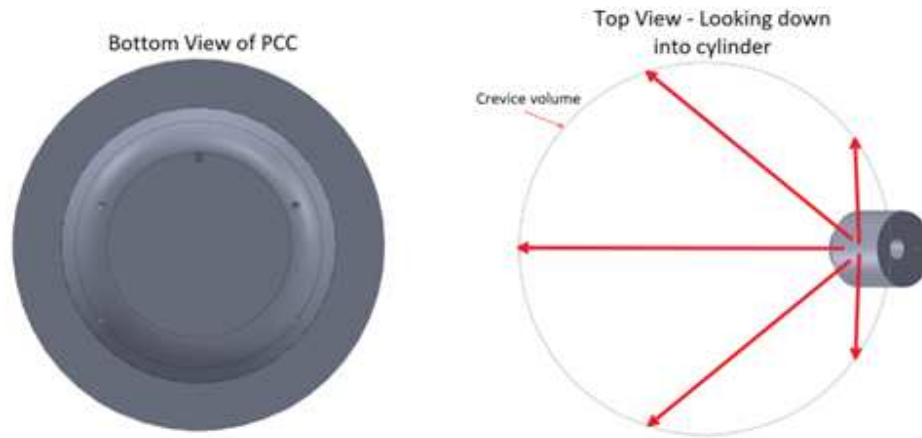


Figure 2.11: 5-nozzle design PCC.

The second prechamber design is a 3-nozzle design. For this model, there are three nozzles, two of the same diameters, 0.1", and the third with a diameter 50 percent larger at 0.15". Figure 2.12 depicts this model in the same fashion as above. The two smaller nozzles are arranged so that their flame-jets are positioned to fire in the direction of the unburned methane pockets left over after combustion seen in the preliminary CFD runs. The third nozzle is positioned to fire directly at the center of the piston. The third prechamber design is also a 3-nozzle design — to prevent confusion, this design will be referred to as 3-nozzle version 1 continuing forward.

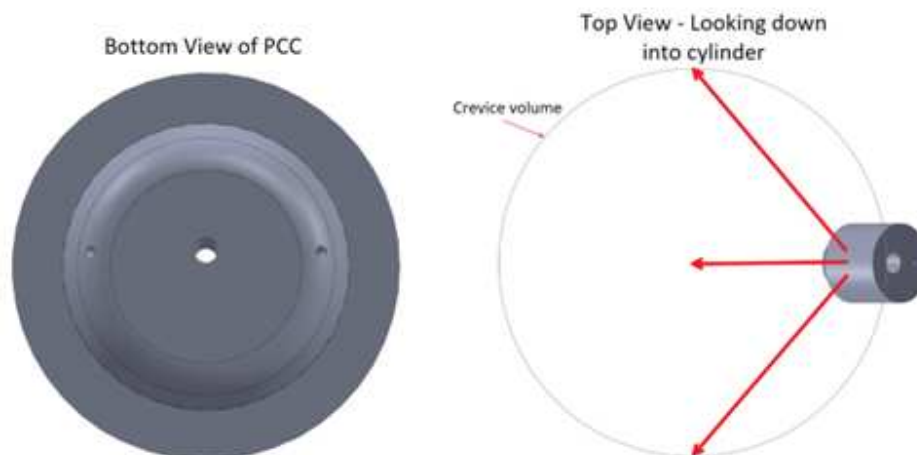


Figure 2.12: 3-nozzle version 1 design PCC.

The third prechamber design, as previously stated, is a 3-nozzle design similar in nozzle configuration and nozzle diameters as 3-nozzle version 1 and will be referred to as 3-nozzle version 2 moving forward. The difference between version 1 and version 2 is where the nozzles are aimed. In version 2, the two smaller nozzles have been adjusted back towards the prechamber but still aimed towards the crevice volume. The third, larger nozzle, has been repositioned to fire towards the far side of the piston crown. The motivation for this design is to include more of the cylinder volume in the initial flame-jet propagation. The area directly under the prechamber is the last to see the flame in the OEM and tested PCC designs because of the nozzle configurations. Figure 2.13 shows the 3D CAD model.

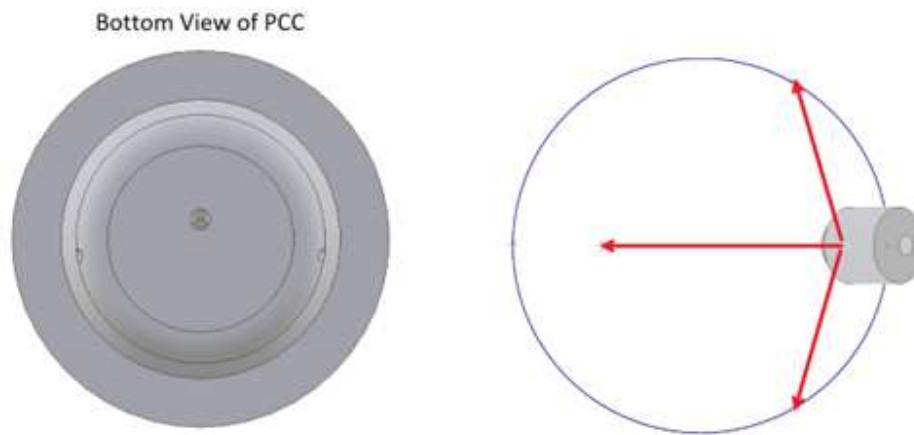


Figure 2.13: 3-nozzle version 2 design PCC

The final prechamber design is a 4-nozzle design. Three nozzles are circular shaped with a diameter of 0.1", while the fourth nozzle is a rectangular shape with dimensions of 0.5"x0.02". The three circular nozzles are aimed toward the far side of the cylinder, still towards the crevice volume, and can be seen in Figure 2.14. The rectangular nozzle is aimed straight down, parallel to the cylinder's axis of symmetry. The motivation of this design is to propagate three faster flame-jets to the far side of the main chamber and one slower flame-jet directly under the PCC in the area that sees the flame front last.

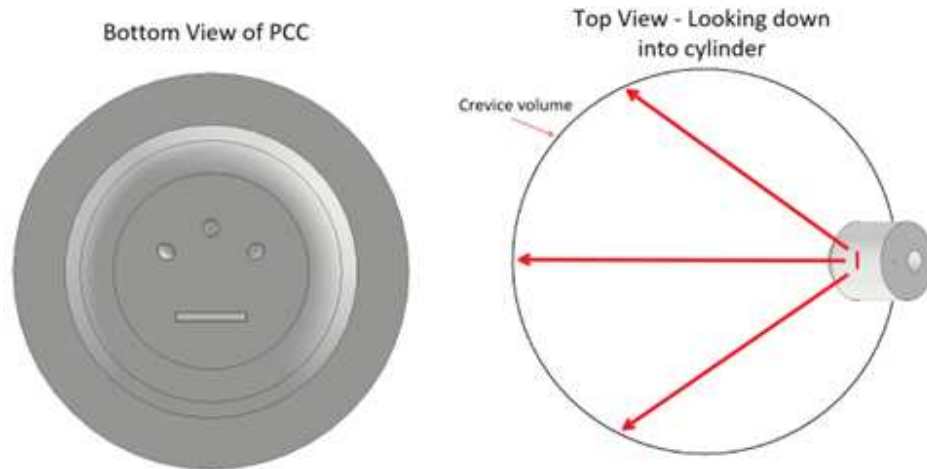


Figure 2.14: 4-nozzle design PCC

The results from this study can be seen in Chapter 4 and were used to guide a PCC optimization study. The PCC design labeled “PCC 3orifice 2” was deemed the most successful model because of the 99% reduction in residual MCC methane coupled with the fact that the design produced 2.3% more power than the OEM design. For the current study, “PCC 3orifice 2” was chosen as the model to be refined.

Three features of the PCC were varied, simulated, and compared to the original design for the PCC optimization study. Again, because the main goal of the study was to reduce the engine out methane emissions, the refined designs were heavily compared based on methane emissions with nitric oxides output also being considered. Using the results of the refinement designs, another configuration combining the two best performing factors was simulated and compared to determine if the results from each individual feature change were cumulative.

The best performing PCC configuration was then manufactured and evaluated on engine at Colorado State University’s (CSU’s) Energy Institute, named The Powerhouse, where a GMV-4TF is housed, and compared against the OEM single nozzle PCC. After the best performing PCC was assessed on engine, the nozzles of said PCC were slightly expanded, and the data points were evaluated again, giving experimental data for the “nominal” PCC and the “expanded” PCC.

As stated earlier, three PCC features were chosen to be refined and simulated in an OFAT experiment. The features chosen to alter were the angles that the nozzles are oriented, the volume of the

PCC, and the total flow area of the nozzles. The “PCC 3orifice 2” PCC, from the previous study, will be referred to as the “original” PCC moving forward.

The two alternative designs simulated are shown in Figure 2.15. The design labeled “Angle 1” had the nozzles adjusted so that they would impinge less upon the cylinder wall. “Angle 2” was made using the same idea, but the nozzles were adjusted “inward” slightly more. Note that the center nozzle was not adjusted.

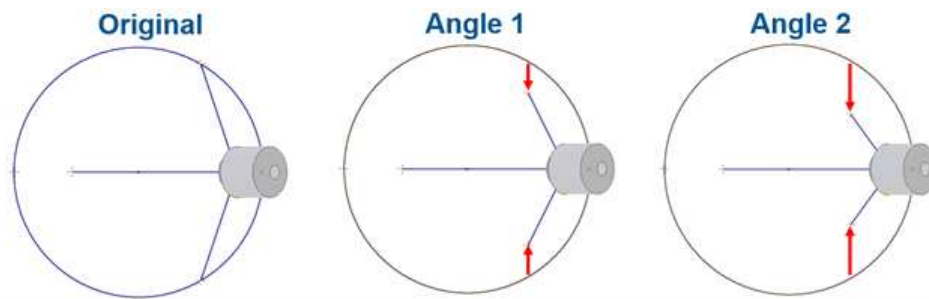


Figure 2.15: A comparison of the original design and its nozzle angles with the two altered designs and their nozzle angles.

For the volume refinement, a model with a 50% increase and another model with a 50% decrease in PCC volume were simulated. Figure 2.16 shows a comparison of the original design with the increased and decreased volume models.



Figure 2.16: A comparison of the original volume, the +50% model, and -50% model.

Table 2.4: The diameter measurements for the center and side nozzles along with the total flow areas with a comparison of the Area 1 and Area 2 designs to the original design.

	Center Nozzle Diam (in)	Side Nozzle Diam (in)	Total Flow Area (in²)	% Change
Original	0.233	0.155	0.080	–
Area 1	0.260	0.173	0.100	+25
Area 2	0.201	0.134	0.060	-25

Finally, the total flow areas of the nozzles were altered so that one model had a 25% increase in flow area and one model had a 25% decrease in flow area, compared to the original. Table 2.4 shows a comparison of Area 1 and Area 2's center and side nozzle diameters, along with the total flow areas, to the original design.

After review of the initial optimization results, two designs outperformed the original design. It was decided to combine the two parameters together into a single design and study whether or not the performance benefits could be see stacked.

2.2.2 Premixed Fuel and Air Injection Setup

The simulation of premixing fuel and air being injected into the PCC utilized a similar baseline to the Directional PCC study. The simulation process consisted of creating a baseline model and tuning the model to an actual engine dataset. From there an ideal case was to be created. The ideal case would be used as a "best case scenario" by having a perfectly mixed, homogeneous, PCC with baseline flow field conditions at time of ignition. After the ideal case, two PCC fuel injection models were created: a high pressure injection model and a low pressure injection model.

Ideal Case Setup

As stated before, the subsequent phase of the investigation was to simulate an ideal scenario reflecting a perfectly distributed fuel and air mixture within the PCC just before spark. For the ideal case, the simulation was started at -6 °aTDC using a mapping file from the baseline case. The mapping file allowed the simulation to start at -6 °aTDC but with the calculated cell values and flow fields of the baseline case. At this point, each cell within the PCC volume had its mass

fraction overwritten so that they were all equal mimicking a perfectly mixed volume. The PCC constituents' mass fractions for the baseline case and the ideal case can be seen in Table 2.5. Figure 2.17 shows a visual comparison of the fuel and air mixtures in the PCC between the baseline and ideal cases. The stratification within the baseline case is very apparent: a rich region is seen in the center of the volume with a lean region at the PCC nozzle. The lean region is from a mixture of fuel and air being pushed into the PCC from the MCC by the upward motion of the piston. A planar view of the flow fields at the PCC nozzle can be seen in Figure 2.19. The ideal case also sees this behavior, but it is not apparent in Figure 2.17 because the simulation had just begun and the cell mass fractions were overwritten.

Table 2.5: PCC constituents mass fractions for the baseline CFD case and the ideal CFD case.

Species	Baseline Case	Ideal Case
CH ₄	0.00106	0.029263
C ₂ H ₄	0.00002	0
C ₂ H ₆	0.00024	0.009941
C ₃ H ₈	0.00008	0.001499
CO	0.0004	0
CO ₂	0.07436	0
H ₂ O	0.05574	0
N ₂	0.74376	0.711089
NO	0.00013	0
NO ₂	0.00005	0
O ₂	0.12416	0.248208

Figure 2.18 shows the standard deviation of the equivalence ratio found in the PCC volume between the baseline and ideal cases. The baseline case's standard deviation at -6 °aTDC is approximately 0.11 while the ideal case is zero. The ideal case's standard deviation immediately increases after the start of the simulation due to the upward motion of the piston pushing a portion of the MCC fuel/air mixture into the PCC. The deviation in the PCC quickly levels out and is approximately 0.065 around the time of spark. The average equivalence ratio in the PCC, at time

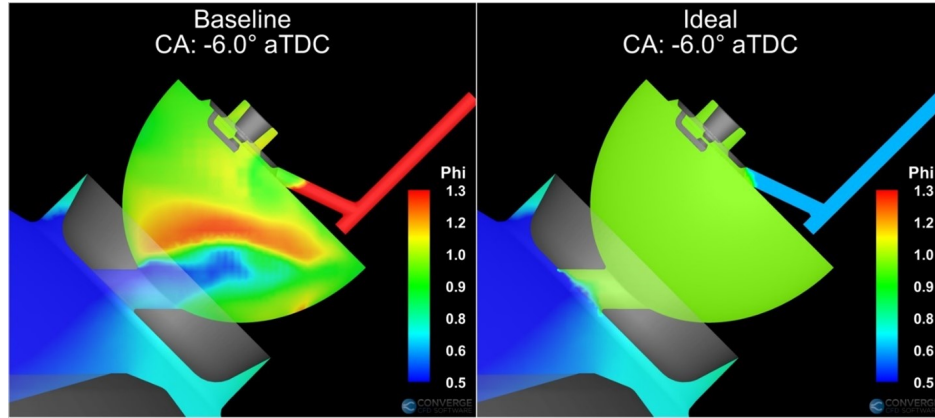


Figure 2.17: A comparison between the baseline and ideal fuel and air mixture within the PCC.

of spark, is 0.99 for the baseline case and 0.97 for the ideal case. The difference in trapped mass of fuel in the PCC, at time of spark, was a 0.02% decrease for the ideal case.

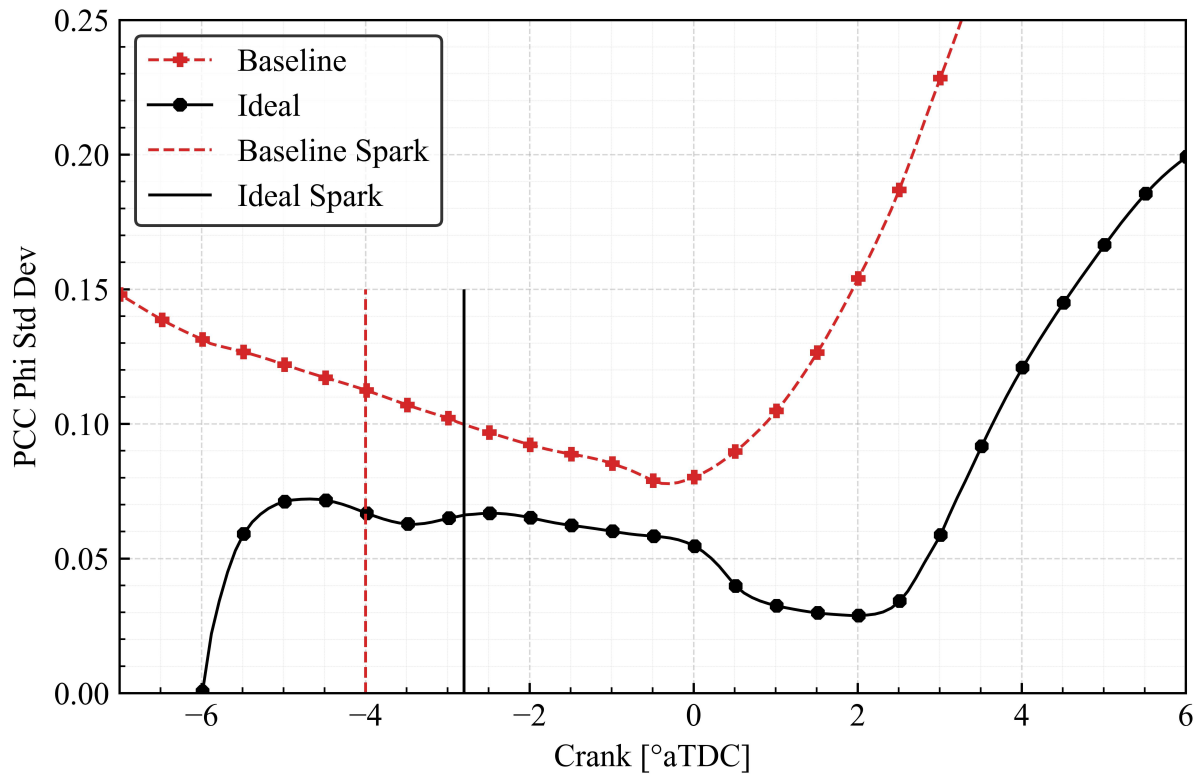


Figure 2.18: The standard deviation of the equivalence ratio in the PCC.

Low Pressure Injection Cases Setup

The low pressure PCC fuel injection cases were set up identical to the baseline case with the exception of the composition of the PCC fuel and the mass flow rate (fueling rate) into the PCC. The PCC fuel composition was adjusted for each case so that there was a differing premixed fuel/air blend being injected. PCC fuel equivalence ratios of 1.5, 4.34, and 7 were simulated using this model.

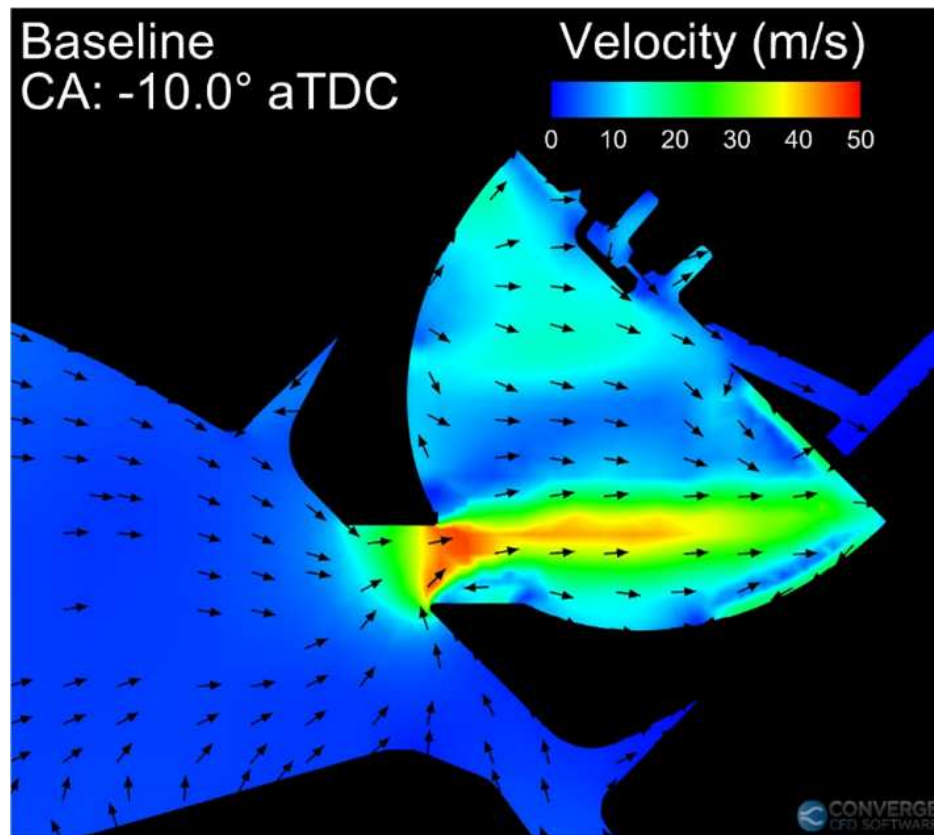


Figure 2.19: Planar view of the flow fields at the PCC nozzle. Gas from the MCC is pushed into the PCC as the piston moves upward, diluting the PCC fuel/air mixture.

With the low pressure PCC fuel injection, PCC injection must take place at a time in the cycle when the in-cylinder pressure is lower than the cylinder pressure and that the check-valve of the fuel injector can be opened by the fuel gas pressure. This occurs between 223 °bTDC and 104 °bTDC. During this time, the piston is moving upward decreasing the volume in the MCC and subsequently increasing the pressure across the system. This pressure increase causes mass to flow

from the MCC into the PCC diluting the PCC mixture to an equivalence ratio that is below that of the injected. Figure 2.19 shows a planar view of the flow fields directions, colored by magnitude, through and around the PCC nozzle.

Table 2.6 details the PCC fuel mass fraction composition used in each simulated case. Each mixture equates to an equivalence ratio equal to the name of the case. The air-fuel ratios, associated mass flow rates, and timing for each case can be seen in Table 2.7. The mass flow rates for each simulation were adjusted so that, when paired with constant timing, the amount of fuel injected into the PCC stayed constant at approximately 4.84 grams.

Table 2.6: Injected PCC fuel mass fraction compositions for the low pressure simulations.

	$\phi = 1.5$	$\phi = 4.34$	$\phi = 7$
Species	Mass Fraction		
CH ₄	0.05815063	0.14893469	0.21689409
C ₂ H ₆	0.00946665	0.02424588	0.03530935
C ₃ H ₈	0.00085835	0.00219840	0.00320155
N ₂	0.75130433	0.15953797	0.14405521
O ₂	0.18022003	0.66508335	0.60053980

Table 2.7: PCC fuel injection mass flow rates and timings for the low pressure simulations.

	$\phi = 1.5$	$\phi = 4.34$	$\phi = 7$
Mass Flow Rate ($\frac{kg}{s}$)	0.04883	0.01687	0.01044
SOI ($^{\circ}$ aTDC)	-223.0	-223.0	-223.0
EOI ($^{\circ}$ aTDC)	-104.0	-104.0	-104.0

High Pressure Injection Cases Setup

A series of premixed injection cases were also simulated using a high pressure electronic PCC fuel injector. The geometry and case setup of the model did not change from the low-pressure

model, only the PCC injection strategy (i.e., PCC mass flow boundary to pressure boundary, start of injection, injection duration).

The high pressure models mimicked an injection pressure of 150 psi (1.034 MPa), a SOI of 100 °bTDC, and an injection duration of 60°CA. The injection timing and duration were arbitrarily chosen but were moved later in the cycle with the intention that more of the injected fuel would stay within the PCC volume, but with enough time to promote good mixing before spark. The EOI was chosen to be at the very latest possible timing (when the PCC fuel injection pressure is slightly higher than the cylinder pressure) of 40 °bTDC. As a first iteration of the model, the injection pressure, SOI, and injection duration were identical for all cases. Injected equivalence ratios of 1.1, 1.5, 2, 2.5, 3, and 7 were simulated. Table 2.8 shows the species mass fractions injected into the PCC for the high pressure simulations.

Table 2.8: Injected PCC fuel mass fraction compositions for the high pressure simulations.

	$\phi = 1.1$	$\phi = 1.5$	$\phi = 2$	$\phi = 2.5$	$\phi = 3$	$\phi = 7$
Species	Mass Fraction					
CH ₄	0.04345139	0.05814862	0.07580122	0.09267605	0.10884499	0.37185590
C ₂ H ₆	0.00707368	0.00946633	0.01234009	0.01508723	0.01771946	0.06053642
C ₃ H ₈	0.00064138	0.00085832	0.00111889	0.00136798	0.00160665	0.00548892
N ₂	0.76526475	0.75130624	0.73454091	0.71851426	0.70315802	0.45336684
O ₂	0.18356880	0.18022049	0.17619888	0.17235447	0.16867088	0.10875192

2.3 Experimental Setup with the GMV

As mentioned previously, two engine fueling configurations were used in testing, (1) HPFI, shown in Figure 2.3, and (2) MGAV, shown in Figure 2.4. For the HPFI configuration, each cylinder is fixed with an active PCC, while the MGAV configuration used a traditional spark plug as the MCCs ignition source.

2.3.1 Hydrogen Fuel Blending

High Pressure Fuel Injection

Two hydrogen fuel sweeps were considered for the HPFI configuration, one blending both the PCC and the MCC fuels in approximately the same percentages (up to 45% by volume), and the second keeping the MCC fuel pure natural gas while the PCC fuel was blended with hydrogen (up to 90% by volume).

The engine was nominally tuned so that brake specific nitric oxides emissions were approximately 0.5 g/bhp-hr. This was done by boosting intake air pressure to 1.34 bar (134 kPa) and the exhaust back pressure to 1.26 bar (126 kPa) at constant load and speed, leading to a trapped ER of 0.55 and a trapped AFR of 29.8 in the MCC. The MCC fuel injection pressure was set to 35.3 bar (3.53 MPa). The mass flow rate of the PCC was adjusted at each data point so that the coefficients of variance (COV's) for the overall engine were minimized. The mole and mass fractions of the fuel constituent's used in testing can be seen in Table 2.9.

Table 2.9: HPFI Natural Gas Fuel Constituents

Fuel Constituent	Mole Fraction	Mass Fraction
CH ₄	0.886	0.792
C ₂ H ₆	0.086	0.144
C ₃ H ₈	0.006	0.014
C ₄ H ₁₀	0.001	0.002
C ₅ H ₁₂	0.000	0.001
C ₆ H ₁₄	0.000	0.000
C ₇ H ₁₆	0.000	0.000
CO	0.000	0.000
H ₂	0.000	0.000
N ₂	0.004	0.007
O ₂	0.000	0.000
CO ₂	0.015	0.036
H ₂ O	0.000	0.000

MGAV Fueling

The MGAV engine configuration utilized simulated piston scavenged air flow into the MCC. Because the engine testing was done in Fort Collins, CO at an elevation of 5,000 ft (1,525 m), both the intake and exhaust pressures were boosted to 1.1 bar (110 kPa) and 1.01 bar (101 kPa), respectively, to create sea-level atmospheric conditions. The engine's fuel injection pressure was set to 2.32 bar (232 kPa). These conditions lead to brake specific nitric oxides emission levels of 7.7 g/bhp-hr, an equivalence ratio of 0.64, and an AFR of 25.5. The fuel constituent's mole and mass fractions can be seen in Table 2.10.

Table 2.10: MGAV Natural Gas Fuel Constituents

Fuel Constituent	Mole Fraction	Mass Fraction
CH ₄	0.884	0.787
C ₂ H ₆	0.085	0.143
C ₃ H ₈	0.007	0.018
C ₄ H ₁₀	0.001	0.003
C ₅ H ₁₂	0.000	0.001
C ₆ H ₁₄	0.000	0.000
C ₇ H ₁₆	0.000	0.000
CO	0.000	0.000
H ₂	0.000	0.000
N ₂	0.005	0.008
O ₂	0.000	0.000
CO ₂	0.015	0.036
H ₂ O	0.000	0.000

2.3.2 Directional Pre-combustion Chambers

HPFI's were used for MCC fueling and electronic pre-chamber injectors (ePCI's) were used to control PCC fueling. The MCC injection pressure was constant at 35.5 bar (500 psi), start of injection was held constant for all test points, and the injection duration was adjusted to meet power requirements. The PCC injection pressure varied between 1.6 bar (23 psi) and 1.9 bar (27.5 psi)

while the start of injection and duration were held constant. Table 2.11 details the approximate fuel composition used in the tests.

Table 2.11: Directional PCC Natural Gas Fuel Constituents

Fuel Constituent	Mole Fraction	Mass Fraction
CH ₄	0.874	0.772
C ₂ H ₆	0.094	0.155
C ₃ H ₈	0.009	0.021
C ₄ H ₁₀	0.001	0.000
C ₅ H ₁₂	0.0002	0.000
C ₆ H ₁₄	0.000	0.000
C ₇ H ₁₆	0.000	0.000
CO	0.000	0.000
N ₂	0.008	0.011
CO ₂	0.012	0.035

The test included two sets of data to be taken: a boost sweep and four data points that represent the engines typical limiting operating conditions (varying high and low speed and load), that will be referred to as “4-corners”. The boost sweep dataset held the location of peak pressure (LoPP), the power output, the engine speed, and the intake/exhaust differential pressure constant while the intake pressure ranged from 32.7 inHg (16.1 psi, 110 kPa) to 41.7 inHg (20.5 psi, 141 kPa) leading to a boost range of 7.5-16.5 inHg (3.6-8.10 psi, 25.4-55.8 kPa). The 4-corners dataset was composed of four data points: (1) low speed, low load, (2) high speed, low load, (3) low speed, high load, and (4) high speed, high load. The engine speeds were set to 270 rpm for low speed and 300 rpm for high speed, and the load was set to 70% for low load and 100% for high load. Two tests were completed – one for the new PCC design as it was delivered to CSU and another where the new PCC design nozzles were expanded. The measurements of the nominal and expanded nozzles can be seen in Table 2.12.

Table 2.12: Nozzle diameter measurements for the nominal and expanded directional PCC designs.

	Side Nozzle Diam, in	Flow Area, in ³	Center Nozzle Diam, in	Flow Area, in ³	Total Flow Area, in ³	Total Flow Area % Change
Nominal	0.132	0.027	0.198	0.031	0.058	—
Expanded	0.169	0.045	0.248	0.048	0.093	+60.3



Figure 2.20: The PCC injector check valve (left half) with the electronic pre-chamber injector (ePCI, right half) attached.

2.3.3 Premixed Fuel and Air Injection

To experimentally test injecting a premixed fuel and air charge into the PCC, a configuration change to the engine was required. The check-valve type injector typically used by itself with the PCCs was now coupled with an electronic pre-chamber injector (ePCI) so that the injection duration could be controlled. Figure 2.20 shows the ePCI (right) attached to the check valve (left).

Table 2.13: Intake, exhaust, boost, and cylinder differential values for the premixed injection baseline data points.

Data Point Name	Intake Pressure (inHg/psi/kPa)	Exhaust Pressure (inHg/psi/kPa)	Boost (inHg/psi/kPa)	Differential (inHg/psi/kPa)
BS_32.7	32.7 / 16.0 / 110	30.2 / 14.8 / 102	7.5 / 3.6 / 26	2.5 / 1.2 / 8.5
BS_34.7	34.7 / 17.0 / 117	32.2 / 15.8 / 109	9.5 / 4.6 / 33	2.5 / 1.2 / 8.5
BS_36.7	36.7 / 18.0 / 124	34.2 / 16.8 / 115	11.5 / 5.6 / 39	2.5 / 1.2 / 8.5
BS_38.7	38.7 / 19.0 / 131	36.2 / 17.8 / 122	13.5 / 6.6 / 46	2.5 / 1.2 / 8.5
BS_40.7	40.7 / 20.0 / 137	38.2 / 18.8 / 129	15.5 / 7.6 / 53	2.5 / 1.2 / 8.5
BS_41.7	41.7 / 20.5 / 141	39.1 / 19.2 / 132	16.5 / 8.6 / 55	2.5 / 1.2 / 8.5

The test plan for this portion started by taking baseline measurements. Six baseline points were taken, all with differing boosted intake levels. Table 2.13 lists the intake and exhaust pressures, boost levels, and cylinder differentials for all the baseline points. Similar to the Fuel Blending and Directional PCC experimental tests, the engines speed, power, and load were held constant for all test points at 300 RPM, 400 BHP (330 kW), and 100%, respectively. The ignition timing for the baseline points were adjusted so that the LoPP was held constant at 18 °aTDC, but the premixed testing points held a constant spark timing for each test set inevitably allowing the LoPP to wander.

The MCCs injection pressure was also held constant at 500 psi (3.44 MPa) with the injection duration being adjusted to keep the engine at the 440 BHP (330 kW) requirement. The baseline data points were all run using a non-premixed charge injected into the PCC (natural gas only). This required allowing the PCC injection pressure to vary, ranging from 23-27.5 psig (158-189 kPa), and instead controlling the mass flow rate of fuel. The SOA and EOA for PCC fueling were not recorded for any data point, nor were the durations for the baseline points. It is known, however, from previous operator experience, that the baseline injection durations are around 80 CAD at nominal pressure. The SOA for each point was moved as forward in cycle time as permissible, without causing fuel slip, and was left constant for the entirety of the test.

Two sets of data points were taken, each with different intake boost levels. One data set took points at 7.5 inHg (3.6 psi, 25.4 kPa) of boost and the other was taken at 12.5 inHg (6.1 psi, 42.3 kPa). At each boost level tested, the PCC injection pressure was allowed to vary from 120-135 psi (827-930 kPa), again controlling the mass flow rate of natural gas and air.

The flow controller for the natural gas was held unrestricted for each data point and allowed as much gas as could flow. The natural gas fuel pressure was around 50 psi (344 kPa) on the outlet side of the flow controller. The flow controller for the air supply was adjusted for each data point increasing the mass flow rate of air injected into the system and systematically increasing the AFR of the injected PCC charge. Each data point had the air flow controller set to some value and then the PCC injection duration was varied until the lowest possible COV's of PP were reached.

The fuel constituents mole and mass fractions for this test can be seen in Table 2.14. Results of the test will be shown in Chapter 5 The Feasibility of Premixed Fuel and Air Pre-combustion Chamber Injection.

Table 2.14: Premixed Injection Baseline Data Natural Gas Fuel Constituents

Fuel Constituent	Mole Fraction	Mass Fraction
CH ₄	0.884	0.785
C ₂ H ₆	0.090	0.151
C ₃ H ₈	0.008	0.020
C ₄ H ₁₀	0.002	0.007
C ₅ H ₁₂	0.000	0.002
C ₆ H ₁₄	0.000	0.000
C ₇ H ₁₆	0.000	0.000
CO	0.000	0.000
H ₂	0.000	0.000
N ₂	0.000	0.008
O ₂	0.000	0.000
CO ₂	0.013	0.031
H ₂ O	0.000	0.000

Chapter 3

Understanding How the Use of Hydrogen as a Fuel Can Affect a Two-Stroke Natural Gas Engine

Chapter 3 is all about hydrogen and analyzing how it, as a fuel, affects the performance of the GMV. Because the engine can be run in a multitude of configurations, experimental tests were conducted using two of those configurations: (1) high-pressure fuel injection (HPFI) with PCC ignition and (2) low-pressure fuel injection (MGAV) with traditional spark-plug ignition. This chapter will be apportioned across three sections. The first section, 3.1 Using Hydrogen in a High Pressure Fuel Injection System, will analyze how the fuel affects performance when used with the HPFI system. The second section, 3.2 Using Hydrogen in a Low Pressure Fuel Injection System, will analyze how the fuel affects performance when used with the MGAV system. The final section, 3.3, will explicitly answer the questions presented in the Introduction for this particular technique.

Section 3.1 looks at performance changes in the engine from blending in hydrogen for two HPFI sub-configurations. One sub-configuration entails fueling both the MCC and PCC with a blended fuel while the other sub-configuration only uses a blended fuel for the PCC while the MCC is fueled with solely natural gas. For both sub-configurations, combustion statistics and their changes will be presented followed by how emissions were affected, focusing mostly on residual methane and residual nitric oxides.

Section 3.2 looks at engine performance from blending in hydrogen with the MGAV system. Similar to section 3.1, combustion statistics will be presented followed by emission performance.

Section 3.3 will utilize the presented results to answer two research questions: (1) How does the addition of hydrogen to a fuel supply affect the combustion stability of a lean burn large bore natural gas engine? and (2) What are the emission trade-offs when operating a lean burn large bore natural gas engine with varying fuel blend ratios?

3.1 Using Hydrogen in a High Pressure Fuel Injection System

3.1.1 Blending the Main Combustion and Pre-combustion Chambers

A sweep of natural gas/hydrogen blends was completed at the following percentage intervals: 8.4%, 12.9%, 29.0%, 31.6%, 38.5%, and 41.3%. Each percentage corresponds to the amount of hydrogen in the fuel by volume. A data point for the 15-18% range was also taken but due to a “dead spot” in the Coriolis flow controller accuracy, precise measurements of the hydrogen percentage were not attainable. Both the MCC and PCC fuels had approximately the same proportions of hydrogen and natural gas blended together. For this round of testing the boost pressure was left constant at the nominal value of 1.34 bar (134 kPa). Spark timing was held constant leaving the LoPP uncontrolled. The power and torque outputs were held constant at 440 bhp and 7,700 lb-ft, respectively. Because the boost pressure and power and torque outputs were left constant, nitric oxides emissions varied as well.

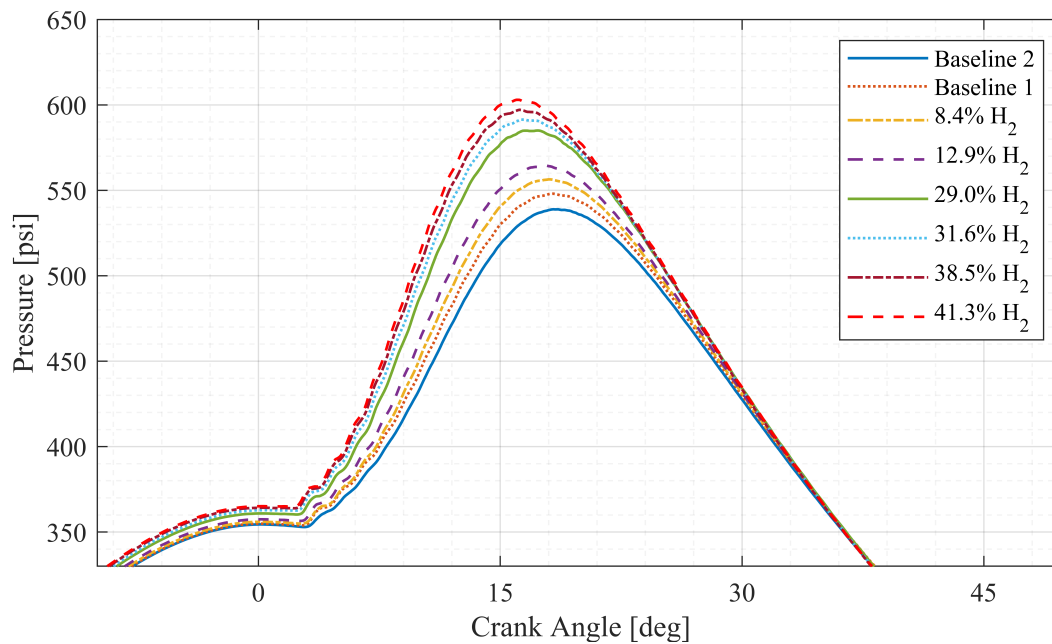


Figure 3.1: MCC/PCC Hydrogen Sweep: MCC pressure traces.

Combustion Statistics

Pressure Traces, LoPP, and COV's of Peak Pressures

For each blend (data point) tested, 1,000 individual combustion/scavenging cycles were recorded, and the average of those cycles were compared to a nominal point (solely natural gas) labeled “baseline #”. The results of the sweep can be seen in Figure 3.1. Two baseline points were taken during testing; baseline 1 was taken before the hydrogen sweep and baseline 2 was taken after. Both baselines show an average MCC peak pressure near 550 psi (37.9 bar, 3.79 MPa) with the LoPP at 18.2 °aTDC. As the percentage of hydrogen blended into the natural gas increases, the average peak pressure also increases reaching a local maximum of 636 psi (438. bar, 4.38 MPa), a 15% increase, with the 41% blend. The LoPP also moves earlier in the cycle because of the faster flame speed. The average LoPP advanced to 15.3 °aTDC (nearly 3° ahead of the baseline) with the 41% blend. A table of values for the peak pressure, LoPP, and the COVs of peak pressure¹ can be seen in Table 3.1.

Table 3.1: MCC/PCC Hydrogen Sweep: Comparison of average peak pressure, location of peak pressure, and COV of peak pressure for each test point.

Test Point/ H ₂ %	Peak Pressure (psi/MPa)	LoPP (°aTDC)	COV of PP (%)
Baseline 1	551/3.79	18.2	4.82
Baseline 2	552/3.80	18.2	4.85
8.4	566/3.90	17.7	4.47
12.9	579/3.99	17.2	4.11
29.0	609/4.19	16.2	3.61
31.6	618/4.26	15.8	3.44
38.5	627/4.32	15.5	3.19
41.3	636/4.38	15.3	3.04

The same peak pressure and LoPP trends can be seen for the PCC pressure traces in Figure 3.2. As the percentage of hydrogen blended into the natural gas increases, the peak pressure rises, and

¹The peak pressure is typically used as a reference for judging the intensity of a combustion cycle. The COV of peak pressure is used to analyze the cycle-to-cycle variability of the combustion intensity.

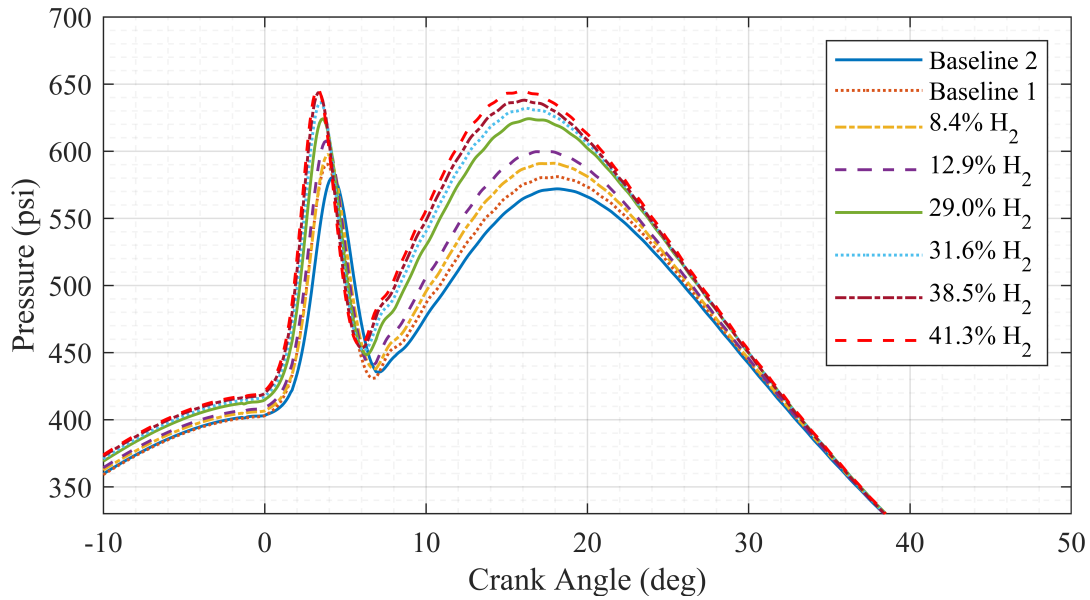


Figure 3.2: MCC/PCC Hydrogen Sweep: PCC pressure traces.

the LoPP moves forward in time. Similar results were seen in [29] and [30]. These trends can be explained as being due to the high diffusive velocity of the hydrogen which creates a more homogeneous mixture. This is advantageous to the flame propagation and combustion process as a whole. This more homogeneous mixture ignites faster and in turn creates greater pressure inside the combustion chambers. The lower COVs of peak pressure can be explained as misfires and/or partial combustion cycles reducing in frequency as the hydrogen content increases due to the ease of ignition of hydrogen mixed natural gas versus solely natural gas.

Ignition Delay, Combustion Duration, and BSEC

Ignition delay, defined as the time in crank angle degrees for 0-10% of the mass of fuel to burn (also known as mass fraction burned, MFB), was 8.79 and 8.90 degrees for baselines 1 and 2, respectively. Table 3.2 presents values for each hydrogen blend percentage pertaining to ignition delay, combustion duration, BSEC, and the percent change in BSEC from baseline 2. A graphical representation can be seen in Figure 3.3. The data points show a decrease in ignition delay as the percentage of hydrogen increases, with the shortest ignition delay, 7.12 degrees, coming from the

fuel blend with the highest hydrogen percentage. Similar trends were seen in the testing completed by [19].

Table 3.2: MCC/PCC Hydrogen Sweep: Ignition delay, combustion duration, brake specific energy consumption, and the change in brake specific energy consumption from baseline 2 values.

Test Point/ H ₂ %	Ignition Delay (deg)	Combustion Duration (deg)	BSEC (Btu/bhp-hr)	BSEC (% change from Baseline 2
Baseline 1	8.79	25.0	8167	0.79
Baseline 2	8.90	24.9	8232	–
8.4	8.59	24.1	8229	-0.04
12.9	8.27	23.5	8157	-0.91
29.0	7.72	21.9	8185	-0.57
31.6	7.48	21.6	8070	-1.97
38.5	7.27	21.3	8088	-1.75
41.3	7.12	20.8	8084	-1.79

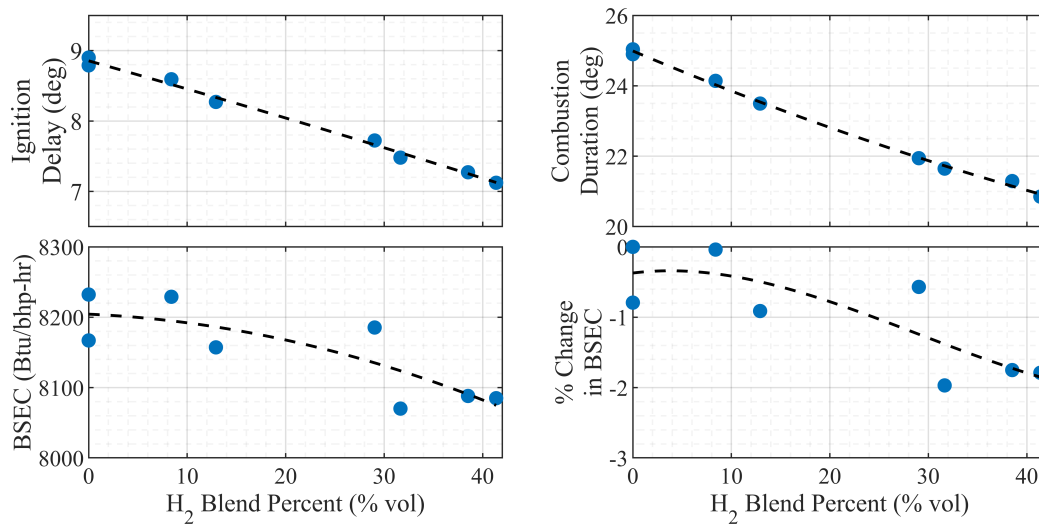


Figure 3.3: MCC/PCC Hydrogen Sweep: Ignition delay, combustion duration, brake specific energy consumption, and the change in brake specific energy consumption from baseline 2 values.

For combustion duration, defined as the time for 10-90% fuel MFB, baselines 1 and 2 were at 25.0 and 24.9 degrees, respectively. Again, the shortest duration, 20.8 degrees, came from the

highest hydrogen percentage fuel blend. Both the ignition delay and the combustion duration times followed very linear patterns over the tested blending percentages. [26] and [27] saw similar trends using natural gas/hydrogen and methane/hydrogen fuel blends, respectively. The engines BSEC saw decreases as the percentage of hydrogen in the fuel increased. The baseline 1 data point showed a lower BSEC value of 8,167 Btu/bhp-hr compared to baseline 2, which had a value of 8,232 Btu/bhp-hr. Even though there is a clear, but small decline in BSEC as the percentage of hydrogen in the fuel increases (using baseline 2 as a reference), the 8.4% and 29.0% blends had a higher value than baseline 1. The 12.9% blend was only slightly under the baseline 1 value. Comparing the BSEC of each blend to the baseline 2 BSEC, the engine saw a 1.79% decrease at the 41.3% blend, but the maximum decrease of 1.97% was seen at the 31.6% blend. Because of the larger difference between baseline 1 and baseline 2's BSEC values, and the random variability shown in the blends, the magnitude of the effect the hydrogen blends have on BSEC appears to be below experimental uncertainty.

Emissions

Total Hydrocarbons and Methane

The brake specific total hydrocarbon (THC) emissions for baseline 1 and baseline 2 were 7.26 and 7.52 g/bhp-hr, respectively. While a decrease in THC emissions was seen for all fuel blends (Figure 3.4) a maximum reduction of 28.7% (5.17 g/bhp-hr) in emissions came from the 31.6% fuel blend (Figure 3.5). The decrease in emissions was still present but less pronounced at higher hydrogen percent blends. This maximum in percent reduction (minimum in g/bhp-hr output) indicates that there is an ideal percentage of hydrogen to blend into the natural gas, around 30%, if minimizing emissions output is key.

The brake specific methane emissions for each fuel blend, along with the percent change for the brake specific methane emissions, can also be seen in Figure 3.4 and Figure 3.5. As methane emissions are a component of the THC emissions the expectation is that the methane emissions follow the same trends and in roughly the same magnitudes. This is exactly what the emissions showed, same trend, similar magnitudes, with only small variations in the percent change of methane. The

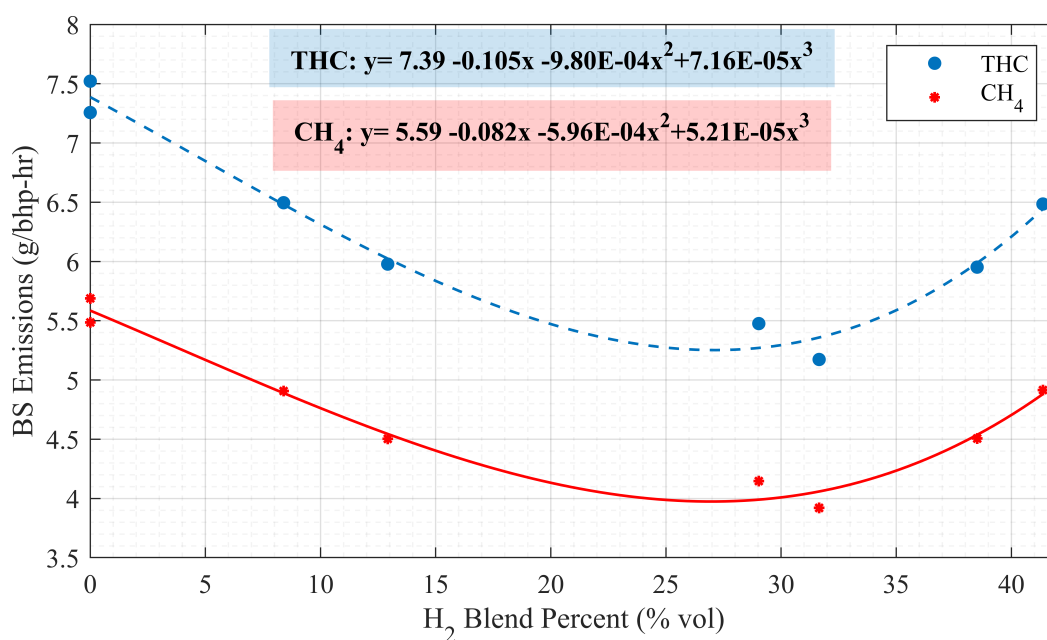


Figure 3.4: MCC/PCC Hydrogen Sweep: Brake specific THCs and brake specific methane emissions at each fuel blending percentage

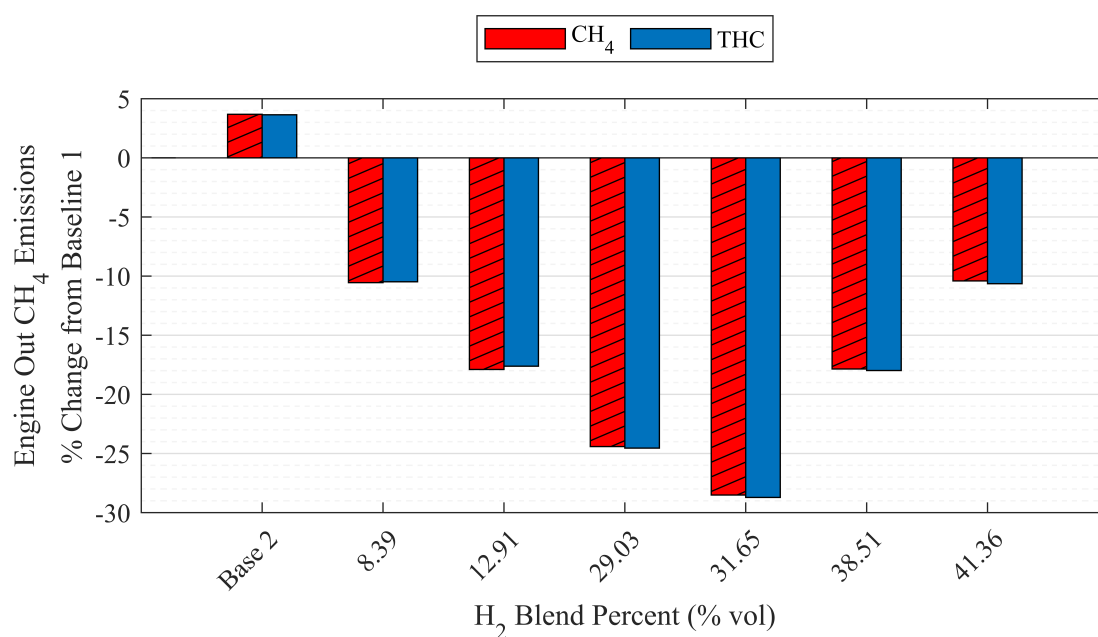


Figure 3.5: MCC/PCC Hydrogen Sweep: Percent change of brake specific THC and methane emissions from baseline 1 emissions

lower hydrogen percent fuel blends (8.4% and 12.9%) had slightly larger methane reductions, compared to the THC reductions, than the higher hydrogen percent fuel blends.

Even though there was a decrease in methane emissions as the percentage of hydrogen increased, when accounting for the carbon in the natural gas being replaced by hydrogen, the combustion process is less impressive when focused on methane reduction. Figure 3.6 depicts where the brake specific methane emissions should be based solely on carbon in the natural gas being replaced by hydrogen. The reduction seen in the testing follows the reduction based on carbon content very closely up to and including the 31.6% hydrogen blend. From this percent blend onward the experimental reduction, while less compared to baselines 1 and 2, are higher than the emissions based on carbon content. This illustrates that while the addition of hydrogen is increasing the flame growth and propagation rates (decreased ignition delay and combustion duration times), it is not improving the efficiency of combustion of carbon-based molecules.

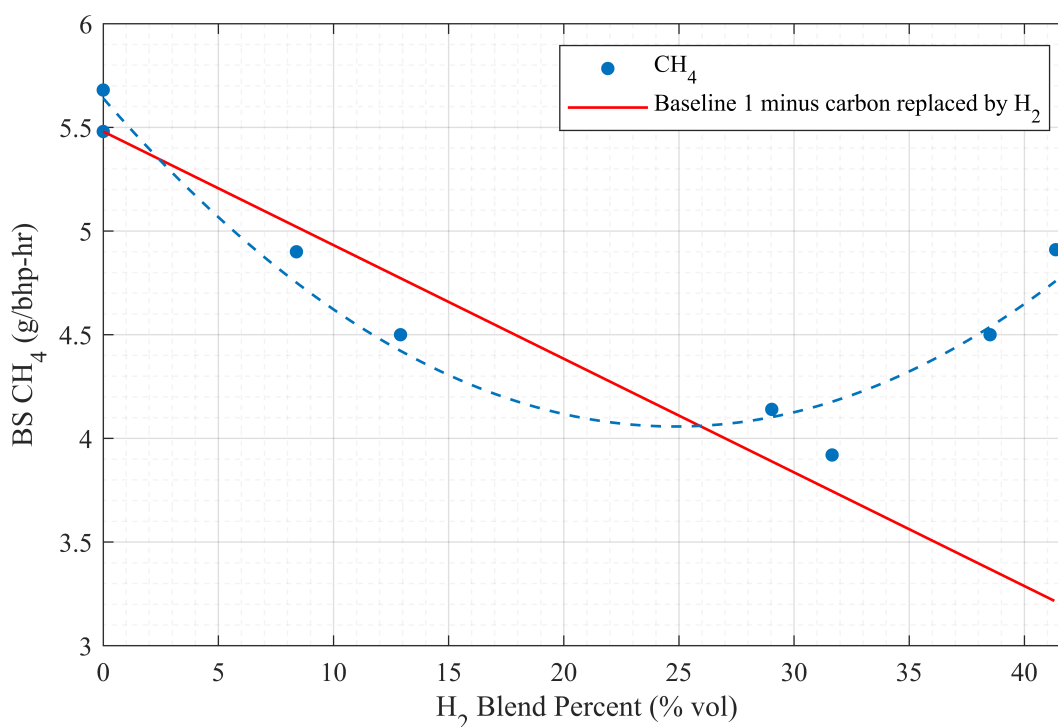


Figure 3.6: MCC/PCC Hydrogen Sweep: Brake specific methane emissions versus hydrogen blend percent. The solid line projects where the methane emissions should be based solely on carbon in the natural gas being replaced with hydrogen.

Oxides of Nitrogen

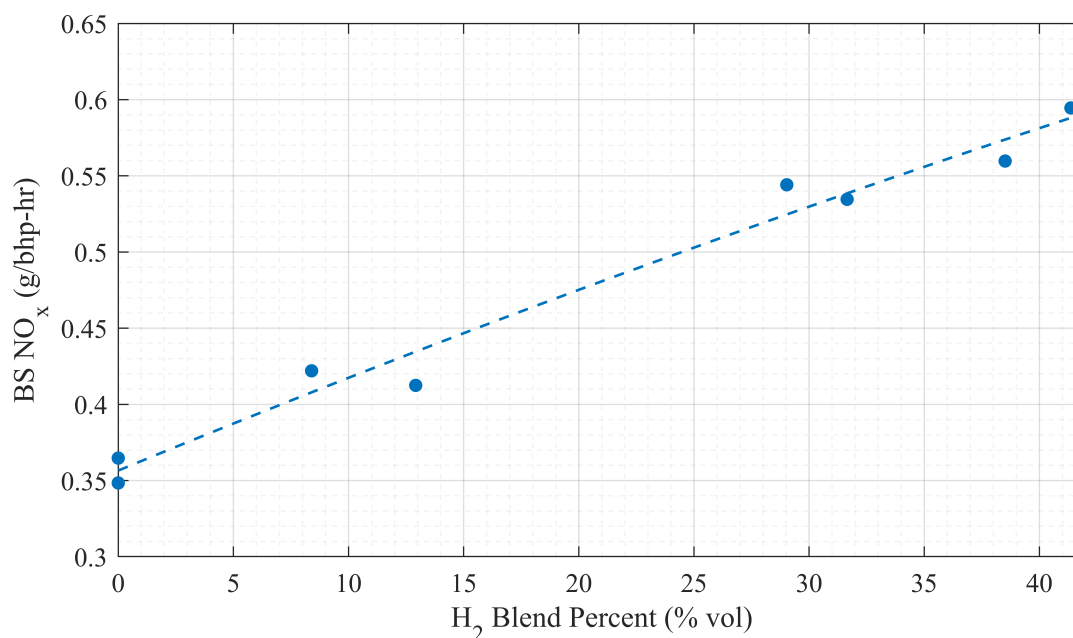


Figure 3.7: MCC/PCC Hydrogen Sweep: Brake specific nitric oxides emissions versus hydrogen blend percent.

Baselines 1 and 2 produced 0.35 and 0.36 g/bhp-hr of nitric oxides, respectively. As anticipated, by [19], [25], and [31], nitric oxides output levels increased as hydrogen percent rose. The 41.3% hydrogen blend produced the largest nitric oxides values at 0.59 g/bhp-hr. While the magnitude of the increase is relatively small (0.35 to 0.59 g/bhp-hr), the percentage the value increased is quite large at 71% over baseline 1. These higher nitric oxides values can be attributed to the hydrogen induced increased flame temperature. Figure 3.7 compares the brake specific nitric oxides values for each fuel blend. A relatively linear trend can be seen from the data set showing that as hydrogen percent increases the corresponding nitric oxides value will increase as well.

The trade-off between methane and nitric oxides emissions is just as important as each are individually so a comparison between the two should be made. A graphical representation of that comparison can be seen in Figure 3.8. The baseline cases have a nominal brake specific methane value of 5.5-5.7 g/bhp-hr and nominal brake specific nitric oxides value of 0.35-0.36 g/bhp-hr. As

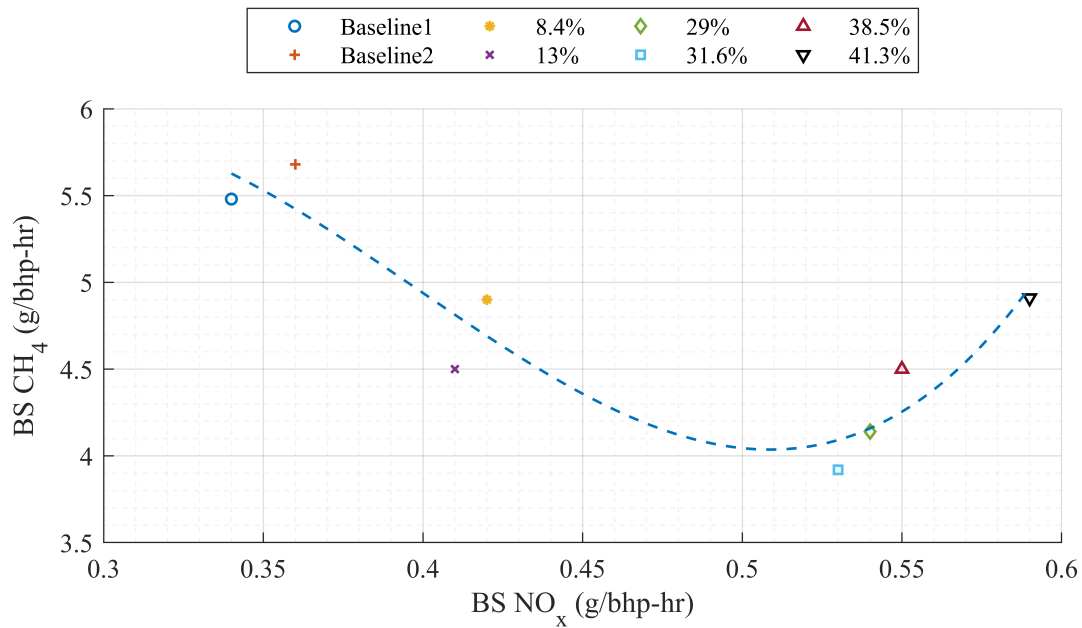


Figure 3.8: HPFI MCC/PCC Hydrogen Sweep: Brake specific nitric oxides emissions versus brake specific methane

the percentage of hydrogen in the fuel increases the methane emissions are shown to fall accompanied by an increase in the nitric oxides emissions until a minimum point for methane is found at around the 30% hydrogen blend. After this point, any additional hydrogen added to the fuel causes not only the nitric oxides emissions to rise but the methane emissions as well.

3.1.2 Blending Only the Pre-combustion Chamber

For this portion of the testing, the MCC fuel was set to solely natural gas while the PCC fuel was blended with hydrogen. A sweep of natural gas/hydrogen blends was completed again over a range of 0% to 90% hydrogen percent at 10% increments. The same nominal engine configuration and conditions as the MCC/PCC testing was adopted.

In short, the PCC fuel blending test combustion statistic (pressure traces, LoPP's, COV's of peak pressure, ignition delay, combustion duration, BSFC) and emission results, for each hydrogen percent blend, were largely unchanged from the baselines. Because of this, the following will only include the emission outputs and will be brief.

Emissions

Total Hydrocarbons and Methane

Figure 3.9 shows the brake specific THC and methane emissions as a function of hydrogen blend percent. A slight reduction in both emissions can be seen as hydrogen percent increases. Baselines 1 and 2 produced 7.21 and 7.33 g/bhp-hr of THC, respectively, and 5.48 and 5.62 g/bhp-hr of methane, respectively, while the 90% hydrogen blend produced the lowest output of 6.64 g/bhp-hr of THC and 5.04 g/bhp-hr of methane, a 9% reduction of both values over baseline 1. Figure 3.10 shows the percent reduction of both THC and methane emissions for each fuel blend. An increase in percent reduction as hydrogen content increases can be noticed with the 30% blend being an outlier.

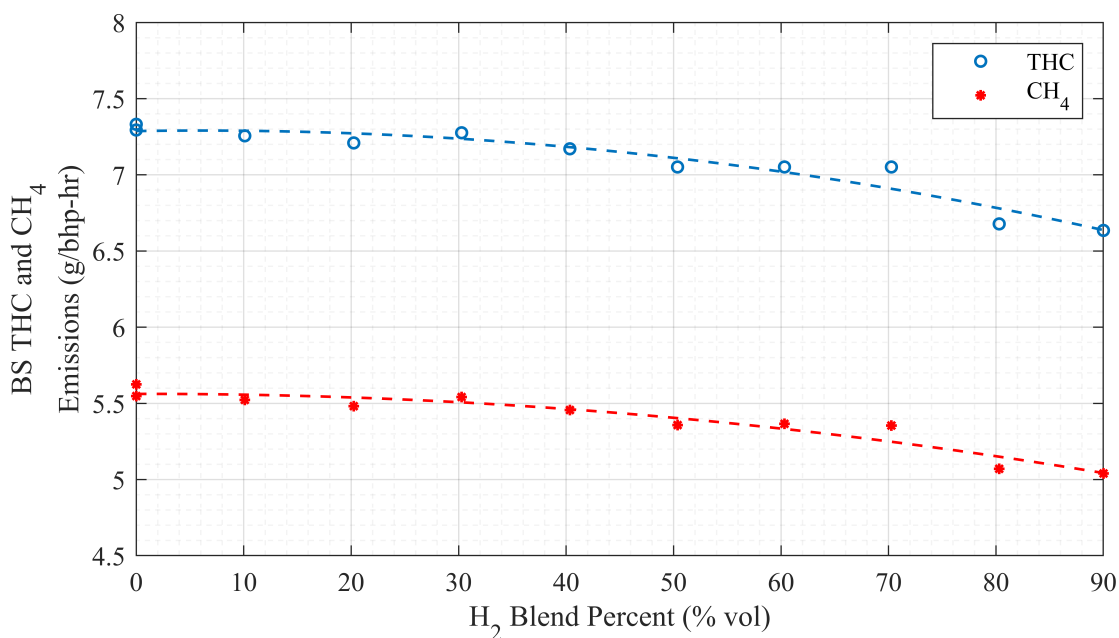


Figure 3.9: PCC Hydrogen Sweep: Break specific THCs and brake specific methane emissions at each fuel blending percentage

Oxides of Nitrogen

Figure 3.11 shows break specific nitric oxides emissions as a function of hydrogen percentage. Baselines 1 and 2 put out 0.34 and 0.32 g/bhp-hr, respectively, running at nominal conditions.

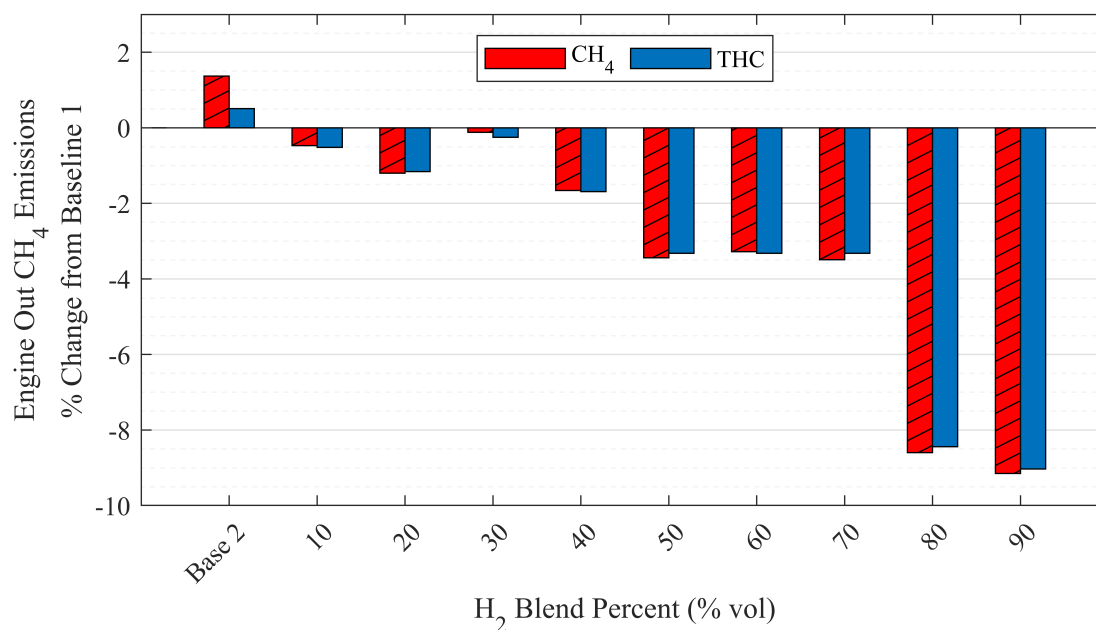


Figure 3.10: PCC Hydrogen Sweep: Percent change of brake specific THC and methane emissions from baseline 1 emissions

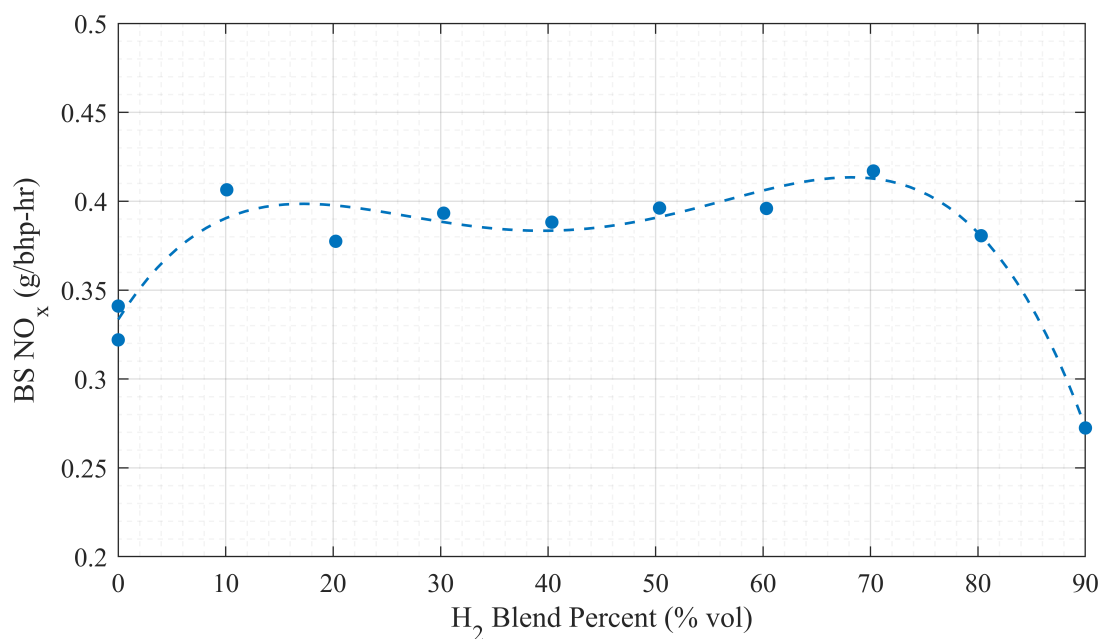


Figure 3.11: PCC Hydrogen Sweep: Brake specific nitric oxides emissions versus hydrogen blend percent

Once hydrogen was introduced into the PCC fuel, there was an increase in nitric oxides emissions that was fairly stable at about 0.4 g/bhp-hr. While the magnitude of the increase is very small

(0.06-0.08 g/bhp-hr), the relative percentage increase was quite large, running between 9.6% and 18.2%. This increase was present until the 90% blend, where a reduction down to 0.27 g/bhp-hr (a 25.1% decrease) was produced.

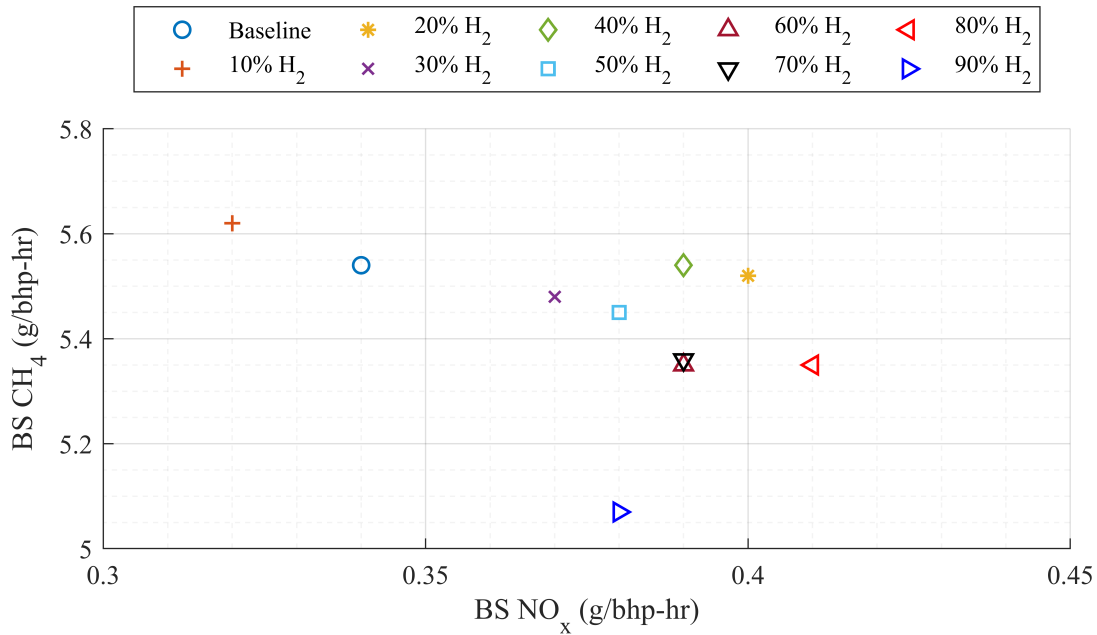


Figure 3.12: PCC Hydrogen Sweep: Brake specific nitric oxides emissions versus brake specific methane

Again, the trade-off between nitric oxides and methane should be made. Results are shown in Figure 3.12. The baseline cases produced a nominal brake specific methane emission of around 5.5 g/bhp-hr and a nominal brake specific nitric oxides emission of 0.32-0.34 g/bhp-hr. As the amount of hydrogen in the fuel increases the resulting emissions show a trend pushing them to the right and slightly down of the baseline - more nitric oxides, less methane. The data points where the blended hydrogen amount were 80% and 90% resulted in a significant percent reduction in methane emissions compared to the lower percent blends. The 90% data point, however, also came with a reduction in nitric oxides over the baseline. It is unclear why this point differed from the rest.

It should be noted that the test plan included a data point that used 100% hydrogen as the fuel as well. When the engine was operated using only hydrogen as the PCC fuel, all of the engines

cylinders started to knock - the engine never reached a steady operating state. The fuel supply to the MCC and PCC were cutoff along with stopping the ignition system in an attempt to immediately halt the operation of the engine and the subsequent knocking, but the engine was, at that point, in thermal runaway. The fuel in the PCC fuel lines between the shutoff valve and the injectors was still under pressure and therefore continued being injected each cycle. It is believed that a hot spot within the PCC (possibly an unchamfered edge) was still able to ignite the hydrogen-air mixture and continue operation until the remaining fuel in the PCC fuel lines was at a pressure lower than the cracking pressure of the check-valve injectors. No other attempts at running 100% hydrogen were made.

3.2 Using Hydrogen in a Low Pressure Fuel Injection System

Test Plan

The test plan for the MGAV engine arrangement included a natural gas/hydrogen fuel blend sweep for fixed spark (uncontrolled LoPP) configuration and a load sweep configuration for 0% hydrogen and 20% hydrogen. The fuel blending set-points began with solely natural gas as the baseline and went up to 24% hydrogen by volume.

Pressure Traces, LoPP, and COV's of Peak Pressures

Figure 3.13 shows the pressure trace for each hydrogen fuel blend tested and Table 3.3 displays values for the peak pressure, LoPP, and COV's of peak pressures. The baseline data point had an average peak pressure of 533 psi (3.67 MPa). There is a general trend of increase in peak pressure as the percentage of hydrogen in the fuel increases leading to a maximum peak pressure of 560 psi (3.90 MPa) at the 24.0 hydrogen blend. Accompanied with the increased cylinder pressure is an advancement in LoPP. The trend for LoPP is the same as the peak pressure, a gradual increase as hydrogen percentage increases leading to a LoPP of nearly 2° before the baseline case.

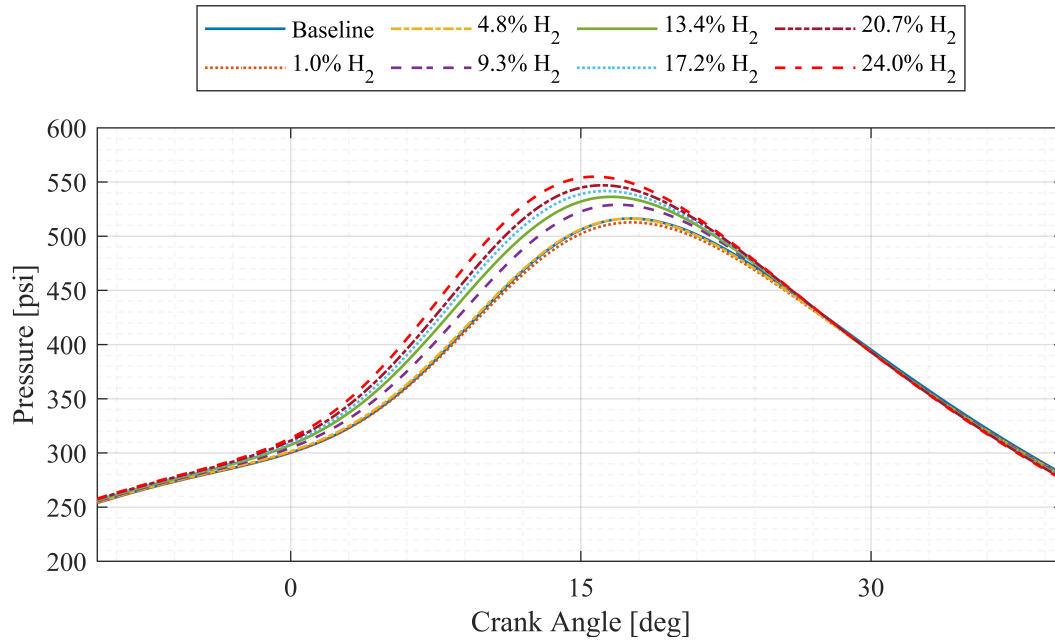


Figure 3.13: MGAV Hydrogen Sweep: MCC pressure traces for hydrogen sweep

Table 3.3: MGAV/Hydrogen Sweep: Comparison of average peak pressure, location of peak pressure, and COV of peak pressure for each data point.

Test Point/ H ₂ %	Peak Pressure (psi/MPa)	LoPP (°aTDC)	COV of Peak Pressure (%)
Baseline	533/3.67	17.9	9.13
1.0	529/3.64	18.0	9.06
4.8	532/3.66	17.8	8.34
9.3	543/3.74	17.3	7.95
13.4	550/3.79	16.9	7.42
17.4	555/3.82	16.6	7.00
20.7	560/3.86	16.4	6.92
24.0	560/3.90	16.1	6.88

Ignition Delay, Combustion Duration, and BSEC

As expected, ignition delay and combustion duration both decreased as hydrogen percentage increased. The baseline case's ignition delay was 13.7 degrees, and the combustion duration was 20.8 degrees. At a 24% mixture of hydrogen, the ignition delay decreased to 12.3 degrees and the combustion duration decreased to 19.6 degrees, a change of 1.4 degrees and 1.2 degrees. Keeping the engine running at the same load and power output level permitted a decrease in BSEC. The

Table 3.4: MGAV Hydrogen Sweep: Ignition delay, combustion duration, brake specific fuel consumption, and the change in brake specific fuel consumption from baseline values.

Test Point/ H ₂ %	Ignition Delay (deg)	Combustion Duration (deg)	BSEC (Btu/bhp-hr)	BSEC (% change from Baseline 2
Baseline	13.7	20.8	8417	–
1.0	13.8	21.0	8368	-0.59
4.8	13.6	20.6	8329	-1.05
9.3	13.2	20.3	8328	-1.06
13.4	12.9	20.1	8286	-1.56
17.4	12.8	19.9	8264	-1.82
20.7	12.6	19.8	8240	-2.11
24.0	12.3	19.6	8227	-2.26

nominal BSEC value was 8,417 Btu/bhp-hr, and at the highest hydrogen blend percentage tested, a BSEC of 8,227 Btu/bhp-hr was calculated, a 2.26% reduction from the baseline. Table 3.4 and Figure 3.14 show tabulated values and graphical representations of ignition delay, combustion duration, BSEC, and BSEC percent change from baseline.

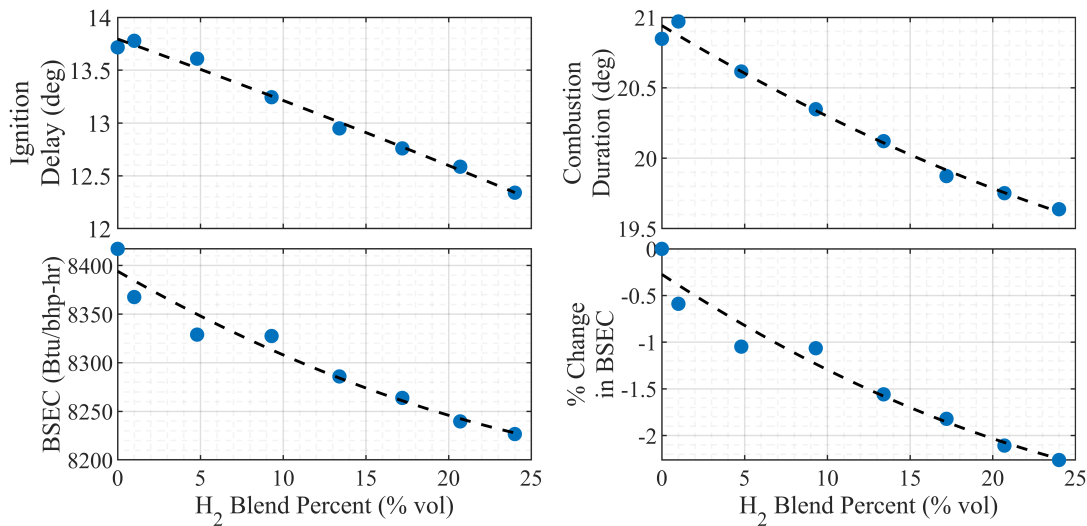


Figure 3.14: MGAV Hydrogen Sweep: Ignition delay, combustion duration, brake specific fuel consumption, and the change in brake specific fuel consumption from baseline

Emissions

Total Hydrocarbons and Methane

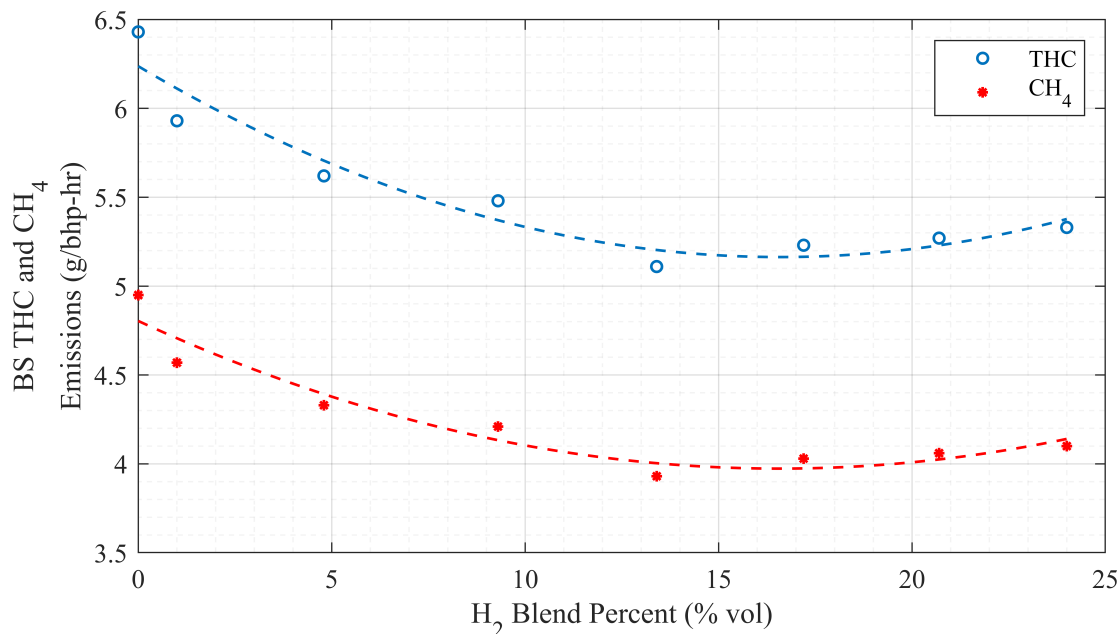


Figure 3.15: MGAV Hydrogen Sweep: Brake specific THCs and brake specific methane emissions at each fuel blending percentage

Figure 3.15 shows the brake specific THC and methane emissions as a function of hydrogen percent. Both parameters show a slight decrease in emissions at lower levels of hydrogen blending. At around 12%, the emissions seem to slightly increase or hold steady. Overall, however, a decrease is seen compared to the baseline. Figure 3.16 shows the brake specific THC and methane changes compared to the baseline. Similarly, to Figure 3.15, a maximum reduction is seen at the 13.4% hydrogen blend. A rapid increase in percent reduction is shown for the blends before the 13.4% blend, at which point the reduction gradually starts to decrease until the final percentage tested is reached.

Oxides of Nitrogen

nitric oxides emissions were relatively unchanged for each test point. The baseline data point produced 7.73 g/bhp-hr, whereas the blended fuels produced between 7.0 g/bhp-hr (1% hydrogen)

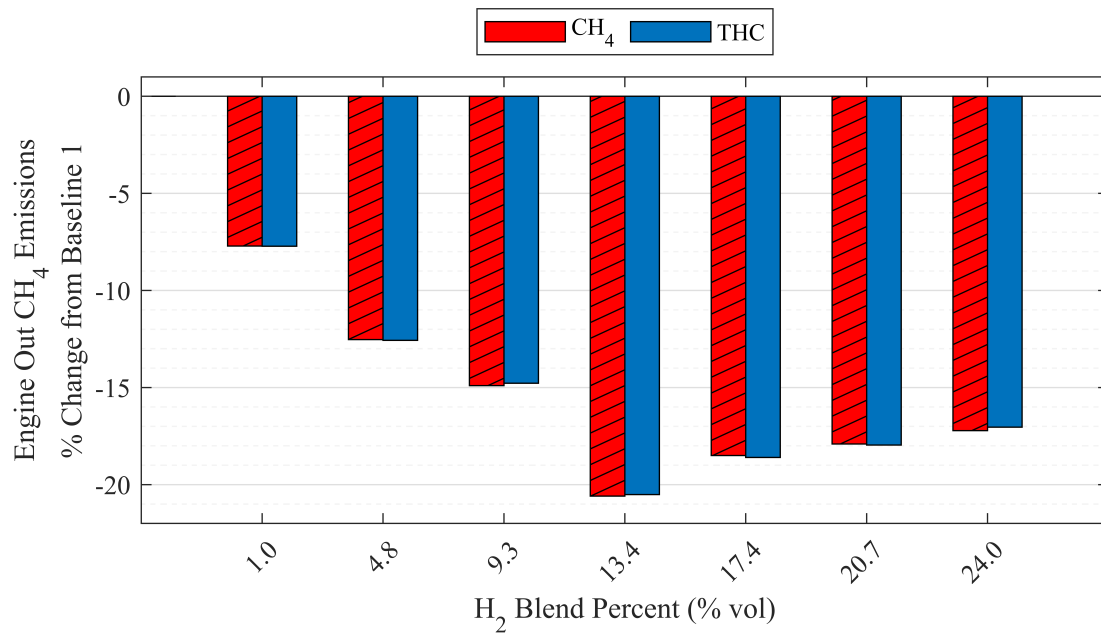


Figure 3.16: MGAV Hydrogen Sweep: Percent change of brake specific THC and methane emissions from the baseline

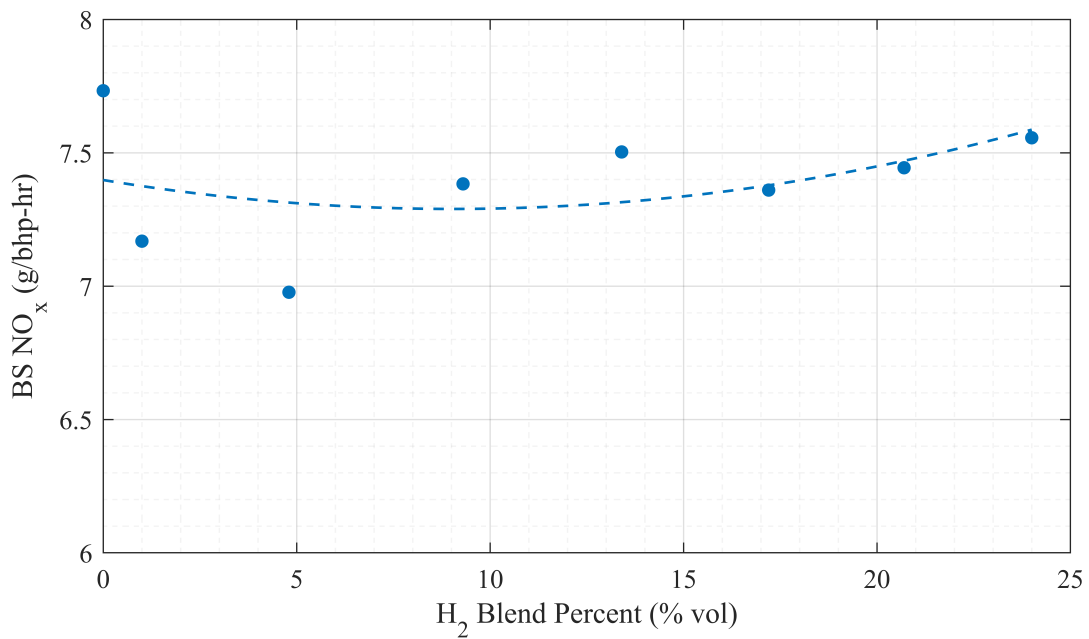


Figure 3.17: MGAV Hydrogen Sweep: Break specific nitric oxides emissions at each fuel blending percentage

and 7.55 g/bhp-hr (24% hydrogen). Individual emissions for each blend percent can be seen in Figure 3.17.

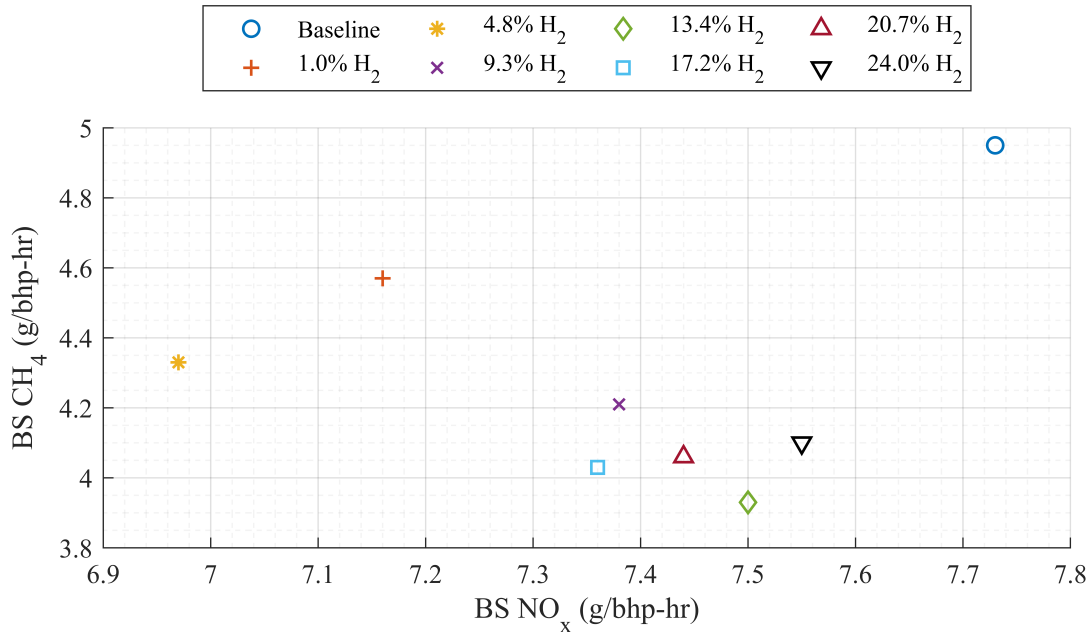


Figure 3.18: MGAV Hydrogen Sweep: Brake specific nitric oxides emissions versus brake specific methane

Figure 3.18 shows the resulting brake specific nitric oxides emissions versus the brake specific methane emissions. Both emissions fell compared to the baseline case as the percentage of hydrogen increased but with no recognizable pattern. The 1% and 4.8% blends saw a large relative reduction in nitric oxides values over the higher blends, but the higher blends saw a large relative reduction in the methane values over the 1% and 4.8% blends. All tested blends, however, produced less nitric oxides and less methane than the baseline.

3.3 Answers to Research Questions

The first question this portion of the research is set to answer is *How does the addition of hydrogen to a fuel supply affect the combustion stability of a lean burn large bore natural gas engine?* This question, however, needs to be applied to every engine operating condition or configuration as the answer may change.

When asked against the HPFI configuration another division needs to be made between the MCC/PCC blending configuration and the PCC only blending configuration. When hydrogen is blended into the MCC and PCC fuel supplies the COV of peak pressure (the typical parameter used to measure the stability of combustion intensity) was shown to drop from 4.8% with the baseline cases linearly as the percentage of hydrogen blended into the fuel increased to a low of 3.0% with the 41% hydrogen blend - an improvement in stability. This implies that combustion phasing is more repeatable, ignition delay variability is reduced, and the heat release rate timing is stabilized, thus emission outputs are more stable and reliably known.

When only the PCC fuel supply is blended with hydrogen a decline in COV of peak pressure is seen with a nearly flat minimum (4.02-4.05%) between the 50% and 70% blends, beyond those percentages the COV's increase but to a magnitude that is still lower than the baselines (4.55%). Similar to the MCC and PCC blending results, this improvement in stability implies that combustion phasing is more repeatable, ignition delay variability is reduced, and the heat release rate timing is stabilized, thus emission outputs are more stable and reliably known.

For the MGAV injection experiment the combustion stability was also improved shown by the decrease in the COV's of peak pressure from baselines 9.13% to 6.88% with the 24% blend. Again, implying the improvement in stability and reliability of emissions because of the improvement in combustion phasing repeatability, reduction in ignition delay variability, and stabilization of the heat release rate timing.

To fully answer the question *How does the addition of hydrogen to a fuel supply affect the combustion stability of a lean burn large bore natural gas engine?*, the experimental results show that, given any of the tested configurations, an operator should expect to see improvements in combustion stability (measured by COV of peak pressure) anywhere between negligible amounts in the case of the HPFI PCC blending and about a 2.5% decrease in the case of the MGAV configuration, dependent upon the blended hydrogen percent.

The second question this portion of the research is set to answer is *What are the emissions trade-offs when operating a lean burn large bore natural gas engine with varying fuel blend ratios?*

Again, this question needs to be applied to every engine operating condition or configuration as the answer may change. Note that only the methane, THC, and nitric oxides emissions will be presented - other emissions such as CO, carbon dioxide, and carbon dioxide equivalent can be found in Appendix B.2 Extra Plots.

With the HPFI MCC and PCC blending results, an operator should expect hydrocarbon emissions to decrease linearly with the increase of hydrogen blended into the natural gas fuel (28.7% maximum in this case). However, when the fuel mixture moves beyond approximately 31% hydrogen an increase in hydrocarbon emissions is seen. It is not clear what causes this behavior but the working hypothesis is that at higher hydrogen blend levels there is not enough mass being injected into the PCC to create a homogeneous mixture and keep efficiencies high. The flame speed is still faster and the stability is still an improvement over the baseline because of how energy dense hydrogen is over natural gas. The combustion event may be transitioning from a deflagration event to a more detonation type of event leaving pockets of unburned hydrocarbons. More testing would be required for an explanation.

Again, the methane and nitric oxides trade-off is important and the HPFI MCC and PCC blending results show that as the percent of hydrogen increases, nitric oxides emissions increase and methane emissions drop (up to around 31% hydrogen, which after they increase slightly). When analyzing the change in brake specific methane emissions normalized by the hydrogen blend percent used, the reduction in g/bhp-hr for the 8.4% blend was 0.093, 12.9% blend was 0.092, 29.0% blend was 0.053, 31.6% blend was 0.056, 38.5% blend was 0.031, and the 41.3% blend was 0.019. This shows that the largest impact on methane emissions comes from the lowest levels of hydrogen blend percents with diminishing results at blend percentages increase. An operator should expect reductions following this trend.

Analyzing the increase in brake specific nitric oxides in g/bhp-hr, when normalized by the hydrogen blend percent, units of (g/bhp-hr)/hydrogen blend percent, shows different results from the methane emissions. At the 8.4% blend an increase of 0.009 is seen, 12.9% shows 0.005, 29.0% shows 0.007, 31.6% shows 0.006, 38.5% shows 0.005, and the 38.5% blend shows 0.006. The

highest increase in brake specific nitric oxides emissions comes from the lowest hydrogen blend percentages and then slightly lowers and levels out to a value of roughly 0.006 for the higher blend percentages.

When the question is applied to the HPFI PCC blending experiment, the results are less complicated. Hydrocarbon emissions decreased as the percentage of hydrogen increased, very linearly. Similar to the MCC and PCC blending experiments, the highest return in methane emissions reduction came from the lowest hydrogen blend tested, 1%, with a reduction of approximately 0.0065 g/bhp-hr/hydrogen blend percent. As the amount of hydrogen increased the magnitude of the reduction decreased.

The MGAV results show that an operator should expect to see, as the amount of hydrogen in the fuel increases, the methane and THC emissions reduce with diminishing returns as the amount of hydrogen increases. The reduction in methane, in (g/bhp-hr)/hydrogen blend percent, was highest at the 1% blend with a value of 0.088 and the lowest value of 0.012 when using the 24.0% blend. The nitric oxides emissions should be expected to drop as well following an inverse log or inverse natural log curve. Again, the highest reduction of nitric oxides, in (g/bhp-hr)/hydrogen blend percent, was 0.2 at the 1% blend with reductions leveling off at around 0.03.

Chapter 4

Optimizing Pre-combustion Chambers for Methane Emissions and Combustion Efficiency

The following chapter is split into four sections. The first section is titled Evaluating the Influence of Nozzle Design, the second titled Targeting Unburned Methane Through Pre-combustion Chamber Jet Interaction, the third titled Experimental Evaluation of Pre-combustion Chamber Performance, and the fourth section titled Synthesis and Answers to Research Questions. The first three sections serve to present and evaluate the research technique into separate categories. The first and second sections look at simulation results, specifically, section 4.1 analyzes the flame jet and overall combustion statistics, and section 4.2 will analyze the engine emissions. Section 4.3 will detail the experimental results that use the manufactured best performing PCC design. Finally, section 4.4 will explicitly answer the questions presented in the Introduction for this particular technique.

More specifically, section 4.1 will present and evaluate the jet structure, penetration, mixing, and general engine combustion statistics. It will go over in detail the directional PCC simulation results. The results from the "initial" study will be presented first. Those results were used to further the research and refine the best performing design. That best performing design was then simulated again with varying parameters, not including nozzle angle, and had its results compared to further study the affect of the PCC parameters on the engines functionality. Those results will be presented in line also. The final portion of the section will go over a design where two parameter adjustments were merged together in an attempt at stacking performance results.

Section 4.2 focuses on engine emissions from the simulation. Because the basic goal of the research is to reduce methane emissions, the results are heavily focused on residual methane output along with the closely coupled residual nitric oxides emissions.

Section 4.3 will analyze in detail the engine performance, combustion statistics, and emissions output for the experimental portion of the research. The analysis will include the OEM PCC design, the best performing PCC design from the simulations, and finally, the best performing PCC design with increased nozzle diameters. Note that the experimental and simulation results have been separated since the experimental data represents an engine averaged value whereas the simulation data represents a single combustion cycle from a single cylinder.

Section 4.4 will synthesis the simulation and experimental results and answer two questions: (1) Can combustion efficiency be increased by targeting pockets of unburned methane within the combustion chamber utilizing PCC design? and (2) How does PCC geometry affect methane emissions from a lean burn large bore natural gas engine?

4.1 Evaluating the Influence of Nozzle Design

Versions 1 and 2 of the 3-nozzle designs performed as intended. Both designs had their flame-jets impinge on the targeted areas, consuming the fuel where the would-be residual methane pockets were located, and quickly ignite the rest of the main chamber, although with a slower overall combustion rate than the OEM PCC. Version 2 performed better in this case because the two side nozzles projected flames contact the cylinders wall earlier and utilize the turbulence generated to speed up the flame progression so that the flame fronts for each jet meet on the far side of the cylinder. Thus, the two side nozzles promote rapid burning, early in the cycle, in the regions where residual methane was observed in the baseline case. The Version 1 side nozzles projected flames do not make the same contact with the wall (Figure 4.1 and Figure 4.2), resulting in reduced levels of turbulence, and ultimately have a slower moving flame front which leads to the three nozzles flames failing to meet.

The flame fronts in the figures shown were created by visualizing specific discrete values or "contours" of the computational cell temperatures. The minimum contour shown is 1,600 K and the maximum value is 2,400 K with approximately 6 contours in-between. Although displaying the temperature is technically not the flame front, it is a popular and well accepted method in flame

visualization. The method used to view the unburned methane is known as “value blanking”. The colored areas shown only display computation cells that have a methane mole fraction greater than 0.001 and does not indicate the actual concentration of methane within the volume, only that the cell contains methane over the prescribed value.

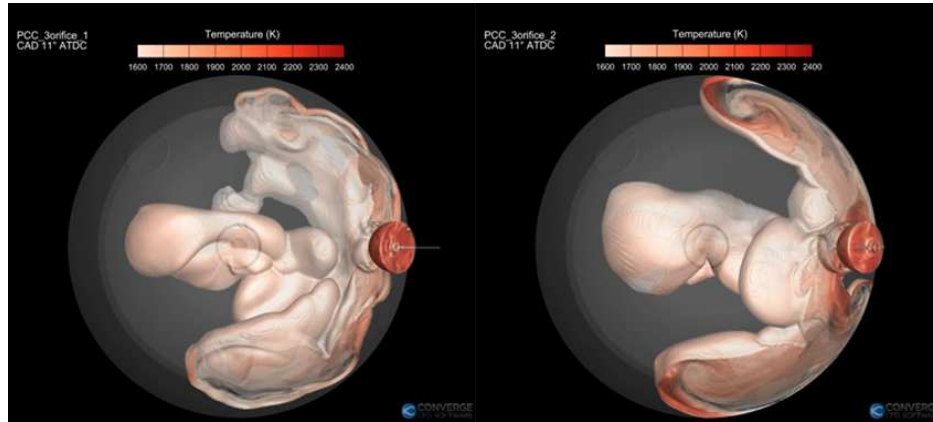


Figure 4.1: Top-down view of both 3-nozzle designs flame front at 11 °aTDC. Version 1 (left) does not propagate as fast and as far as version 2 (right)

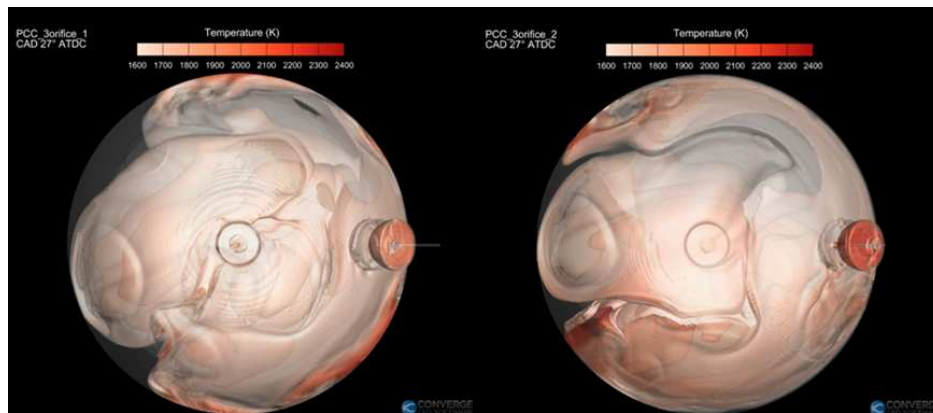


Figure 4.2: Top-down view of both 3-nozzle designs flame front at 27 °aTDC.

The 5-nozzle design behaves similarly to version 1 of the 3-nozzle design. It expends most of its energy at the beginning of the combustion process producing a flame front that cannot fully extend to the far side of the cylinder. When the flame front extends to its limit, the flame is relatively cool compared to the high temperatures found at the beginning of the process, slightly above 1600 K

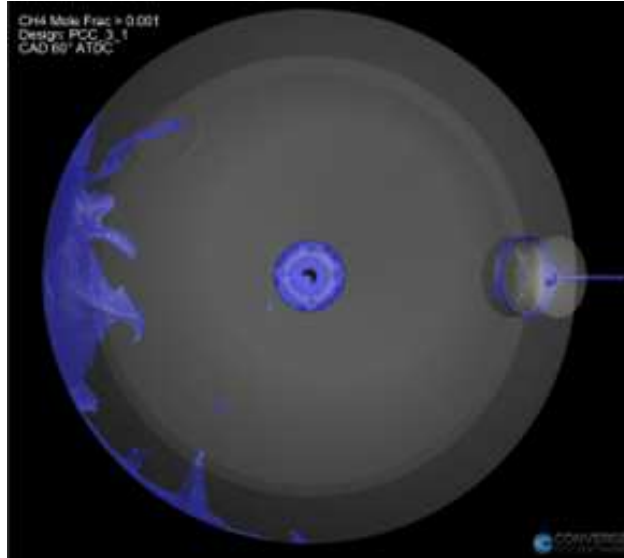


Figure 4.3: Residual methane in the MCC of 3-nozzle version 1 PCC at 60 °aTDC.

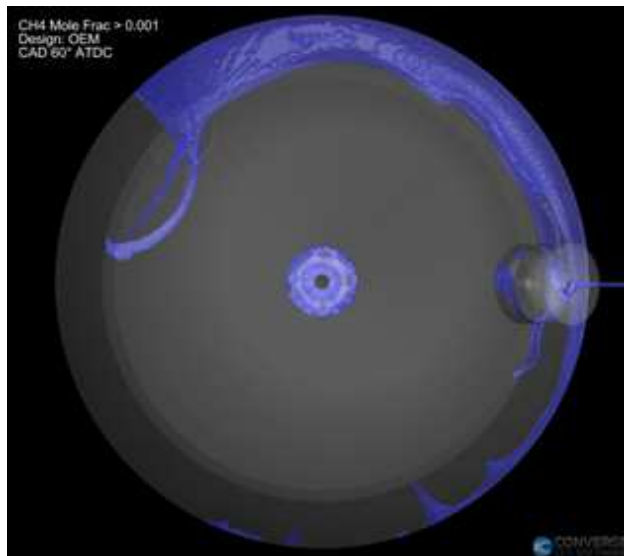


Figure 4.4: Residual methane in the MCC of the OEM PCC at 60 °aTDC.

(Figure 4.5). Because the PCC of the GMV4 is off-center, three of the nozzles resulted in wasting a large portion of energy due to how they are angled relative to each other and the surrounding engine geometry – the flame-jets impinge on each other creating a large combustion event directly under the PCC with respect to the cylinders line of symmetry.

The slot design PCC's three large round nozzles are angled in such a way that the flame-jets, as they exit into the main chamber, interact with each other but without disrupting each jet's prop-

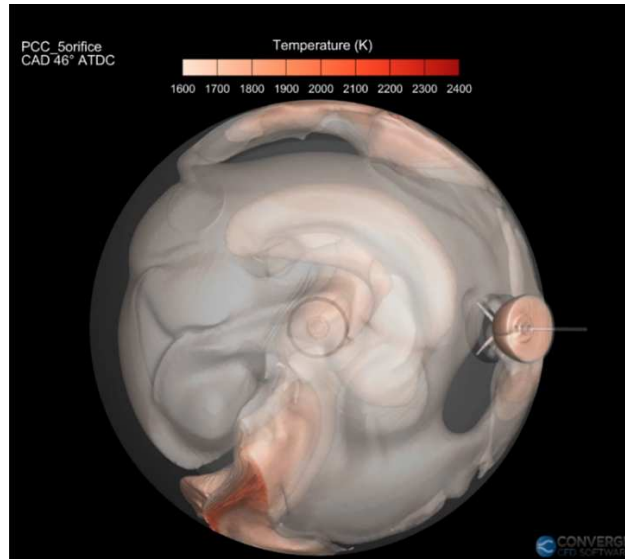


Figure 4.5: Top-down view of the 5-nozzle PCC flame front at 46 °aTDC. The flame is unable to reach the distant side of the cylinder (in comparison to the PCC location) and the portion of the flame front that makes it closest is at a relatively cool temperature when it does.

agation. The jets combine and quickly disseminate through the main chamber as a single flame front. The atypical rectangular nozzle functioned as intended – it created a very thin flame-jet that spreads directly under the PCC, an area typically last to combust (Figure 4.6). The small flame-jet also creates a substantial amount of turbulence that allows the two flame lobes to continue along the cylinder walls for an extended period.

The main combustion cylinder pressure traces for each PCC design can be seen in Figure 4.7. The OEM case does not start to show an increase in main cylinder pressure until approximately 1.5 °bTDC. Version 2 of the 3-nozzle design is the only design that mimics that behavior and shows a pressure increase at approximately the same crank-angle. Version 1 of the 3-nozzle design, the 5-nozzle, and the slot designs all show pressure inflection locations closer to TDC to 0.7 °aTDC. After the inflection points, the pressure traces vary for each design. The Version 1 pressure trace starts off slow and gradually increases until its peak. Version 1 shows a decrease in PCP of 0.24 MPa, compared to the baseline, with the LoPP nearly 5° further into the cycle. Version 2 shows much similarity to version 1 up to about 12 °aTDC where the pressure rise becomes less significant leading to an even lower PCP, about 0.36 MPa less than OEM. The location of version 2 PCP is

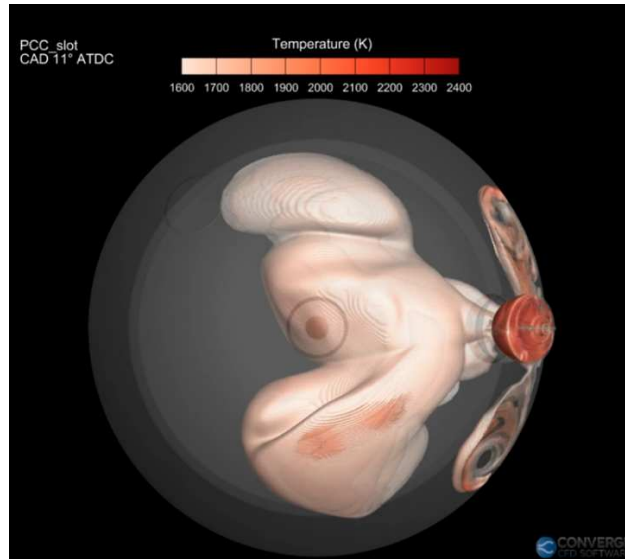


Figure 4.6: A top-down view of the slot PCC design with the flame front visualized. The three circular nozzles extend from the PCC and merge together creating a large flame front without impinging on the jet's propagation.

shown to be 7° further into the cycle as well. For the slot design, the pressure traces inflection point is later than both 3-nozzle versions, but the pressure rise is much faster in comparison to the two (still slower than the OEM) and then reaches a maximum value nearly 0.41 MPa lower than the OEM design. The LoPP of the slot design was revealed to be 3.2° further into the cycle compared to the OEM design as well. The 5-nozzle design falls far short of the OEM design, as well as the other PPC designs. The initial pressure rise follows the 3-nozzle version 1 design closely, nearly until the maximum pressure location of the 5-nozzle design. The PCP for the 5-nozzle design is 1.09 MPa lower and a LoPP of nearly 3° forward of the OEM case. The pressure trace takes a shape closer to a plateau than a typical single peak.

While first glance at the main cylinder pressure traces do not look promising for each design, but an examination of the pressure-volume (P-V) diagrams tells a different story. Figure 4.8 shows the P-V diagram for the 3-nozzle version 1 design PCC and Figure 4.9 shows the P-V diagram the slot design PCC, both compared to the OEM. For the slot design, the PCP and LoPP have already been discussed, but viewing the P-V diagram shows that the examined design was able to hold higher pressures for a longer duration. This is indicated by the portion of the pressure trace representing

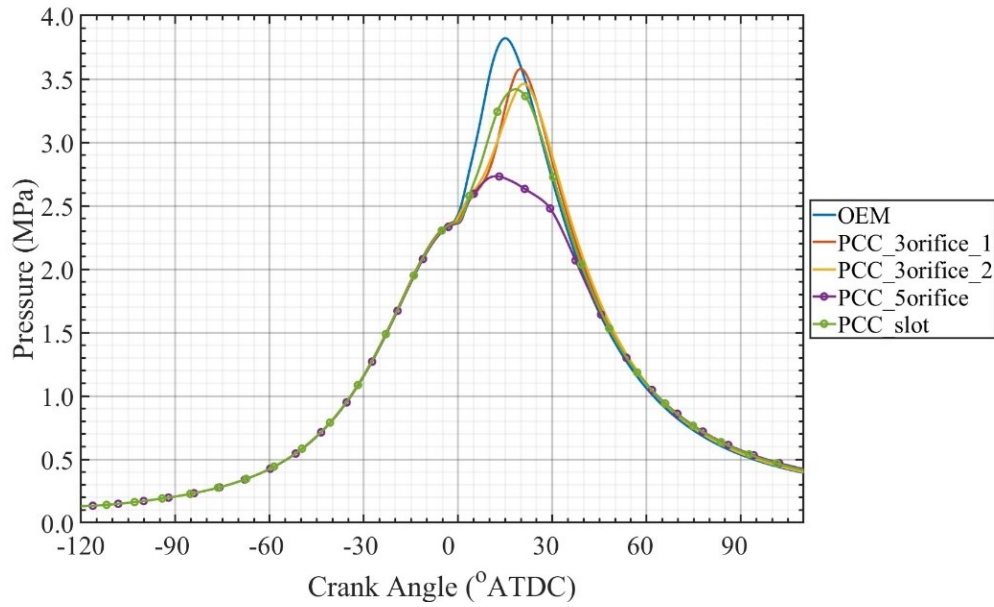


Figure 4.7: Pressure trace comparison of all PCC designs.

the downward stroke (TDC to nearly BDC) where the PCC design is higher than the OEM. When the work is calculated for the cycle, the slot design shows an increase in power of nearly 1.5% demonstrating that the extra area under the curve, added by the increased down-stroke pressure, is enough to make up for the missing area due to the reduced PCP. The same behavior is seen for the 3-nozzle version 1 design, but in this case, the added area is not enough to cover the loss resulting in a power decrease of approximately 2%.

Figures 4.10 and 4.11 illustrates the same P-V diagrams but for the 2nd version of the 3-nozzle design and the 5-nozzle design, respectively. Again, the same behavior is seen for both PCC designs – the pressure on the downward stroke is higher than the OEM case for nearly the entire duration of the downward stroke. The 3-nozzle version 2 follows suit with the slot design, producing an increase in power of over 2%, while the 5-nozzle design falls short of the OEM power by over 8%.

A comparison of each model's power output, normalized to the baseline model, can be seen in Figure 4.12. Version 1 of the 3-nozzle design produced 2.6% less power than the baseline case. Version 2 of the 3-nozzle design showed a 2.3% increase in power output. The 5-nozzle design

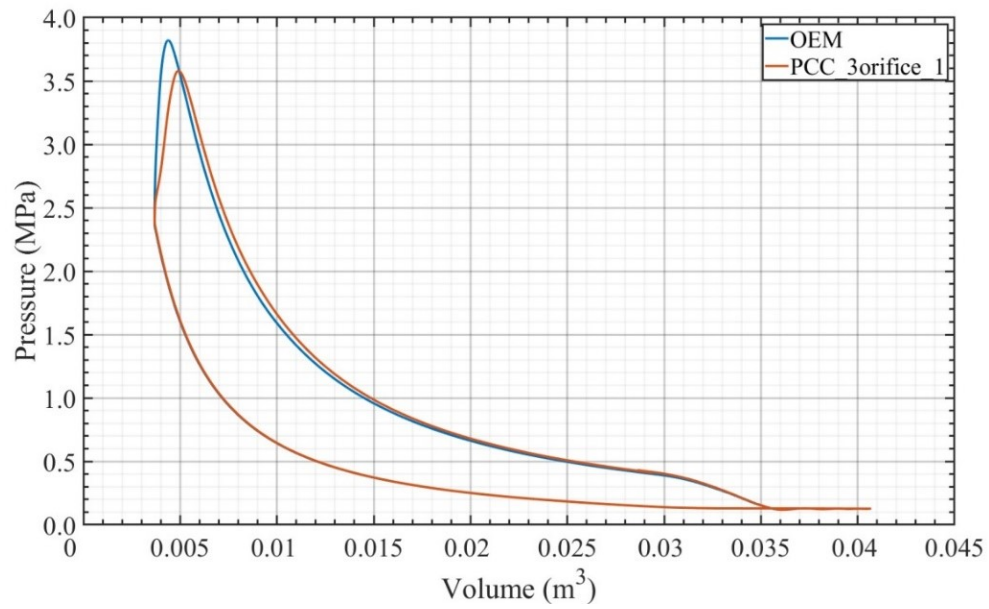


Figure 4.8: P-V diagrams for the 3-nozzle version 1 and OEM PCCs.

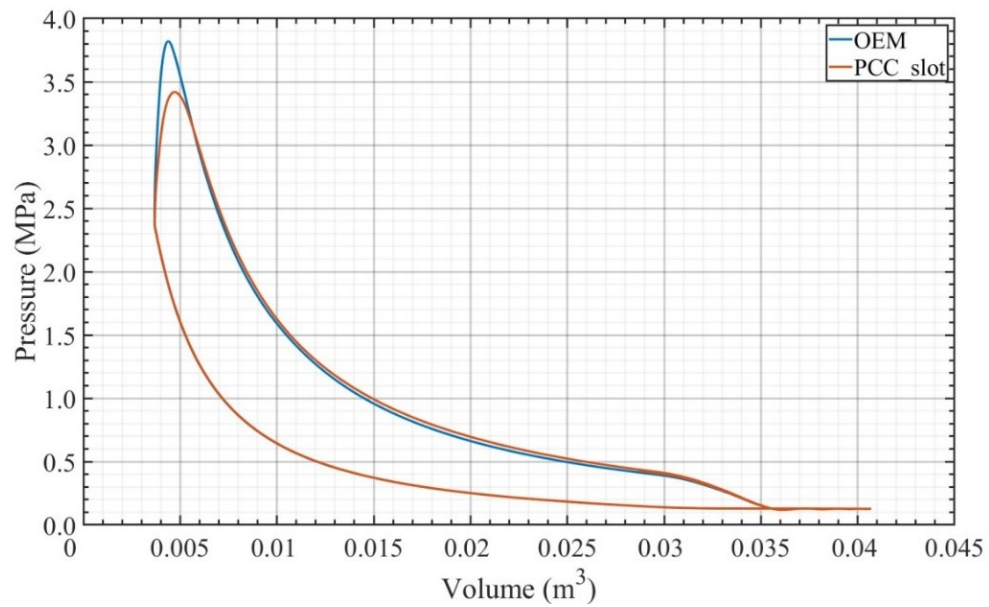


Figure 4.9: P-V diagrams for the slot and OEM PCCs.

had an 8.7% reduction in power. The slot design PCC saw a 1.5% power increase over the baseline model.

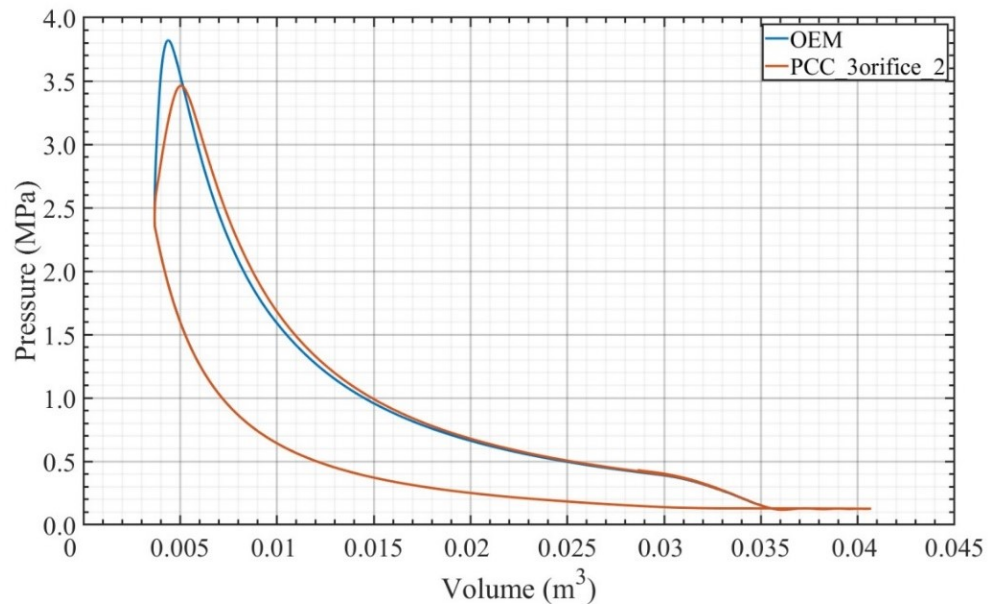


Figure 4.10: P-V diagrams for the 3-nozzle version 2 and OEM PCCs.

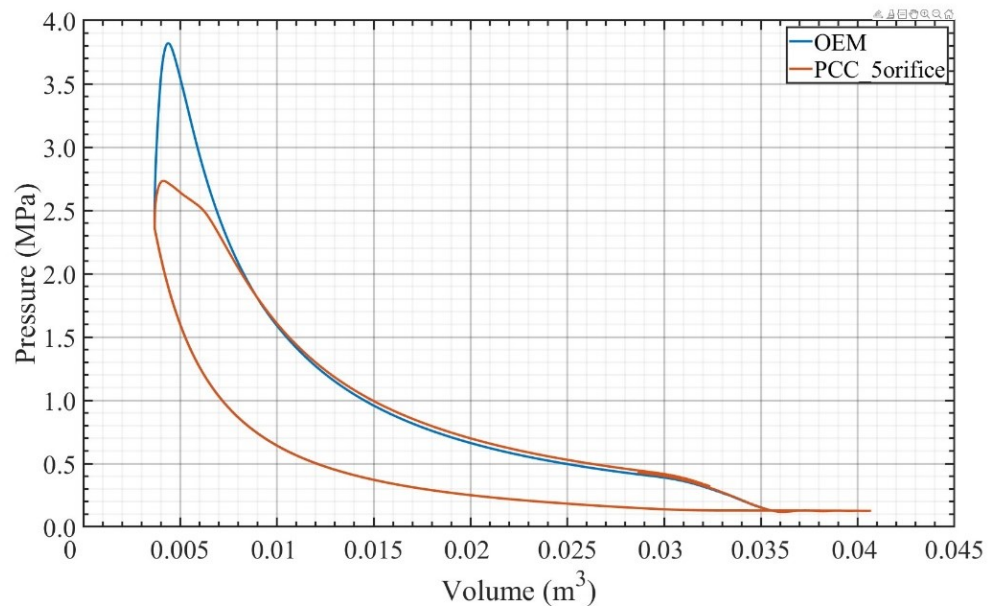


Figure 4.11: P-V diagrams for the 5-nozzle and OEM PCCs.

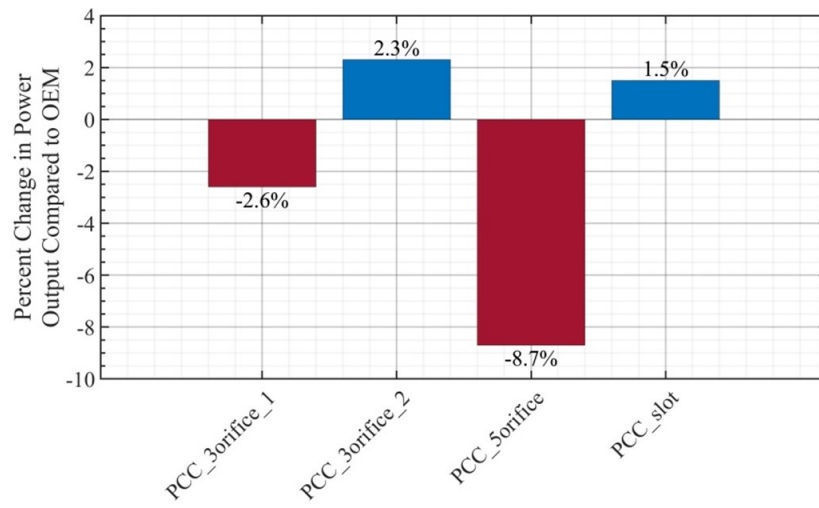


Figure 4.12: Power output for each PCC design normalized to baseline power output

4.2 Targeting Unburned Methane Through Pre-combustion Chamber Jet Interaction

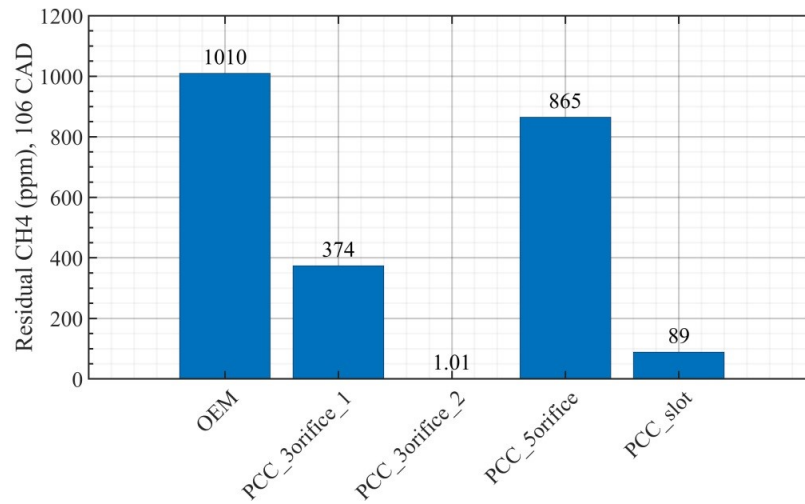


Figure 4.13: Residual methane in the MCC at EPO for each PCC design.

Figure 4.13 shows the residual methane present at the time of exhaust ports opening in parts per million (ppm) for each PCC design. The baseline case utilizes the OEM PCC design and produces 1010 ppm. The 3-nozzle version 1 design produced 374 ppm (63% reduction compared to baseline), version 2 of the 3-nozzle design produced 1 ppm (99.9% reduction), the 5-nozzle design produced 865 ppm (14% reduction), and the slot design produced 89 ppm (91% reduction).

As stated earlier, this research led to an optimization study of the best performing design to investigate further reductions in residual methane. The PCC design labeled “PCC 3orifice 2” was deemed the most successful model because of the 99% reduction in residual MCC methane coupled with the fact that the design produced 2.3% more power than the OEM design. For the current study, “PCC 3orifice 2” was chosen as the model to be refined.

The residual emission results of adjusting the angle of the nozzles can be seen in Figure 4.14. Angling the nozzles inward resulted in an increase in residual methane for both cases and a de-

crease in nitric oxides produced for both cases, with Angle 2 significantly reducing the nitric oxides produced compared to the original design.

The increase in residual methane can be attributed to how the flame jets exit from the PCC's side nozzles. Figure 4.15 shows the flame jets disseminating from the PCC to the MCC. Because the angles, in both designs, were moved towards the center of the piston, the side nozzles no longer allow the entirety of the jet to propagate around the periphery of the cylinder walls where the residual methane pockets were simulated to be. Now, the crown of the piston splits the jets, causing a portion of the flame to fall inside and onto the piston face. This results in a less efficient combustion cycle, increasing residual methane but also forming less nitric oxides.

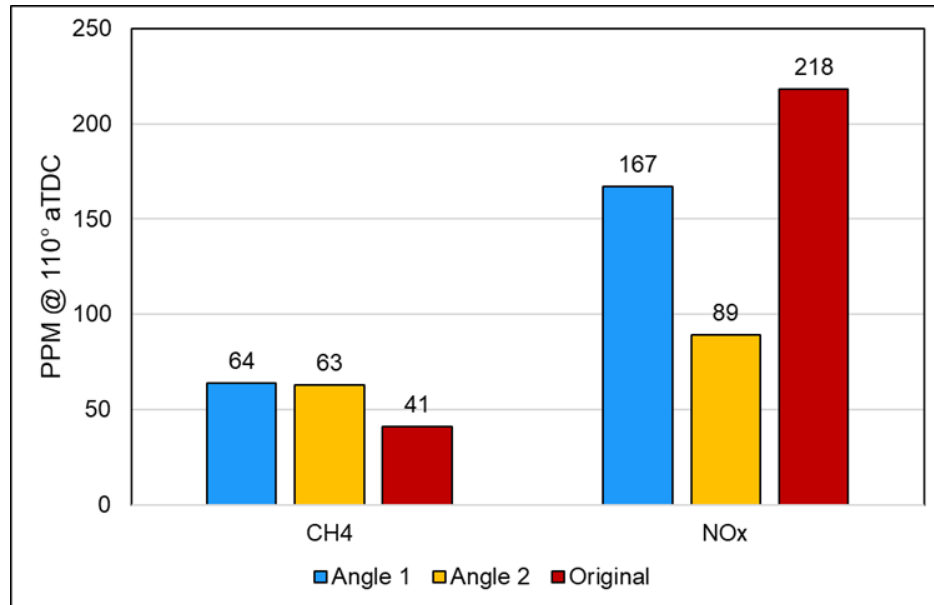


Figure 4.14: Residual methane and nitric oxides emissions just before EPO for the angle adjusted refinement CFD cases.

Adjustments to the PCC volume resulted in dramatic changes to the combustion cycles. Figure 4.16 and Figure 4.17 show the MCC pressure traces and the apparent heat release rates (AHRRs), respectively. It is seen that reducing the PCC volume by 50% resulted in an advancement in the timing of the AHRR initial rise, leading to an advancement in the MCC pressure profile and an increase in peak pressure. This advancement is caused by an increase in flame jet speed. Because

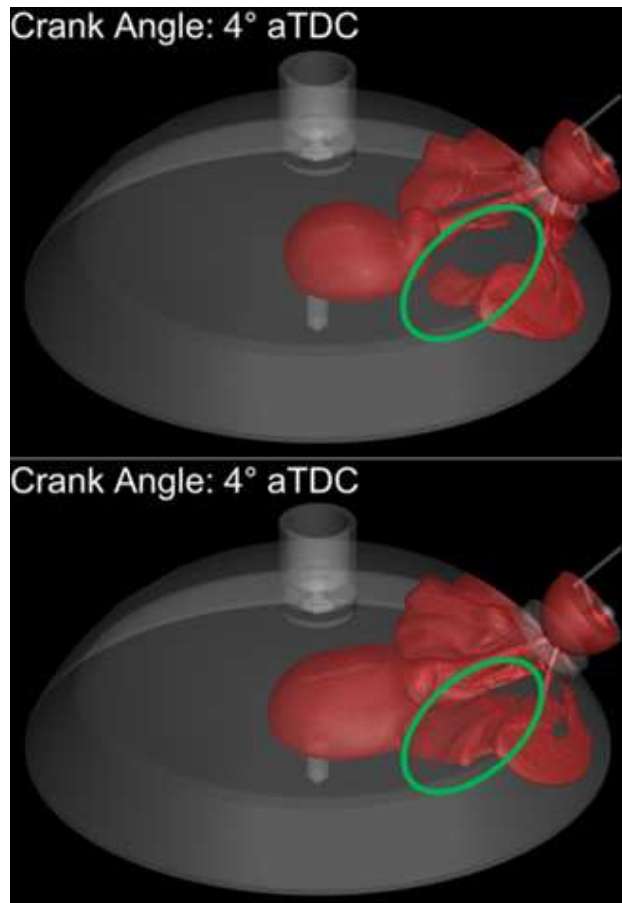


Figure 4.15: An isometric transparent view of the CFD GMV cylinder models. The top image is of the “Angle 1” design, and the bottom image is of the “Angle 2” design. The red area denotes high temperature computational cells that represent the flame front as it expands from the PCC to the MCC. The green circle focuses on an area where the flame is seen splitting, allowing a portion to fall inside the piston bowl instead of circulating around the cylinder periphery.

the volume has been reduced, the pressure in the PCC rises quickly, causing the jets to exit through the PCC nozzles faster and propagate through the MCC more quickly, resulting in the advanced and stronger MCC pressure trace. The opposite is true for the increased PCC volume case. The larger volume results in a slower PCC pressure increase and slower flame jet exit speed and propagation through the MCC—resulting in a delayed and weak pressure trace and AHRR trace. The reduced volume case produced an extraordinary 478 ppm of residual methane as compared to the increased volume’s 56 ppm and the original case’s 41 ppm, as can be seen in Figure 4.18.

Modifications of the nozzle flow areas resulted in very promising outcomes. Increasing the flow area of the nozzles by 25% impeded the flame jet speed, resulting in a reduced pressure trace,

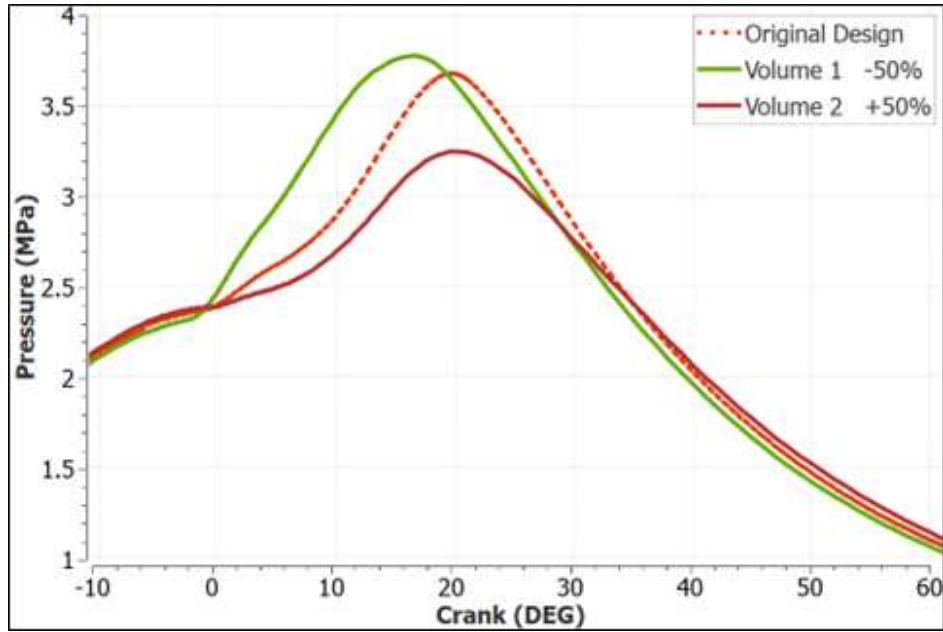


Figure 4.16: MCC pressure traces for the PCC volume adjusted cases.

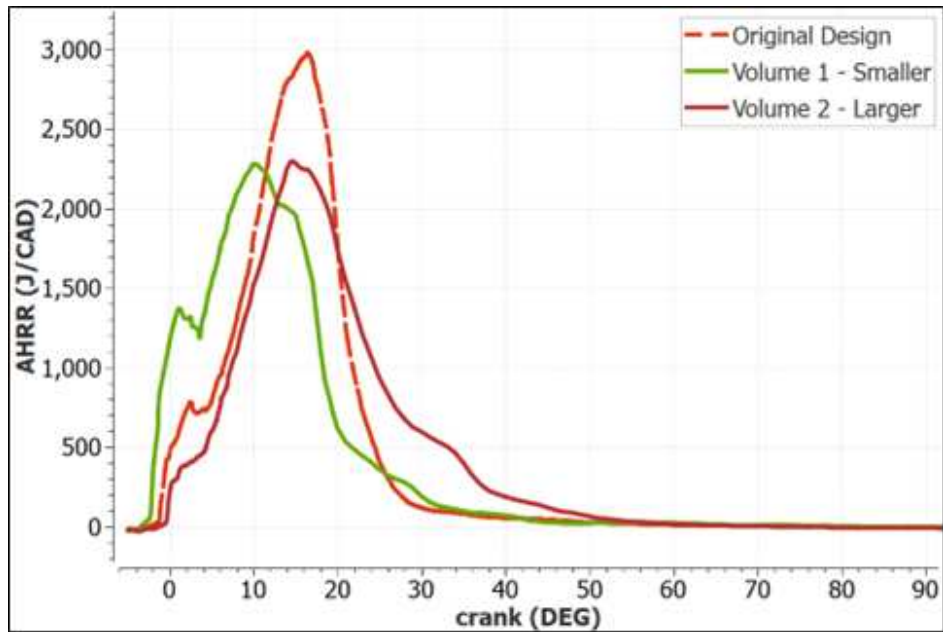


Figure 4.17: AHRRs for the PCC volume adjusted cases.

compared to the original, and an AHRR trace that had similar timing, but a much lower peak (Figure 4.19). Reducing the nozzle flow area by 25%, however, produced an MCC pressure trace and AHRR nearly identical to the original, all while reducing the amount of residual methane and

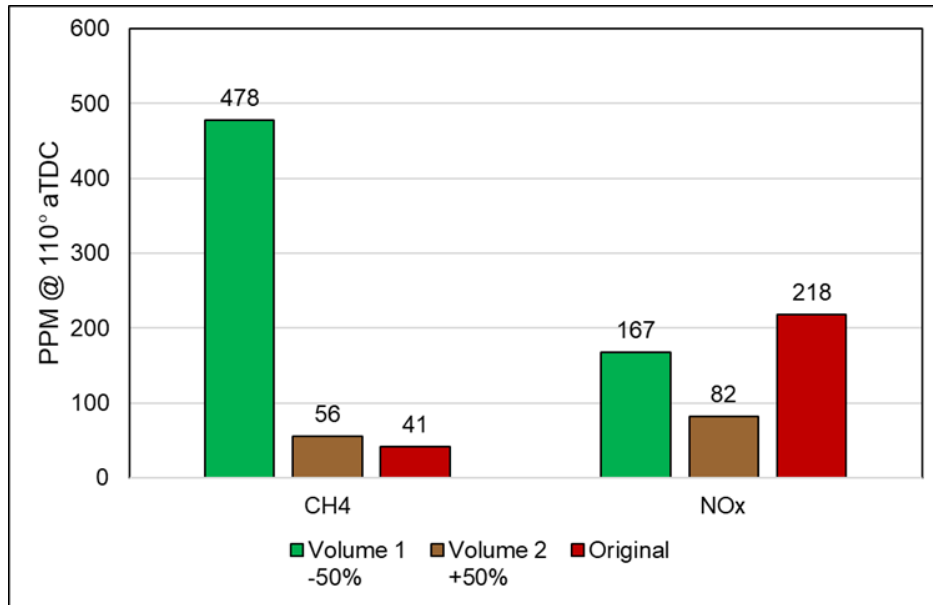


Figure 4.18: Methane and nitric oxides emissions at EPO for the volume adjusted cases.

the amount of nitric oxides produced. Figure 4.20 shows the resulting methane and nitric oxides emissions EPO.

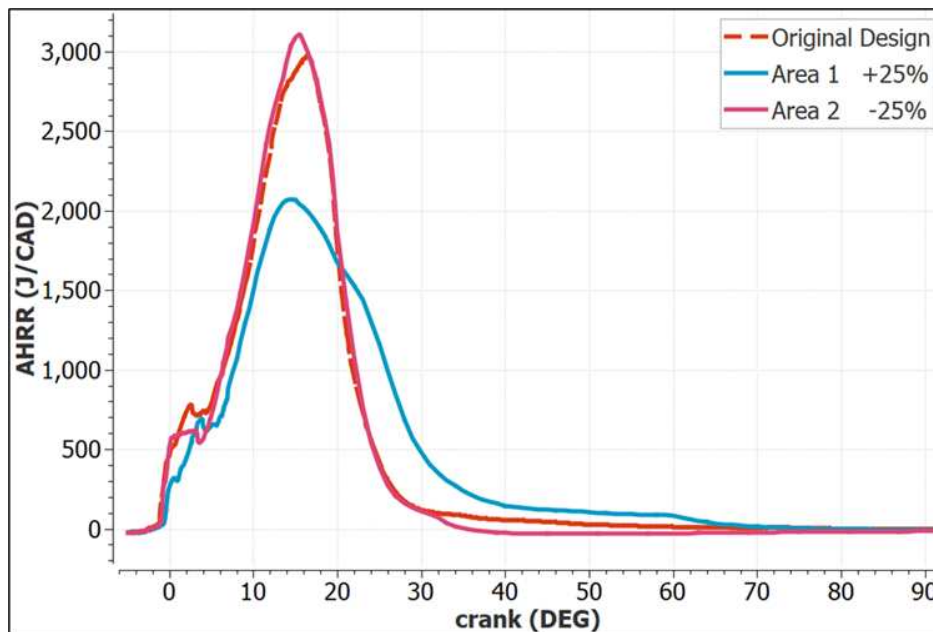


Figure 4.19: AHRR of the flow area adjusted cases.

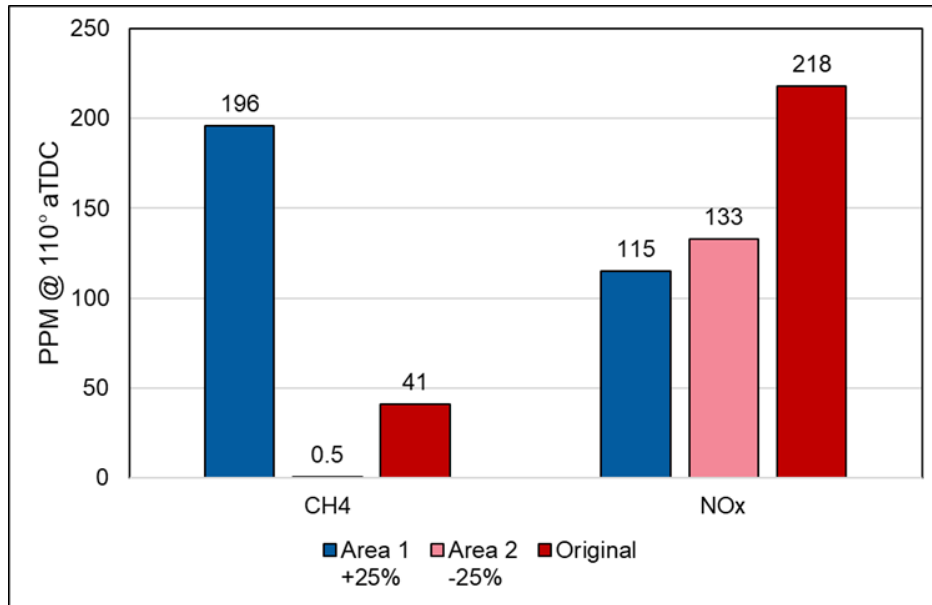


Figure 4.20: Methane and nitric oxides emissions comparisons, at EPO, of the flow area adjusted cases.

A trade-off plot between methane emissions and nitric oxides production (Figure 4.21) shows the results of all the designs. Note that Volume 1 produced such a high amount of methane that it is off the scale of the graph. The reduced flow area design, Area 2, was the best performing refinement regarding residual methane, but the increased volume design, Volume 2, also showed promise, as it just slightly increased the residual methane, compared to the original, but had the lowest nitric oxides production of all the designs.

Another design, named “Area2 Vol2,” that used both a 25% reduced nozzle flow area and a 50% increased PCC volume was then simulated. The goal was to explore whether the improvements from each refinement are additive and if a design utilizing both refinements could produce results that lie between the two individual cases on the trade-off plot.

Two cases of the “Area2 Vol2” design were simulated, one with spark timing the same as the original design and another with retarded spark timing. The nominal case produced a pressure trace and AHRR that were far advanced and produced much higher peaks compared to the original. The second case, with retarded spark timing, was simulated so that the MCC peak pressure was much closer to the original designs.

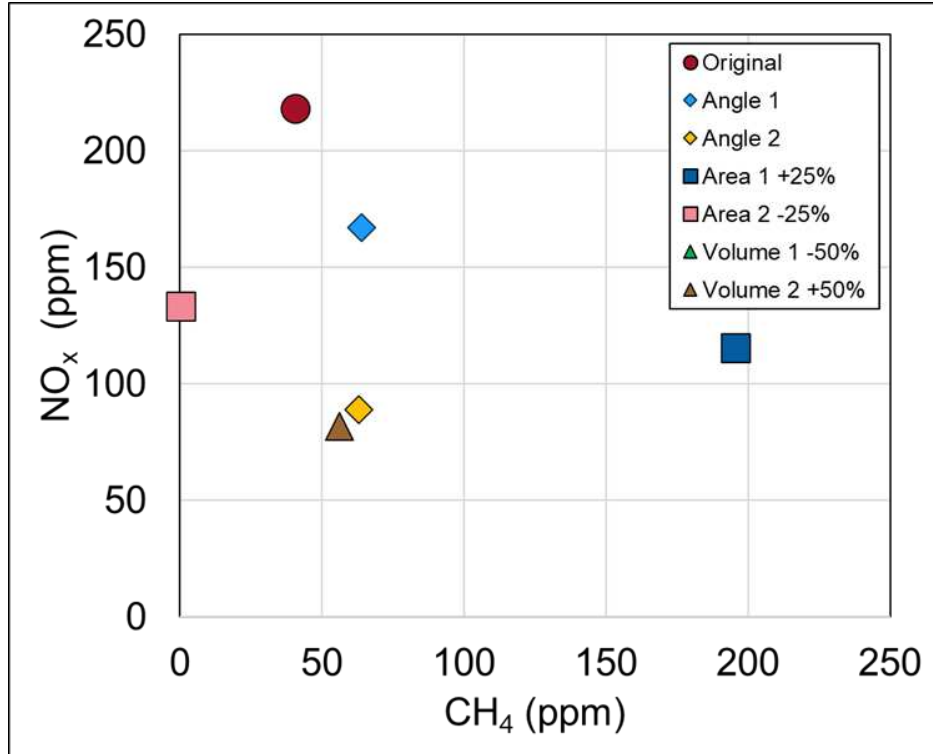


Figure 4.21: Methane and nitric oxides trade-off plot for initial refinement cases.

As seen in Figure 4.23, both cases resulted in far lower methane emissions but wavered on nitric oxides production. With nominal spark timing, the design produced slightly higher nitric oxides than the original design. By retarding the spark timing by 1.5° , the nitric oxides production was significantly lowered while only slightly increasing the methane output. Although “Area2 Vol2” resulted in better emissions than the original design, the Area 2 design produced lower methane and nitric oxides.

While the reduction in methane is a great improvement, the PCC design should not simply move the pockets of unburned hydrocarbons from one section of the MCC to another, and instead should actively improve/increase the surface area of the flame front, improving overall fuel consumption. Figure 4.13 shows the locations of the residual methane emissions in each of the simulated PCC cases. The images were taken at or near 65° aTDC when the bulk of the combustion process was complete. Value blanking was utilized and removes all calculation cells that have a methane mole fraction less than 0.001. The volume of the residuals does not indicate more or less methane as the

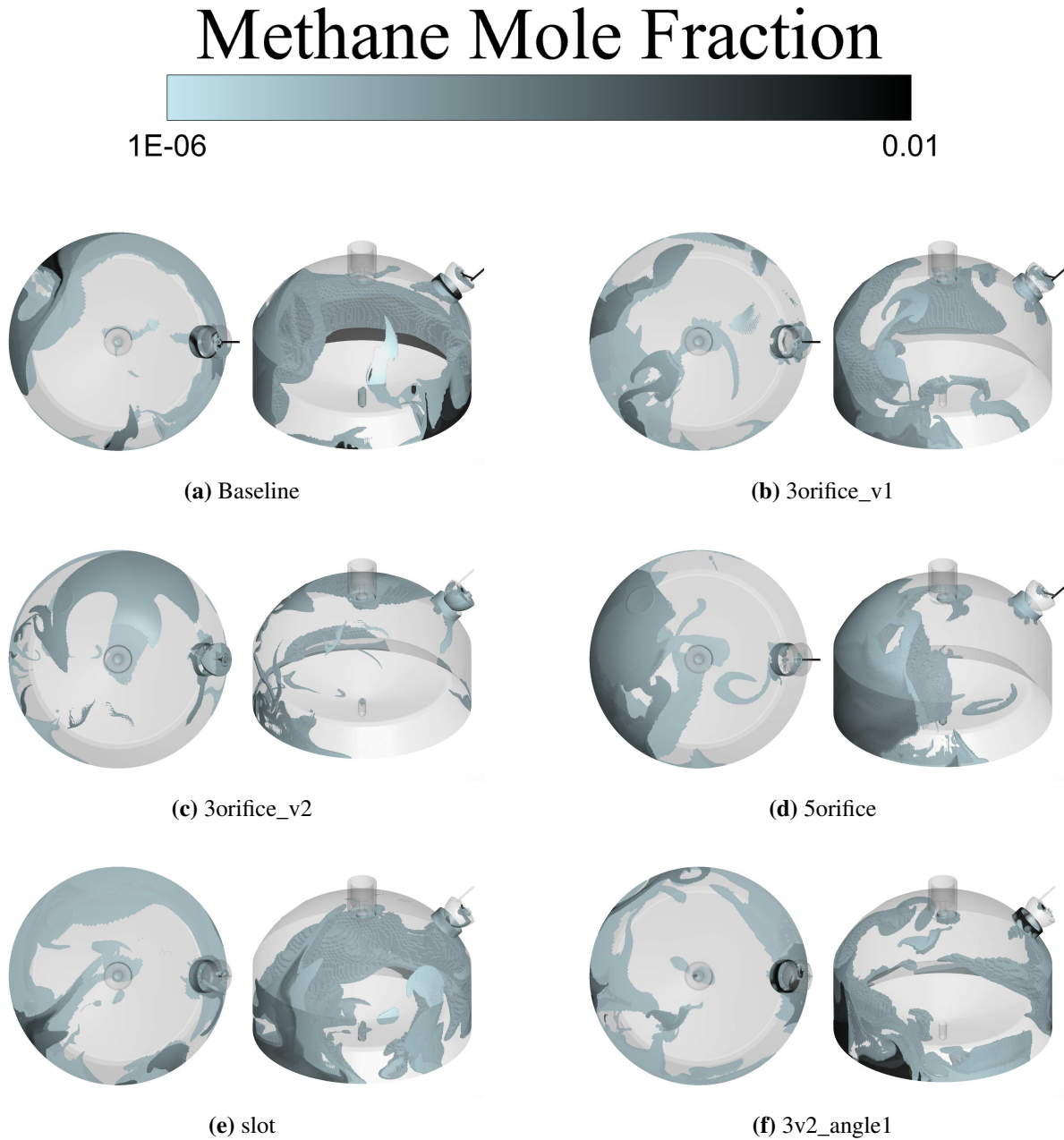
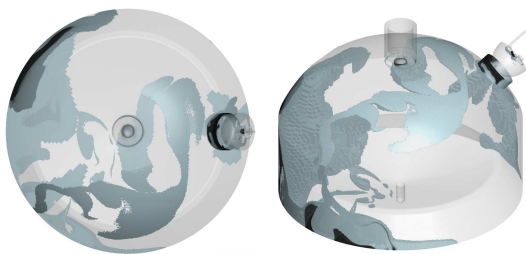
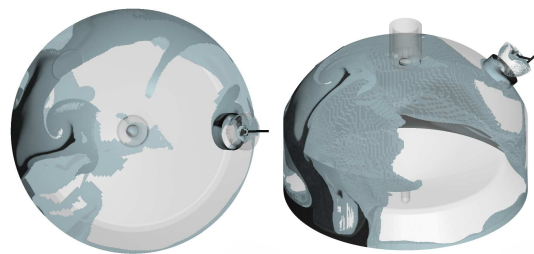


Figure 4.22: Locations of residual methane pockets in each simulated directional PCC design. Images were taken at or near 65 °aTDC when the bulk of the combustion process was complete. Value blanking was utilized and removes all calculation cells that have a methane mole fraction less than 1e-6. The color of the residuals indicates the mole fraction of the cell; the more methane in a cell, the darker that cell will be—black being high concentrations of residual methane.



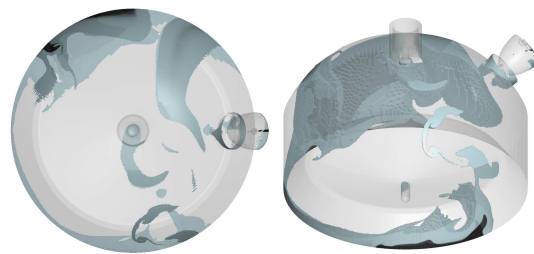
(g) 3v2_angle2



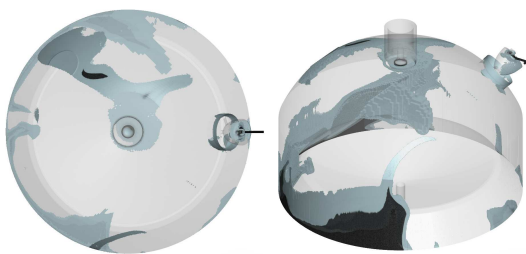
(h) 3v2_area1



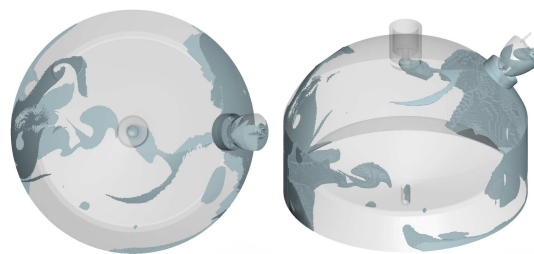
(i) 3v2_area2



(j) 3v2_volume1



(k) 3v2_volume2



(l) 3v2_area2_volume2

Figure 4.22: Locations of residual methane pockets in each simulated directional PCC design. Images were taken at or near 65 °aTDC when the bulk of the combustion process was complete. Value blanking was utilized and removes all calculation cells that have a methane mole fraction less than $1e-6$. The color of the residuals indicates the mole fraction of the cell; the more methane in a cell, the darker that cell will be—black being high concentrations of residual methane.

color of the residuals is only for viewing and does not describe the concentration apart from that the colored volume has a higher methane mole fraction than 0.001.

Figure 4.22c and Figure 4.22i show very small, high concentration residual pockets compared to all other designs. This signifies either that any residual methane in the MCC and PCC has minimal concentrations (spread thinly over the entire volume, and all cells have a mole fraction less than 0.001 and are being blanked) or that more fuel was consumed during combustion, in which case, the mass of methane would be less than the baseline, and that is what was shown earlier when analyzing the residual emissions. These two designs were more successful at improving combustion efficiency, or fuel consumption, across the entire volume and not just specific areas. There were no large methane rich pockets nearing the end of the cycle.

Again, because the goal of the project was to reduce residual methane emissions, the Area 2 model was chosen as the design to move forward with and manufacture for testing on the engine.

4.3 Experimental Evaluation of Pre-combustion Chamber Performance

Cooper Machinery Services, out of Houston, TX, manufactured the PCCs and sent the units directly to CSU for testing. Figure 4.24 shows a frontal view of the PCCs as they were sent to CSU (left) and after expansion of the nozzles (right). Let it be noted that the angles of the nozzles were not adjusted when expansion occurred. The nozzles were expanded in the Rapid Prototyping Lab (RPL) using a 5-axis CNC. The 3D CAD model was used to help orient the PCCs so that the angles were kept exactly as designed.

The resulting brake-specific methane emissions from the boost sweep can be seen in Figure 4.25. Both the nominal and expanded PCCs produced less brake specific methane than the OEM model consistently across all tested boost points. The nominal design cut methane emissions the most out of the two tested PCCs and ranged from a 22.8% to a 31.1% reduction over the OEM. The expanded PCC saw a 19.7% to a 29.2% reduction over the OEM. As boost pressure increased, the

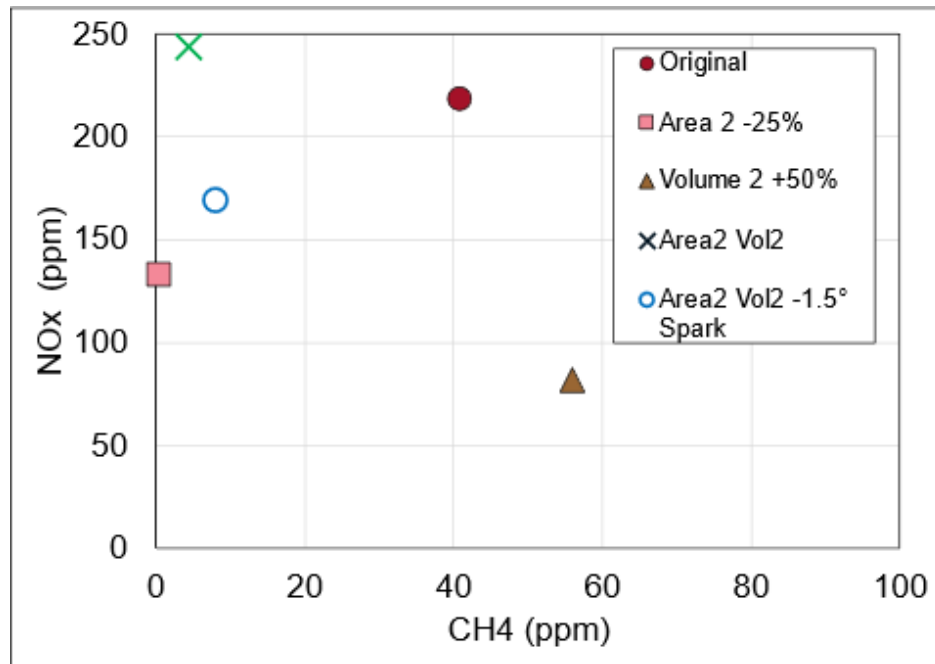


Figure 4.23: A methane and nitric oxides trade-off plot comparing the best performing refinement cases with a case that uses both refinements together (Area2 Vol2).

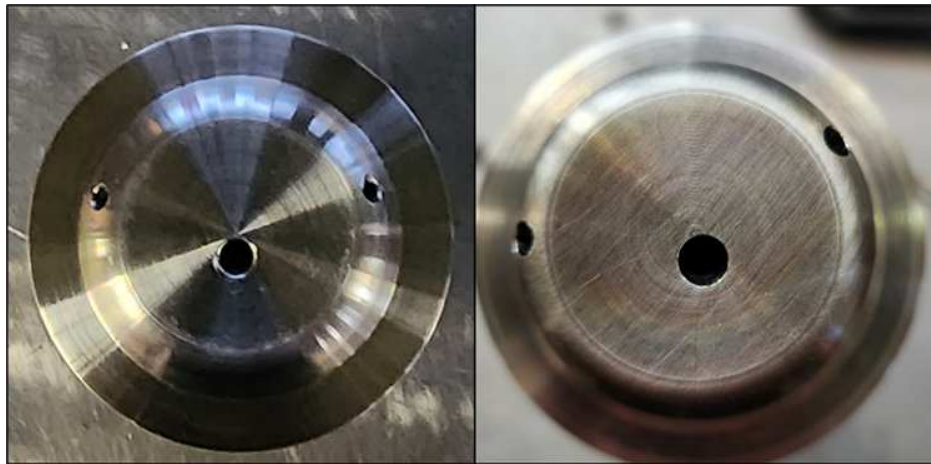


Figure 4.24: Front view of the PCC nozzles. The image on the left is the PCC as delivered, and the image on the right is the PCC after the nozzles were expanded.

percent reduction also increased with both designs—the higher the boost pressure, the greater the reduction in methane emissions.

It is important to highlight that the reduction in methane in the previously mentioned exploratory CFD based project was 99% against the OEM when using the original design. The discrepancy between that, the refinement cases, and experimental values stems from liberties taken with the com-

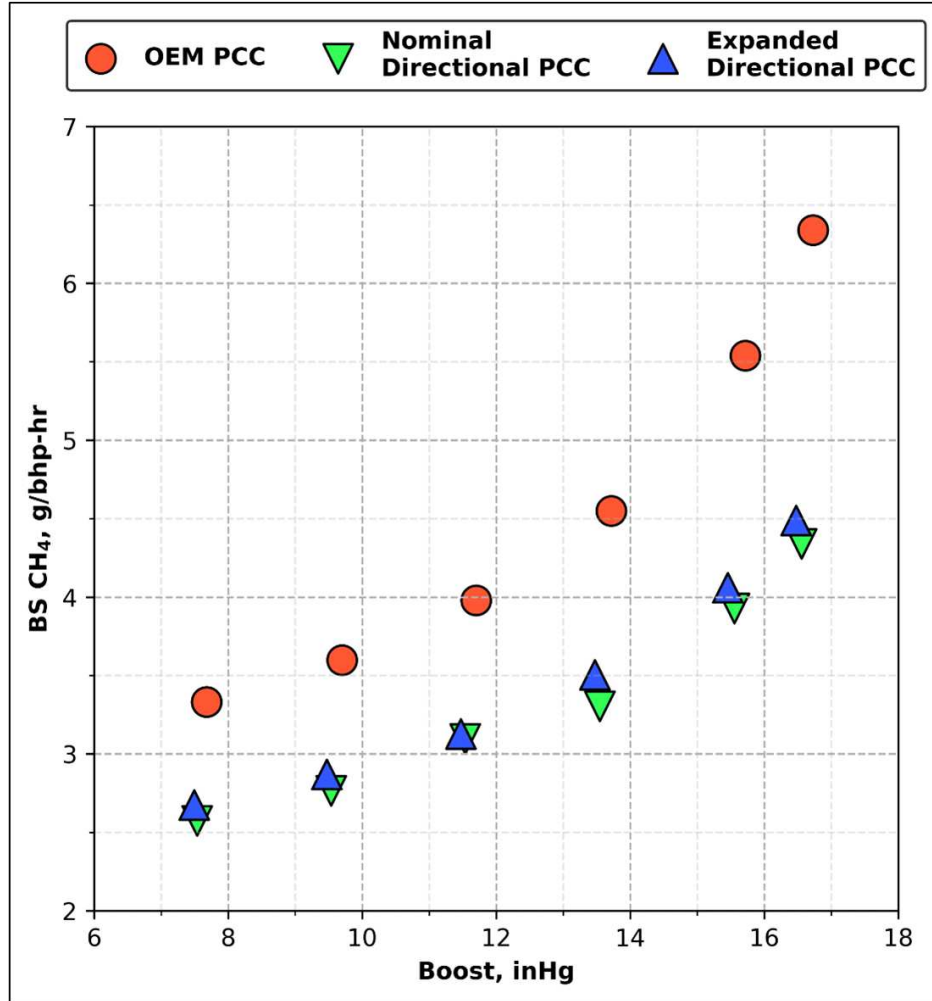


Figure 4.25: Break specific methane emissions for both the nominal and expanded PCCs over the boost sweep.

putational model, such as not including the piston-liner crevice volume, not knowing the trapped mass of fuel in the PCC, and tuning the model with engine averaged experimental data. Some of these liberties were taken to increase the computational speed of the model, such as not including the cylinder-liner crevice volume. Others were taken because they are unknown, like the trapped mass of fuel in the PCC. Another inconsistency is due to the inherent asymmetric cylinder performance caused by Cooper Bessemer's articulating connecting rod geometry. Only a single cylinder of the engine was modeled in CFD, but the experimental results are engine averaged.

Nitric oxides production and emission rose with both tested PCCs compared to the OEM, significantly at low boost pressure. A trade-off plot of the break specific nitric oxides and boost can be

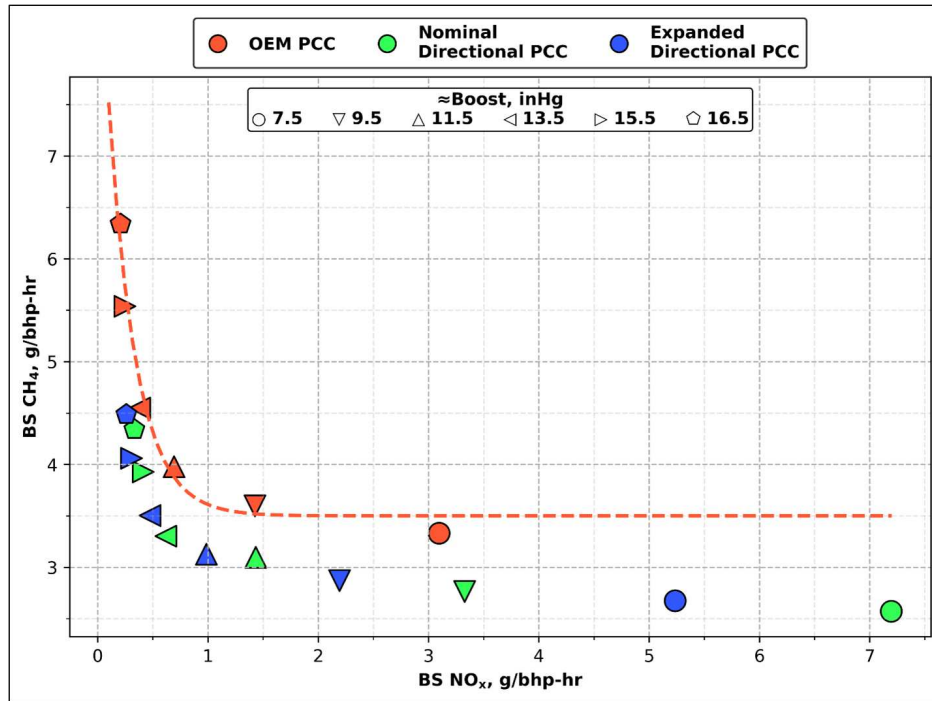


Figure 4.26: Break specific nitric oxides and methane trade-off plot for the nominal and expanded directional PCC designs along with the OEM. The orange dashed line represents the approximate curve of the OEM emissions.

seen in the appendix. Figure 4.26 details the break specific methane and nitric oxides emissions in a trade-off plot. The orange dashed line represents the approximate curve that the OEM emissions would follow at untested emission values. Overall, the nominal and expanded PCCs performed better than the OEM, regarding emissions. Any data point that falls below and to the left of the orange dashed line denotes better emissions performance—all of the nominal and expanded PCCs data points fell in this superior region. The data shows that if the engine is able to boost intake by an additional 2-3 inHg, the same nitric oxides emission level can be achieved while producing substantially less methane.

The emission levels for CO, carbon dioxide, and carbon dioxide equivalent can be seen in Figure 4.27. A reduction in carbon monoxide is shown in the top plot for all boost levels tested for both the nominal and the expanded directional PCCs over the OEM PCC. Because carbon monoxide is a product of incomplete combustion, a reduction would imply that there was an increase in combustion efficiency. In this case, the carbon monoxide would be converted into carbon dioxide

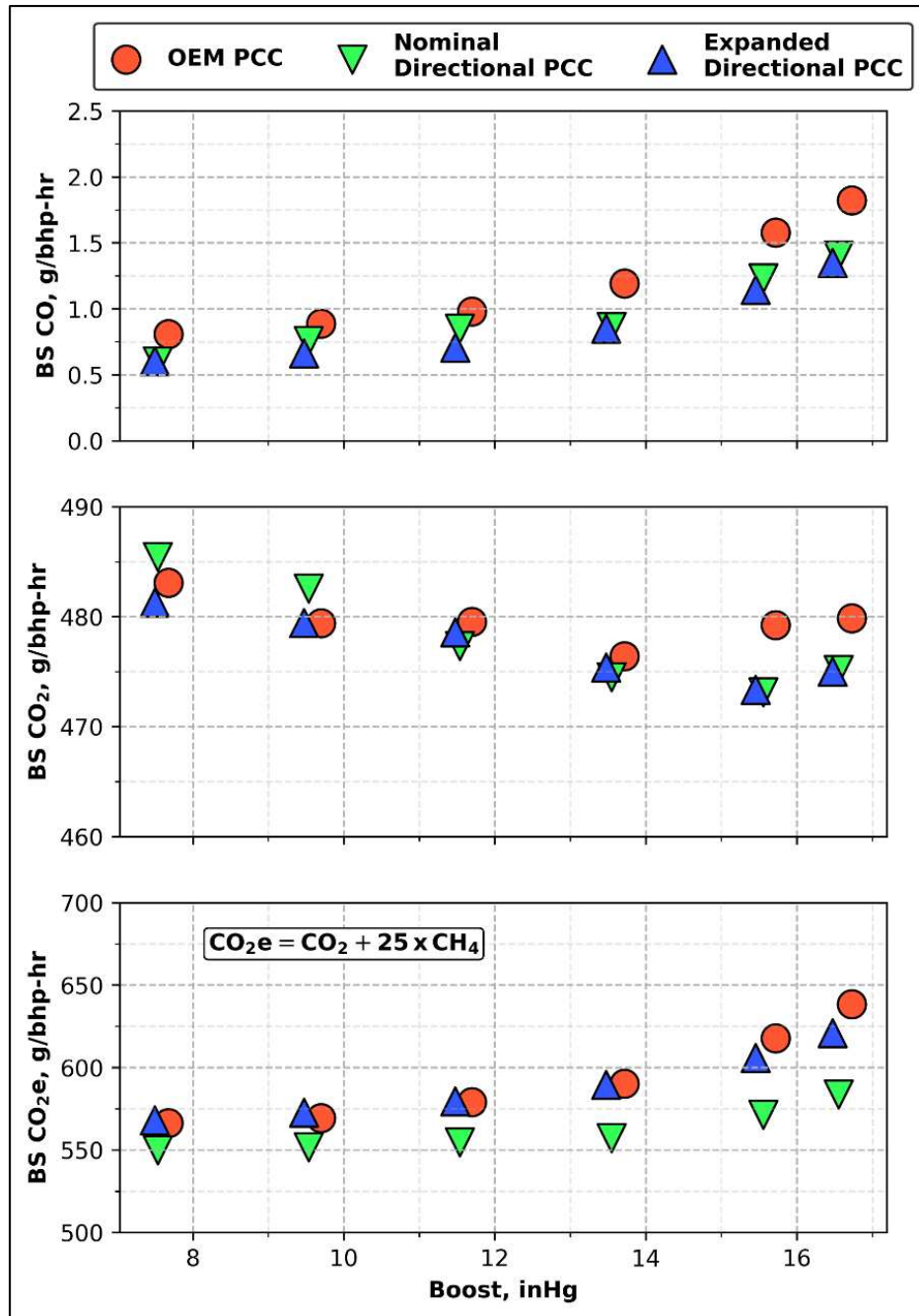


Figure 4.27: Break specific CO, carbon dioxide, and carbon dioxide equivalent emissions as a function of boost for the OEM PCC, the nominal PCC, and the expanded PCC.

and a similar increase would be expected. However, the data shows that there was a reduction in carbon dioxide for boost levels above 11 inHg and similar levels to the baseline for data below 11 inHg of boost. The methane emissions also show a decrease in output over the baseline, especially at the higher boost levels. A reduction in all four emissions, CO, carbon dioxide, carbon dioxide

Table 4.1: Directional PCC experimental percentage change in BSFC and BSEC over the OEM design.

Boost, inHg	7.5	9.5	11.5	13.5	15.5	16.5
Design	BSFC % Change from OEM					
Nominal PCC	0.00	0.00	-0.88	-1.74	-1.74	-2.59
Expanded PCC	-0.87	-0.88	-0.88	-1.74	-0.87	-1.72
Design	BSEC % Change from OEM					
Nominal PCC	-0.01	0.00	-0.68	-1.19	-2.23	-2.58
Expanded PCC	-0.55	-0.61	-0.67	-1.43	-1.12	-1.76

equivalent, and methane, can only be explained by examining the fuel flow rates (Table 4.1). In the nominal direction PCC data, the engine's fuel flow rate is very similar to the OEM PCC's for the two lowest boost levels. After those two levels, a reduction in both BSFC and BSEC is seen. Regarding the expanded directional PCC, reductions are seen in BSFC and BSEC across all boost levels. In these cases, the reduction in CO, carbon dioxide, carbon dioxide equivalent, and methane emissions is due to both an improvement in combustion stability and a lower amount of carbon in the fuel being used to produce the same power.

Figure 4.28 shows the boost sweeps MFB durations in CAD for each of the PCC designs. Both the nominal and the expanded PCCs showed an increase in combustion speed over the OEM PCC, with the expanded directional PCC being slightly slower than the nominal.

Engine coefficients of variance (COV's) also improved with the use of both the nominal and expanded PCCs. At the highest boost level assessed, the indicated mean effective pressure (IMEP) COVs dropped from about 2.6% to 2% using the nominal PCC and 2.25% with the expanded PCC. As boost pressure decreased, the COVs converged toward the same value. The peak pressure COVs, at the same boost level, dropped from 6.9% to 5.5% for both the nominal and expanded models. Even at lower boost pressures, over a 1% reduction is seen for the nominal PCC and just under 1% for the expanded PCC. Plots for IMEP COV and peak pressure COV versus boost can be found in Appendix C.2.

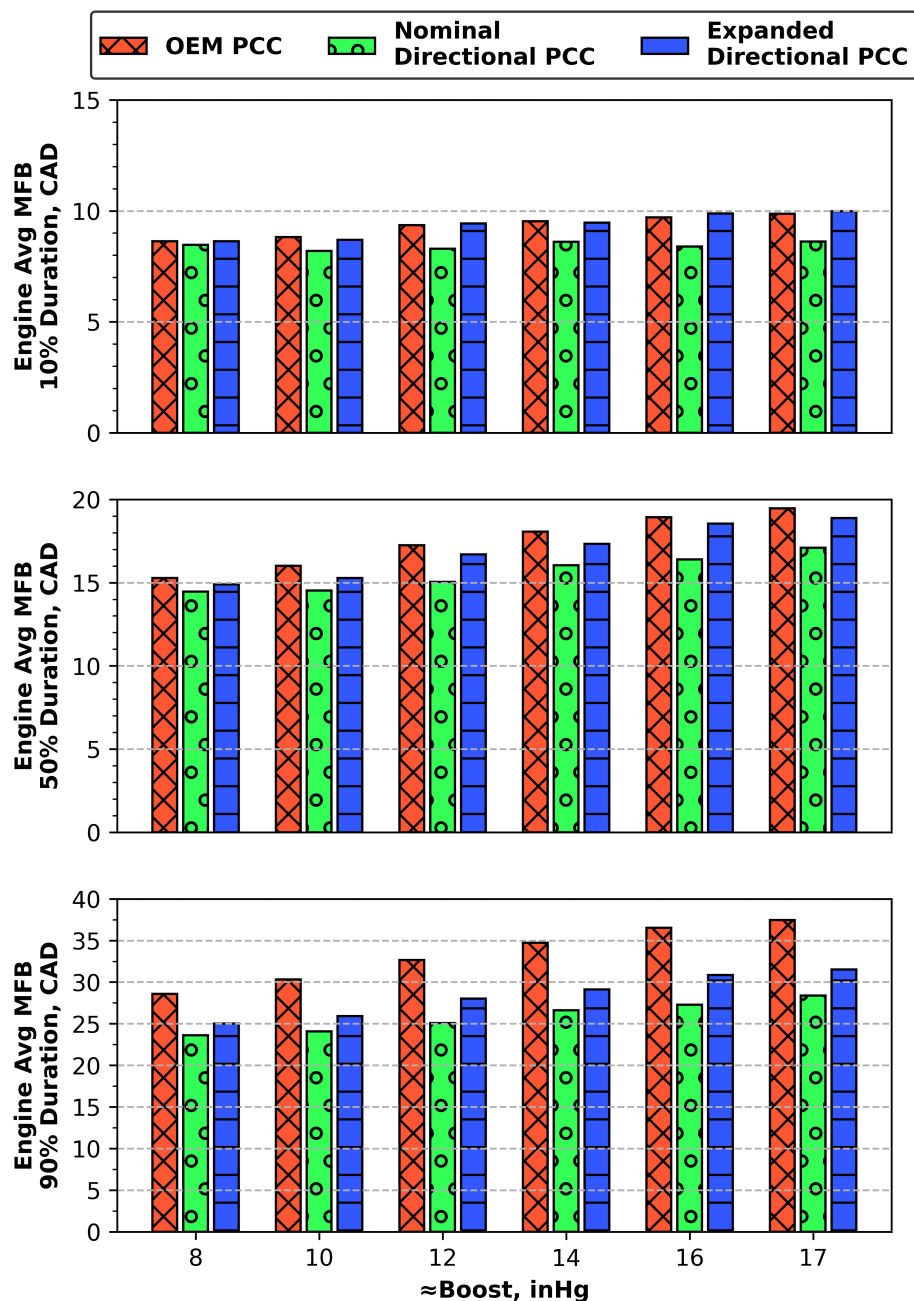


Figure 4.28: The MFB durations in CAD for each PCC tested during the boost sweep.

Varying the speed and load of the engine to its limiting operational conditions resulted in the brake-specific methane emissions plotted in Figure 4.29. Results show that, across all four test points, methane emissions were reduced with the nominal and expanded PCC designs over the OEM PCC. When operating at low load (LL), regardless of high speed (HS) or low speed (LS),

the engines methane emissions were reduced substantially—between 42% and 46% over the OEM PCC when using the nominal design and between 37.8% and 39% when using the expanded design. Even when operating at low speed and high load, methane emissions were reduced by 19.5% with the nominal PCC and 18.3% with the expanded PCC.

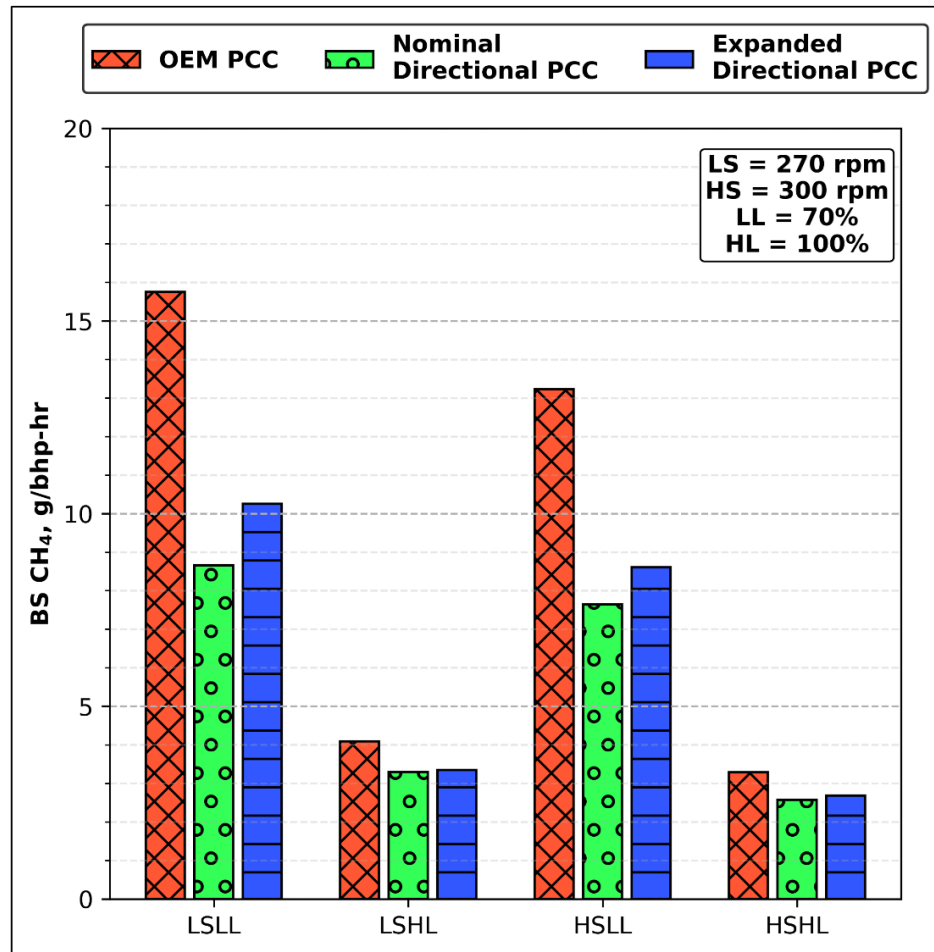


Figure 4.29: Break specific methane emissions for the 4-corner operating conditions.

Figure 4.30 shows the break specific methane and nitric oxides emissions for the 4-corner data points. Similarly to the boost sweep, both methane and nitric oxides emissions fell on the lower and left side of the approximate OEM PCC trace for both PCC designs, showing that. When the engine operates at high load conditions, a reduction in methane is seen but the increase in nitric oxides output outweighs that benefit. It is not until the engine operates at ultra-low nitric oxides

conditions that a performance benefit is seen. Low speed, low load operation saw brake-specific methane emissions drop from approximately 16 g/bhp-hr to 8.6 g/bhp-hr with the nominal PCC and 10.2 g/bhp-hr with the expanded PCC, but only a minor increase in brake-specific nitric oxides output. Similarly, high speed and low load operations saw brake-specific methane emissions drop from approximately 13.1 g/bhp-hr to 7.6 g/bhp-hr with the nominal PCC and 8.5 g/bhp-hr with the expanded PCC, but only a minor increase in brake-specific nitric oxides output.

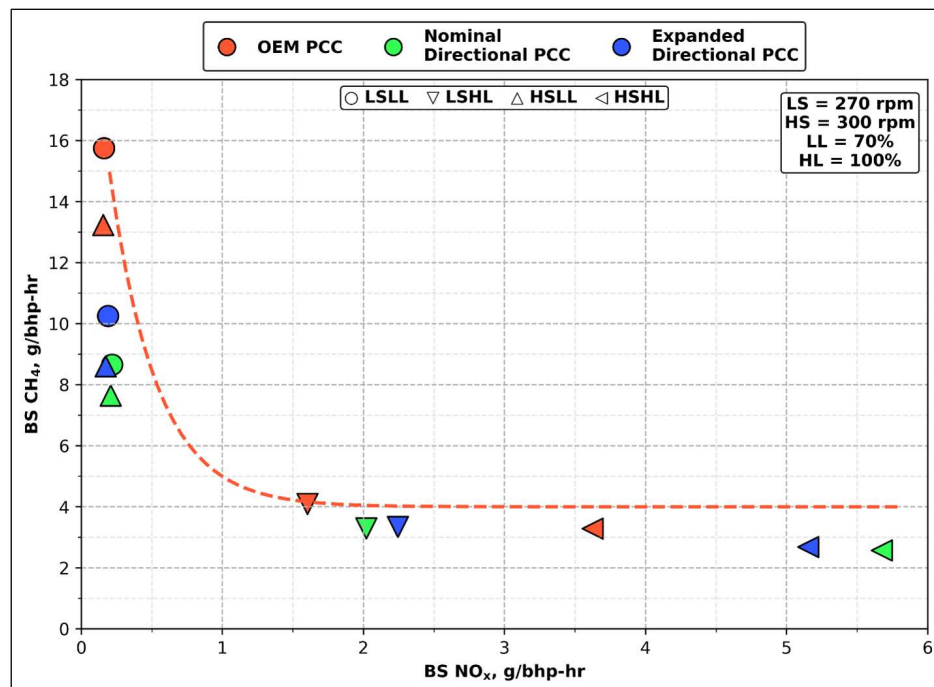


Figure 4.30: Break-specific methane and nitric oxides trade-off plot of the 4-corner data points.

COVs of IMEP² improved across all four data points over the OEM PCC with the use of both nominal and expanded PCC designs and can be seen in Figure 4.31. Peak pressure COVs can be seen in Appendix C.2 Experimental Data. Under high load operation, the expanded directional PCC saw the lowest COVs of the three tested designs, while the nominal design saw the greatest performance when at low load conditions.

²The IMEP is typically used as a reference for judging the stability of the engine. The COV of IMEP is used to analyze the cycle-to-cycle variability of the engines stability.

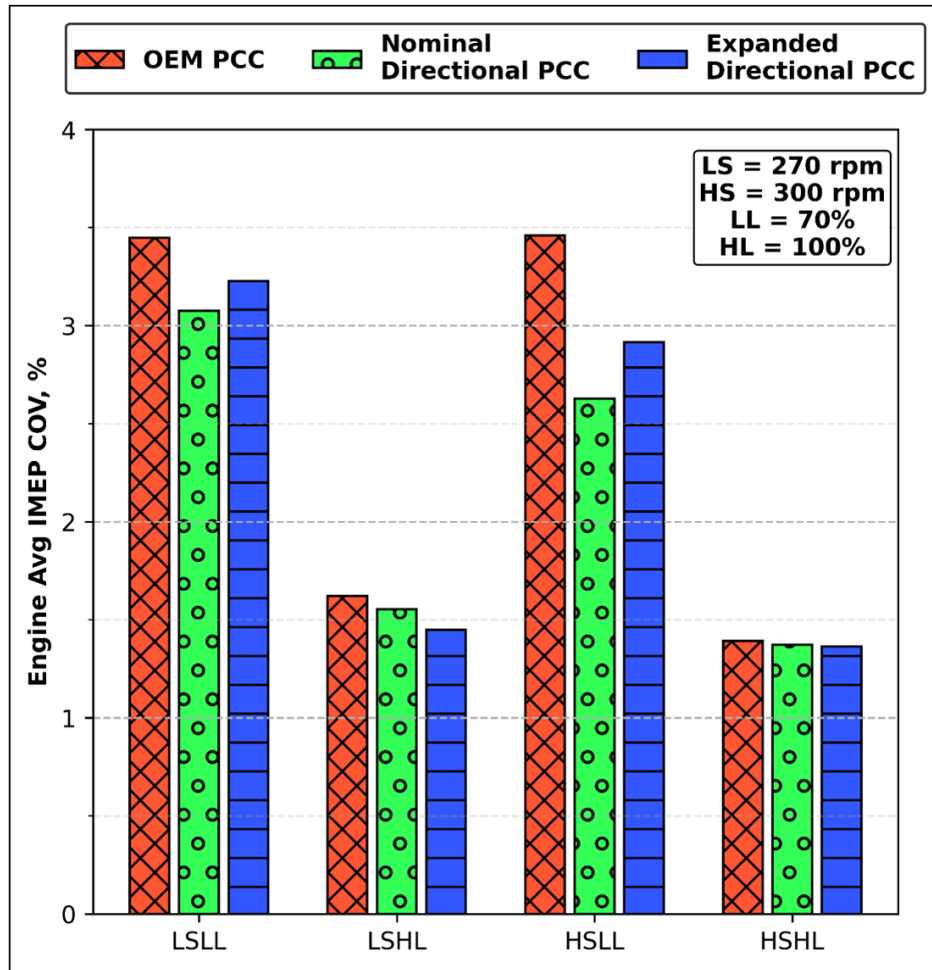


Figure 4.31: IMEP COVs for the nominal and expanded PCC designs for all 4 operating conditions.

4.4 Synthesis and Answers to Research Questions

The first question this portion of the research intends to answer is *Can combustion efficiency be increased by targeting pockets of unburned methane within the MCC utilizing PCC design?* Starting with the simulations of the novel PCC designs, improving combustion efficiency begins with either consuming more of the fuel, and therefore leaving less residual fuel, or by consuming the same amount of fuel, and therefore leaving similar levels of residual fuel, as the baseline case, but producing more power.

The simulation results indicated that the combustion intensity (measured by the average peak pressure in the MCC) for all of the novel designs was lower than the OEM. They also showed that combustion phasing was retarded compared to the OEM. Typically, this would imply a slower

developing flame kernel, but since the engine is using a PCC as the major ignition source, the MCC combustion phasing is really dependent upon the flame jet intensity coming from the PCC. So a retarded phasing of the pressure trace could be from either of these, but is mostly attributed to the flame jet intensity. These outcomes together indicate that if the amount of fuel consumed was the same as the OEM, then less power would have been produced—and that was the case for the “3orifice_1” and the “5orifice” designs. Both produced less power per cycle than the OEM, but they also consumed more fuel, meaning that the combustion efficiency of those two designs was lower than the OEM. The “3orifice_2” and “slot” designs, however, showed increases in power generated along with reduced methane emissions.

The answer to the previously posed question, then, is yes, hypothetically, the combustion efficiency can be improved by targeting pockets of unburned methane within the MCC utilizing PCC design. But this is hypothetical and must be tested under real conditions to test the validity of the design. The designs were based from the OEM PCC that produced its own unique flow fields and were simulated against only one cycle. Whether the novel designs would continue their improved performance when those residual methane pockets are no longer present is another issue.

Examining the experimental test results from the nominal and expanded directional PCCs to evaluate the combustion efficiency, the engine out emissions are evaluated. carbon monoxide is a byproduct of the combustion process when there is insufficient air for the reaction to take place, or, to put it another way, it is the byproduct of incomplete/partial combustion. If the charge inside the cylinder does not have sufficient air for the carbon monoxide to react with, and become carbon dioxide, then there is insufficient air for the fuel to react with as well, resulting in higher hydrocarbon emissions. Figure 4.27 showed that the carbon monoxide emissions dropped for both PCC designs and across all boost levels, implying an increase in combustion efficiency. Table 4.1 displays the change in BSFC and BSEC for each design at the tested boost levels, showing a decrease in most cases. Because the tests were run at a constant power output of 440 BHP, this reduction in fuel means that the engine, when using the directional PCCs, is making the same power as the OEM but consuming less fuel because of an increase in combustion efficiency.

The second question this research intends to answer is *How does PCC geometry affect methane emissions from a lean-burn, large bore natural gas engine?* The second portion of the directional PCC simulation research technique helps address this issue. The main purpose of the research was to optimize the methane reduction of the best performing design by varying certain parameters one at a time. The parameters to be altered were the angle and diameter of the nozzles and the volume of the PCC itself.

The cases investigating the angle of the nozzles showed that because of the shape of the piston head, when the angles between the nozzles were too narrow, the flame jets would simply be split by the piston crown. A portion of the flame would be confined to the inside of the bowl while the other is pushed toward the crevice volume. The portion of the flame that moves toward the crevice volume no longer has sufficient flow, and thus energy, to properly propagate around the cylinder walls as intended. The emission results showed an increase, slight albeit, in methane emissions but any increase would signify a less optimal design in this case. Nitric oxides emissions for both altered angle simulations were lower, significantly in one case. This is expected trade-off behavior—as fuel consumption decreases (producing higher methane emissions) a paired decrease in nitric oxides emissions is expected because of the lower cylinder temperatures. The “area 2” design, however, produced nearly 60% less than the original “3orifice_v2” design.

Figure C.1 in Appendix C.1 shows the locations of nitrogen dioxide inside the MCC and PCC near the highest point of concentration in the cycle, 20 °aTDC. The images, again, show the value blanked cells with a nitrogen dioxide mole fraction greater than $1e-5$. The volume is colored by mole fraction, with higher fractions being colored darker—black having the highest fraction. As can be seen, the bulk majority of nitrogen dioxide in the cylinder occurs around the cylinder’s periphery and at the top of the cylinder head, with the most nitrogen dioxide dense areas nearest the walls. With the bulk formation of nitrogen dioxide near the cylinder walls, it leads to the belief that as the angle between the nozzles decreases and the flame jets move to the inside of the piston crown that nitric oxides levels would drop. The flame inside the bowl would be following behind the middle nozzle’s flame jet, in its wake of combustion products, weakening as it continues and

ultimately merging with the middle flame jet or extinguishing altogether. This weakening and/or extinguishing conclusively results in lower temperatures, and thus, lower nitric oxides emissions.

Adjusting the volume of the PCC showed dramatic effects. The average pressure trace in the MCC increased when the volume was reduced, and the pressure trace dropped significantly when the volume was increased. With the small volume PCC, when combustion initiates, the pressure rises quickly, faster than the original design, and forces the flame jet into the MCC earlier in the cycle, effectively phasing combustion forward by nearly 5 CAD. This very intense combustion event led to nearly 12 times the residual methane that the original design produced. This is not true for the case where the volume was increased. The average MCC pressure trace and the AHRR were very similar in timing, but the adjusted case lacked intensity. This lack of combustion intensity is from the PCC volume being too large. When the volume is too large, the pressure in the PCC rises much slower and doesn't force the hot gases with the same velocity into the MCC, resulting in slow and weak combustion overall. However, the methane emissions it produced were just slightly more than the original design. Increasing the PCC volume showed promise and could be an area to be further studied and, more importantly, optimized.

Figure 4.28 showed a decrease in MFB durations (faster combustion) because of the smaller nozzles, and this is in direct agreement with the residual methane emissions shown in Figure 4.25. The expanded directional PCC showed methane emissions and MFB durations slightly higher than the nominal version—larger nozzles lead to slower flame jets and slower combustion, resulting in less efficient combustion and higher methane emissions.

The nitric oxides emissions followed the expected trend when increasing combustion efficiency — increases across all data points. In some cases, mainly those at low boost pressures, the increase in nitric oxides from the OEM PCC to the directional PCC was nearly 2.5 times. The faster oxidation of fuel results in more energy being released in a shorter amount of time. This energy takes the form of heat and increases the temperature in the MCC compared to the OEM. The majority of nitric oxides formed is thermal nitric oxides that occurs at high temperatures, and production becomes more frequent as the temperature increases.

Chapter 5

The Feasibility of Premixed Fuel and Air

Pre-combustion Chamber Injection

The following chapter details the results of the fuel and air premixing simulations and experimental results. First, characterization of the baseline combustion cycle will be made while comparing the homogeneously mixed PCC ideal simulation case. Second, the simulation results using low pressure PCC injection will be analyzed. Third will present the results of the high pressure simulation and experimental data points. Finally, the results from all simulated cases and experimental data points will be used to answer the research questions posed in Introduction.

5.1 Characterizing Combustion with a Homogeneous Mixture

Characterization of the GMV's combustion cycle is essential because it sets goal values for the experimental tests or simulations to meet or beat. A comparison of the simulation baseline case's trapped mass of fuel and air, along with the TER, will be made against the experimental data. Some basic combustion statistics, such as MCC pressure trace, AHRR, and the MFB locations, will be made to determine the validity of the baseline case. Finally, the most important and relative emissions (methane, nitric oxides, CO) will be presented. After the comparison of the baseline simulation and the experimental data, a comparison between the baseline simulation and the ideal simulation results will be exhibited.

Similarly to the experimental comparison, the baseline, and ideal case comparison will include basic combustion statistics, such as, spark timing and LoPP, MCC pressure traces, AHRR, and MFB durations. Emissions, defined as chemical residuals within the MCC and PCC at or near the EPO timing, will be shared with a possible explanation for any differences seen between the two.

Table 5.1 shows the calculated average mass per cycle per cylinder of air and fuel for the experimental and the trapped mass of air and fuel at the time of spark, for the baseline case, along

with the trapped equivalence ratio; all values are for the MCC. The TER was calculated for the experimental data using the perfect mixing model for the scavenging cycle. The mass of air in the PCC at the time of the spark is unknown, leading to an unknown actual equivalence ratio as well.

Table 5.1: Air and fuel mass per cycle values and trapped equivalence ratio for the experimental data and the CFD baseline case.

	Experimental Data (MCC/PCC)	CFD Baseline (MCC/PCC)
Air (g)	32.0/–	32.9/0.484
Fuel (g)	1.07/0.032	1.11/0.028
TER, ϕ	0.54/–	0.57/0.994

A comparison of the MCC pressure traces and MCC AHRR for the experimental data 1,000 cycle average and the CFD baseline can be seen in Figure 5.1. The pressure traces are a close match to each other, with peak pressures being within 0.02 MPa (3 psi) and the LoPP's being within about 1 crank angle degree (CAD). The AHRR profiles are similar and show that the timing of the combustion process is comparable between the two cases. The baseline case has a maximum calculated HRR of 2,779 J/CAD at 13.0 °aTDC, which is slightly higher than the experimental data set that shows a maximum calculated HRR of 2,633 J/CAD at 12.4 °aTDC.

Figure 5.2 shows the mass fraction burned locations, in CAD, for the experimental data and the baseline model. The 10% burn location (CA10) was the same for both cases at °aTDC. The 50% burn duration (CA50) was also the same for both cases at 15 °aTDC. There is a significant difference between the two cases for the 90% burn location (CA90), with the experimental data at 29 °aTDC and the baseline case at 47.5 °aTDC. This indicates that the fuel consumption and combustion processes are similar up to CA50, where the CFD baseline slows down compared to the experimental.

The emissions comparison between the experimental data and the CFD model can be seen in Table 5.2. The CFD baseline case values were taken from the MCC at 100 °aTDC, close to the CAD of the exhaust ports opening. The CFD case produced 256 ppm of residual methane, falling

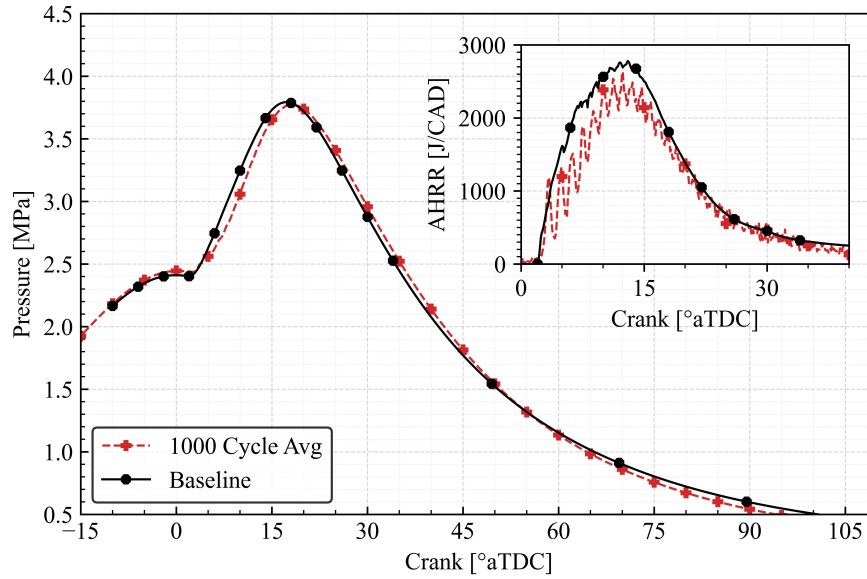


Figure 5.1: MCC pressure traces and apparent heat release rates for the experimental data 1,000 cycle average and the baseline CFD model.

short of the experimental output of 940 ppm. The CFD model was unable to produce results consistent with the experimental data nitric oxides production of 20 ppm—the CFD model produced 636 ppm.

Table 5.2: Experimental and CFD emissions

	Experimental Data	CFD Baseline
CH ₄ (ppm)	940	256
NO _x (ppm)	20	636
CO (ppm)	130	32

While accuracy of the model is one goal, another goal is to achieve an environment that is similar to the experimental conditions. By using the experimental data inputs, known geometry, and geometric movement, a similar environment was achieved. Several factors play into the accuracy of the model, including geometric tolerances (geometric mesh), computational grid size, assumptions (e.g., assuming a single-species diffusion coefficient versus multi-species), and the chemical mechanism. These examples, among others, influence the simulation and lead to disparities in the

outputs. It was decided that even though this model was not accurate, it was sufficient to move forward with, using it as a baseline, in the following CFD investigation, because it can be considered precise and would produce reasonable trends to study. The amount of residual methane, while low compared to the experimental, was adequate to show relative comparisons between tested cases and could show trends.

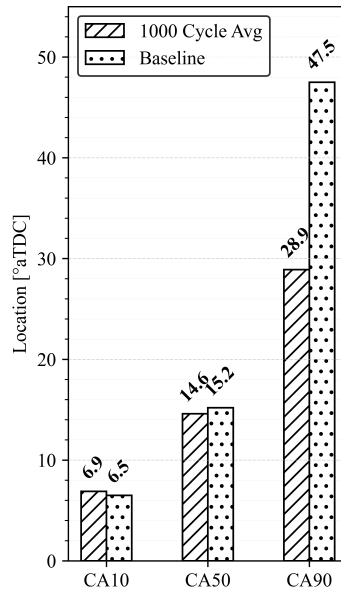


Figure 5.2: Mass fraction burned crank angle locations for the experimental data and the baseline.

The only parameter matched between the baseline and ideal cases was the LoPP. The baseline case had a spark timing of 4 °bTDC, and to keep the LoPPs similar, the ideal case’s spark timing was retarded to 2.8 °bTDC. Both cases shared the same spark energy input and spark duration. Figure 5.4 illustrates a comparison of the pressure traces and the apparent heat release rates for both cases.

The pressure traces differ in peak pressure magnitudes. The ideal case’s peak pressure was 3.66 MPa (530 psi), while the baseline case’s peak pressure was 3.79 MPa (549 psi). This resulted in a 1.3% reduction in power output. The apparent heat release rate profiles are similar, with both simulations showing the same location (CAD) of initial AHRR rise, indicating a faster flame kernel

growth in the ideal case. The slope of the trace in the ideal case is slightly lower than the baseline, causing a shift to the right (later in the cycle) by a couple of degrees.

Similarly, a comparison of the 10%, 50%, and 90% mass fraction burned (MFB) durations can be seen in Figure 5.3. MFB10, commonly referred to as the ‘ignition delay,’ for the baseline case was 11.3 CAD, while the ideal case was shorter at 9.8 CAD. Similar trends can be seen for MFB50 and MFB90. Combustion duration, defined as the difference between MFB90 and MFB10, was comparable for the ideal and baseline cases at 40.0 CAD and 40.7 CAD, respectively.

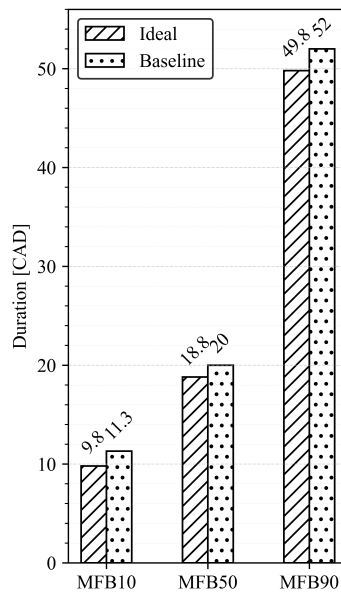


Figure 5.3: Mass fraction burn durations in CAD for the baseline and ideal CFD cases.

This behavior can be explained by examining the PCC equivalence ratio for each simulation in Figure 2.17 again. The ideal case, as intended, has a very uniform equivalence ratio of 0.97 throughout much of the PCC volume, while the baseline shows stratification. The baseline case has a rich pocket near the spark plug that is close to approximately 1.1, meaning that the flame within the baseline’s PCC starts growing quickly. This rapid flame growth (kernel growth) promptly slows down as it makes its way through the different equivalence ratio pockets. Because some pockets have a very low equivalence ratio (0.5-0.6), the flame slows down drastically. Comparing this to

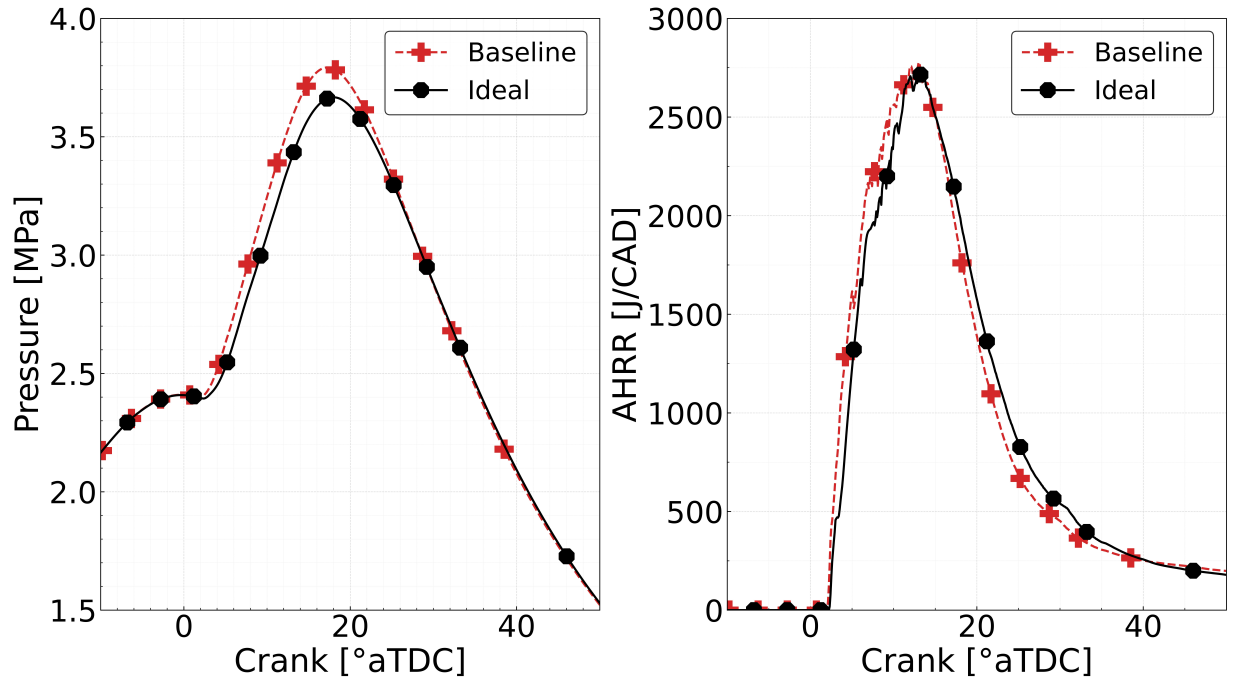


Figure 5.4: A comparison of the pressure traces and apparent heat release rates of the baseline and ideal cases.

the ideal case where there is no stratification, the flame is free to propagate at a relatively high speed and consistently stay at that higher speed, translating to the flame jet exiting the PCC and entering the MCC, leading to a lower MFB10 duration.

This can also be explained by analyzing the hydroxyl (OH) radical production rate and total mass transfer between the PCC and the MCC. From -6 °aTDC to 102 °aTDC, the ideal case produced approximately 17.3% more OH than the baseline in the PCC. The ideal case also transferred approximately 41% more OH radicals from the PCC into the MCC over the same period. Because the OH radical is a precursor to combustion (flame continuance), the additional OH radicals help promote faster flame growth inside the MCC.

Looking at the emissions (residuals in the MCC just before exhaust ports open) in Figure 5.5, carbon dioxide residuals for each case are nearly identical. Residual methane and nitric oxides fell in the ideal case.

nitric oxides emissions fell with the baseline producing 3.74 g/bhp-hr and the ideal producing 3.47 g/bhp-hr. Figure 5.6 mass of nitric oxides produced as a function of crank angle. Much of the

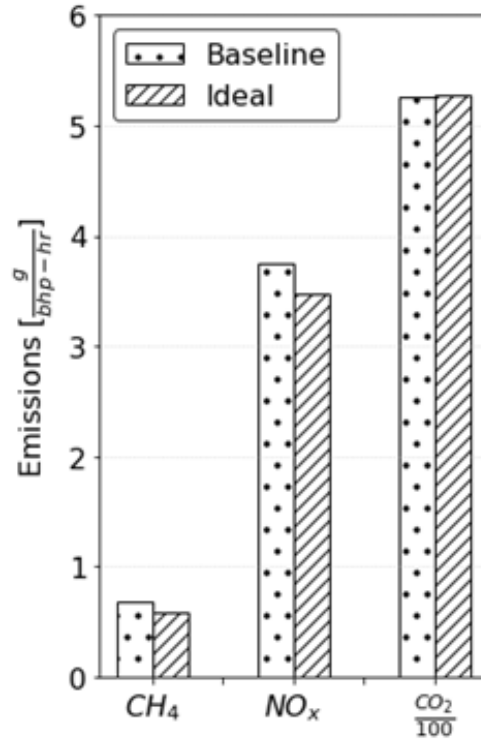


Figure 5.5: Mass fraction burn durations in CAD for the baseline and ideal CFD cases.

nitric oxides produced in the cycle came from the Zel'dovich mechanism (also known as thermal nitric oxides). Thermal nitric oxides dominates in high-temperature combustion ($> 1,500$ K) and was the reason for the sharp incline in nitric oxides from approximately 10°aTDC to 25°aTDC . This period coincided with the hottest part of the combustion cycle (portions of the MCC $> 2,500$ K). Both cases saw similar maximum temperatures in the MCC between $2,500$ K and $2,560$ K. Because the maximum temperatures were similar but the mean temperature in the baseline case was higher, this implies that a larger portion of the baseline MCC, than the ideal case, was hotter and therefore, produced higher levels of thermal nitric oxides than the ideal case.

Brake specific methane emissions dropped in the ideal case by 18% due to the faster flame speed. The baseline case produced 0.68 g/bhp-hr, whereas the ideal case produced 0.57 g/bhp-hr. Even though the fuel consumed was higher in the ideal case, the reduction in power caused the BTE to be lower.

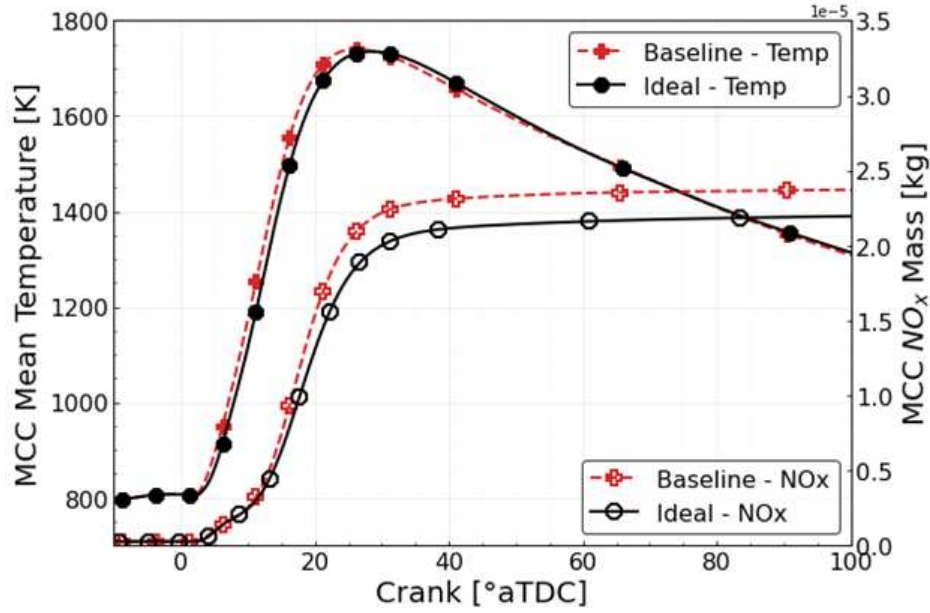


Figure 5.6: A comparison of the baseline and ideal case simulations MCCs mean temperatures and total nitric oxides production as a function of crank angle.

5.2 Analyzing the Effect Premixed Injection Has with Low Pressure Injection

In this section the low pressure fuel injection simulation case results will be presented. The inner flow dynamics and mixture stratification of the PCC will be revealed, followed by how the PCC nozzles impact the MCC flow fields. Combustion statistics, pressure traces, TKE, and emissions will also be disclosed.

Table 5.3: Low pressure injection simulation case fueling parameters

Injected ϕ	AFR	Mass Flow Rate, ($\frac{kg}{s}$)	Avg ϕ @ Spark (MCC/PCC)	PCC ϕ Std. Dev. @ Spark (σ)	PCC Trapped Fuel Mass (% to Baseline)
Baseline (Fuel Only)	–	0.00359	0.57 / 0.99	0.11	100
1.5	11.3	0.04398	0.58 / 0.83	0.04	87.1
4.34	4.7	0.01687	0.57 / 1.05	0.08	106.2
7	2.9	0.01044	0.57 / 1.15	0.11	113.4

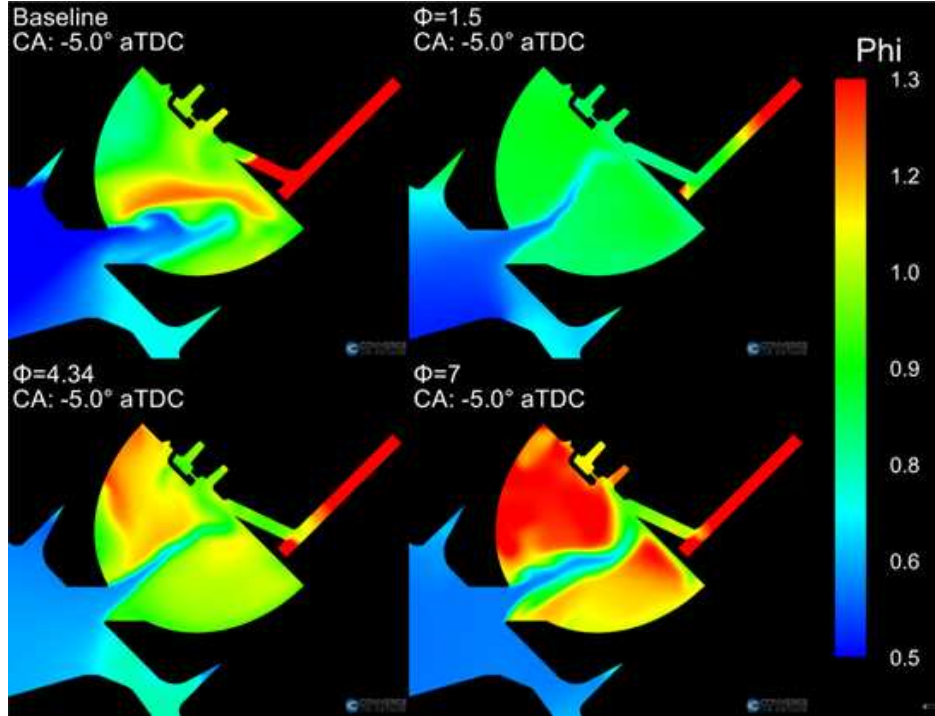


Figure 5.7: A slice through the PCC showing the phi distribution for each simulated case just before spark.

The equivalence ratio distribution through a single slice of the PCC for each premixed injection case can be seen in Figure 5.7. The $\phi=1.5$ case shows the most homogeneous mixture within the PCC right before spark, while the $\phi=7$ case shows the most stratified PCC volume. The average PCC equivalence ratio just before spark is shown in Table 5.3 along with the standard deviation for each case.

While the $\phi=1.5$ case had the most homogeneous mixture ($\sigma = 0.04$), its average PCC phi, 0.83, fell short of the ideal value range of 1.0–1.1. This stems from the injected charge being diluted from air pushed into the PCC by the piston motion. At an injection $\phi=1.5$, there was not enough fuel injected, leaving a trapped mass of fuel of only 87% that of the baseline.

The $\phi=7$ case showed the opposite results. The average phi in the PCC was 1.15 with a standard deviation of 0.11. This premixed injection showed no improvement in mixing over the baseline. This shows the level of effect the mass transfer from MCC to PCC, as the piston moves upwards, has on the PCC stratification. At this injected phi, the trapped mass of fuel in the PCC was 13% higher than the baseline (leading to the higher average phi).

The case where a $\phi=4.34$ was injected resulted in the most ideal average phi of 1.05, which would allow for the fastest flame propagation. It also resulted in a standard deviation of 0.08, which was about a 27% improvement over the baseline. The trapped mass of fuel in the PCC was approximately 6% over the baseline.

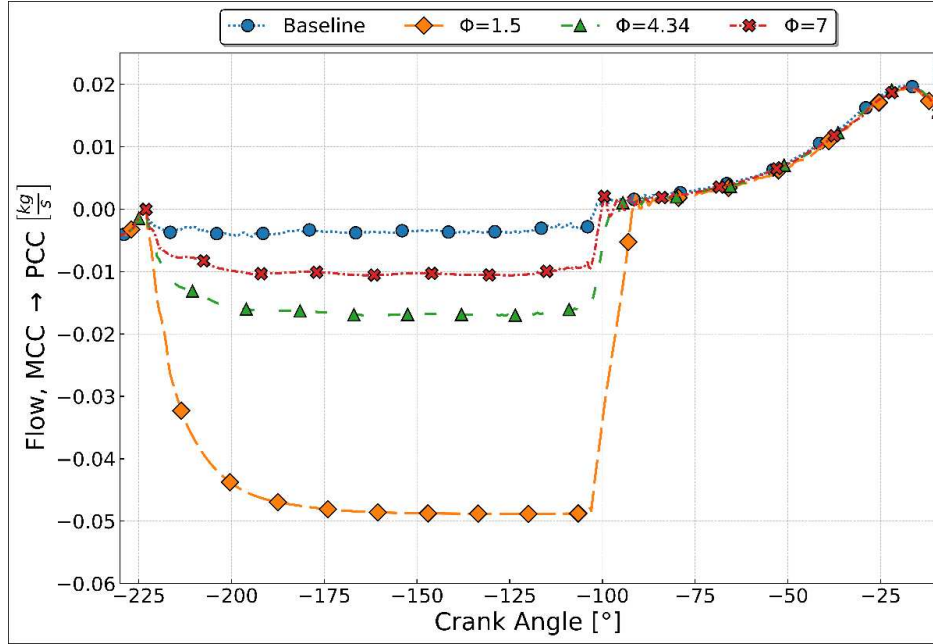


Figure 5.8: Mass transfer rates from the MCC to the PCC during fueling.

The mass transfer rates from the MCC to the PCC can be seen in Figure 5.8. A positive value indicates transfer from MCC to PCC, while a negative value indicates transfer from PCC to MCC. As stated earlier, as the premixed charge decreased in equivalence ratio, the mass flow rate increased, leading to significantly overcharging the PCC. The $\phi=1.5$ case had the largest transfer, as expected, at approximately 13 times that of the baseline's rate. As the injected mixture became richer, the mass transfer lessened.

Not only does the PCC-to-MCC mass transfer rate affect the stratification in the PCC, it also completely changes the flow fields in the MCC. Figure 5.9 shows the difference between the baseline and $\phi=4.34$ flow fields in the MCC and PCC. The $\phi=4.34$ cases mass transfer is so high that an eddy is created towards the center of the MCC, whereas the baseline case has smooth flow.

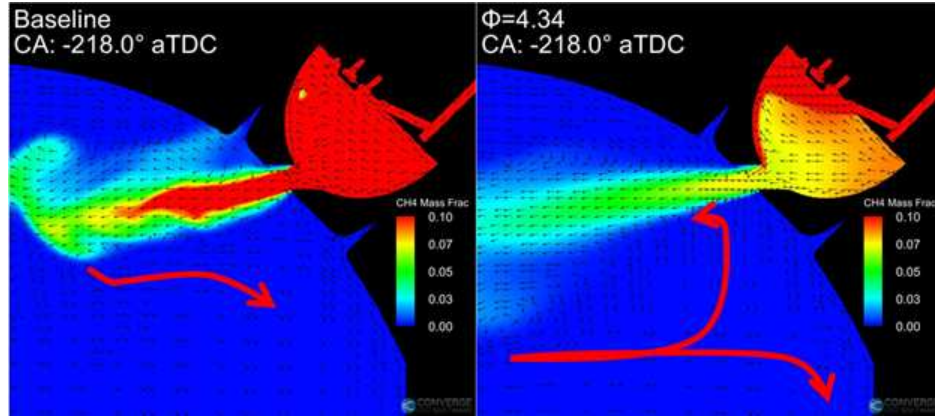


Figure 5.9: A comparison through a plane in the model of the flow fields in the MCC and PCC just after PCC ignition begins.

This change in flow direction and magnitude wholly modifies the flame progression, MCC mixing homogeneity, and combustion overall.

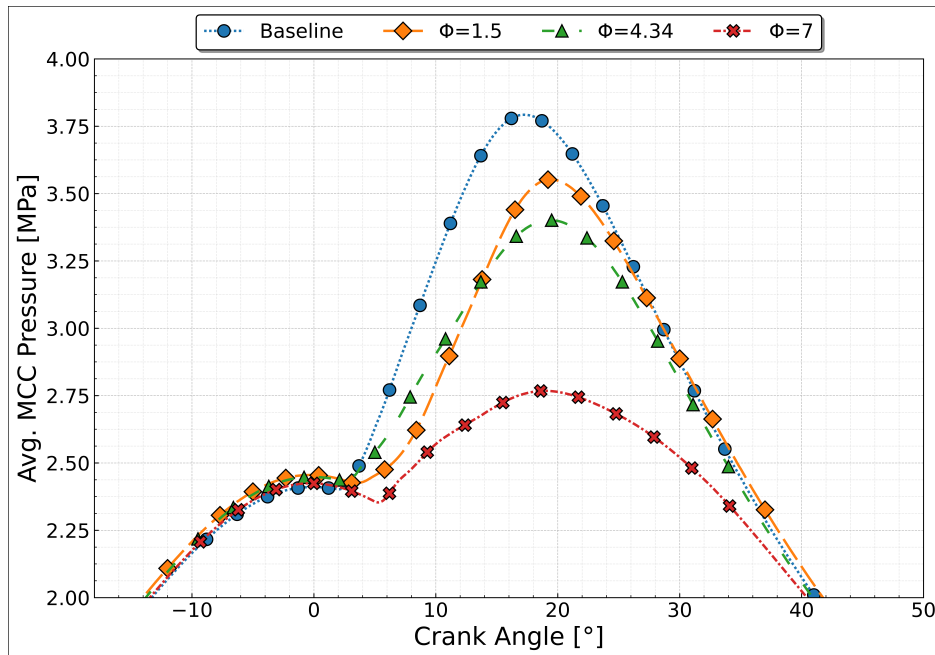


Figure 5.10: Average MCC pressure trace for the baseline and each simulated premixed case.

The resulting pressure traces can be seen in Figure 5.10. Each premixed simulation led to a weaker combustion cycle than the baseline. As the premixed charge became richer, the combustion

became worse, producing less power (shown later). The $\phi=7$ case had such a weak combustion cycle that it would be considered a misfire.

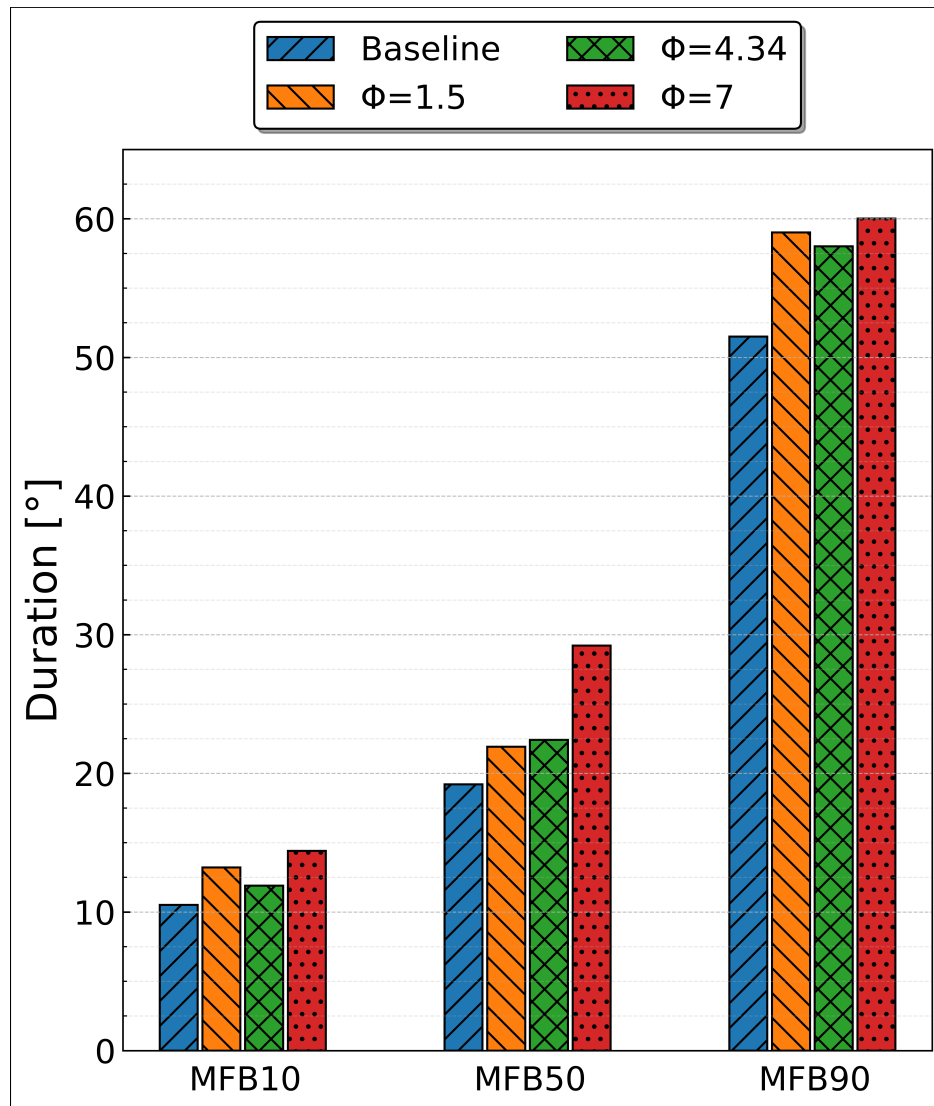


Figure 5.11: MFB10, 50, and 90 durations in CAD.

Looking at the MFB durations for each simulation (Figure 5.11) shows that each case had slow fuel consumption. The $\phi=4.34$ case, while still slower than the baseline, produced a shorter MFB10 and MFB90 than the $\phi=1.5$ case because of the ideal phi in the PCC (faster flame speed). The MFB50 durations for both cases were very similar.

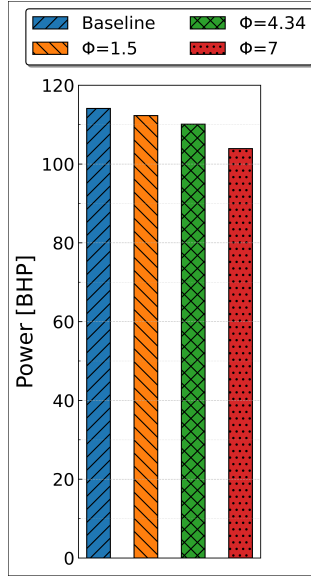


Figure 5.12: Brake horsepower output for each premixed simulation.

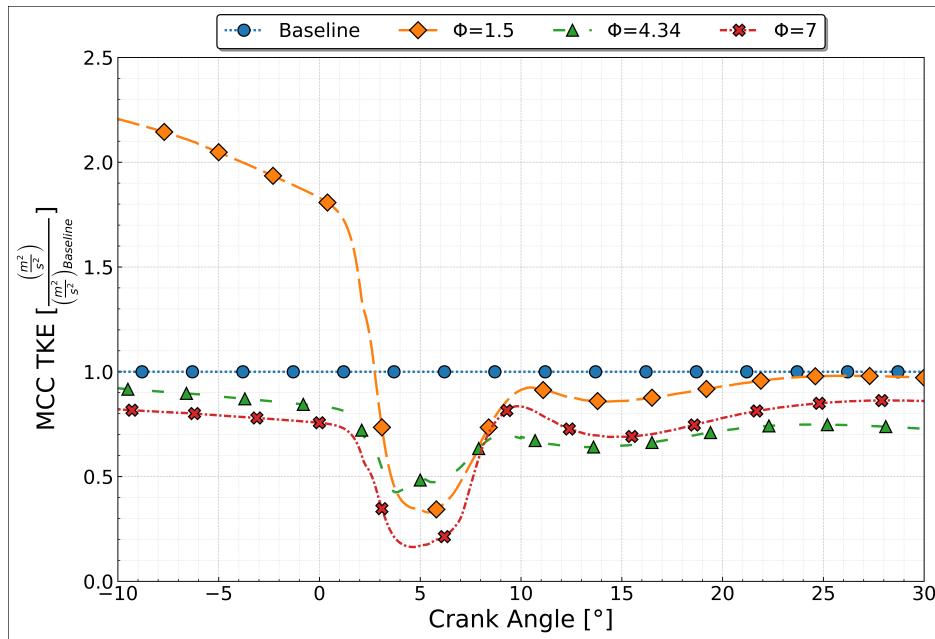


Figure 5.13: A comparison of the MCC TKE for each simulation normalized to the baseline TKE level.

The brake horsepower output (using a constant brake efficiency from experimental data) for each simulation can be seen in Figure 5.12. The baseline produced 114 bhp, the $\phi=1.5$ case produced 112 bhp, the $\phi=4.34$ case produced 110 bhp, and the $\phi=7$ case produced 104 bhp. The reduction in power for all cases, coupled with the constant mass of fuel injected, implies that the BTE decreases for all cases.

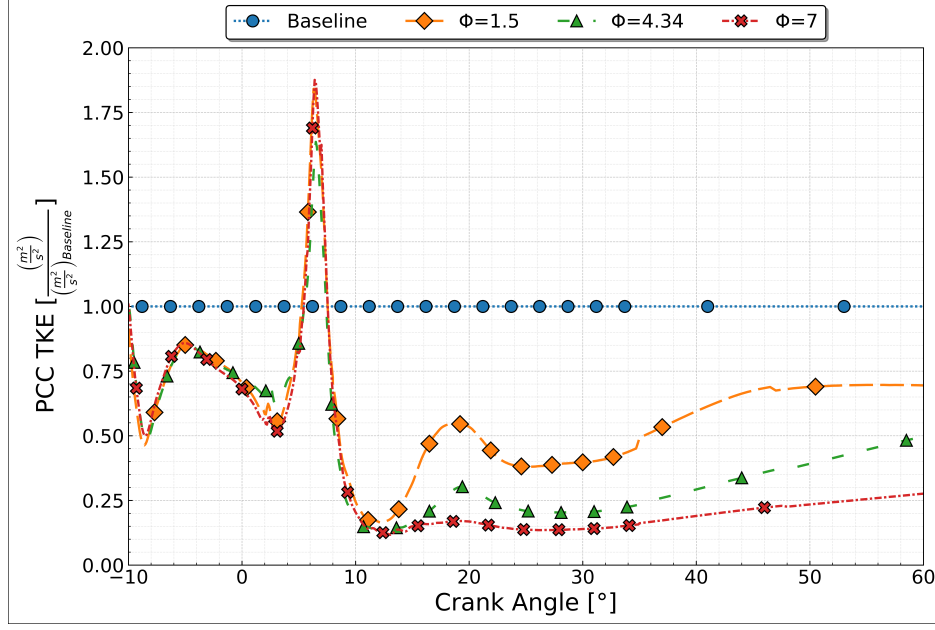


Figure 5.14: A comparison of the PCC TKE for each simulation normalized to the baseline TKE level.

The percent of TKE in the MCC and PCC over the baselines TKE during combustion for all cases can be seen in Figure 5.13 and Figure 5.14. The PCC TKE for all premixed injection cases starts at about 85% of the baseline value, at time of spark. The TKE falls while the flame kernel is growing. Once the flame is properly formed and starts to propagate rapidly, the TKE spikes also rapidly for all cases and then immediately falls to approximately 15-20% of the baseline and stays low for the duration of combustion. As turbulence is a major influence on flame speed, the low TKE's support relatively slow flame growth and propagation. The weak PCC TKE also spreads to the MCC. TKE in the MCC for all cases is very low compared to the baseline after spark. The reduction in TKE ranges from approximately 50-80% of the baseline roughly 10°CA after spark and then rises slightly for all cases but still below the baseline levels. Note that the TKE in the MCC for the $\phi = 1.5$ is around twice the levels of the baseline before spark because of the high transfer rate between the MCC and PCC.

The slow and poor combustion for each premixed simulation resulted in high brake specific methane emissions (Figure 5.15). The baseline produced 0.71 g/bhp-hr of methane while the $\phi=1.5$

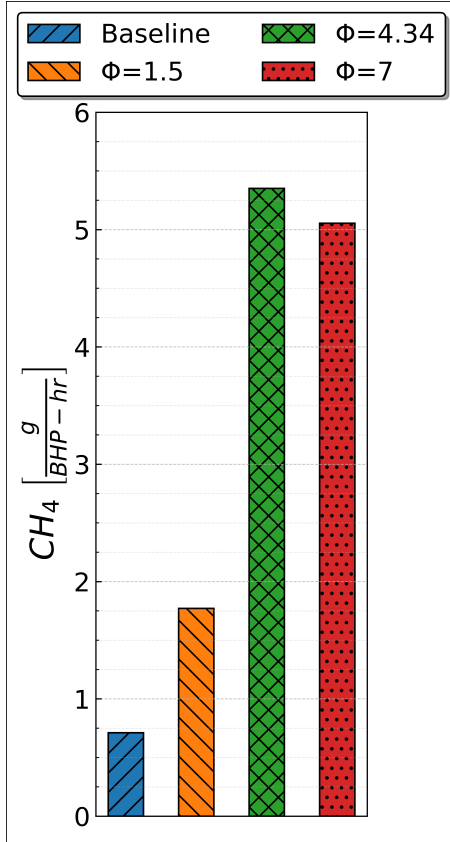


Figure 5.15: Brake specific methane emissions taken from the MCC just before EPO.

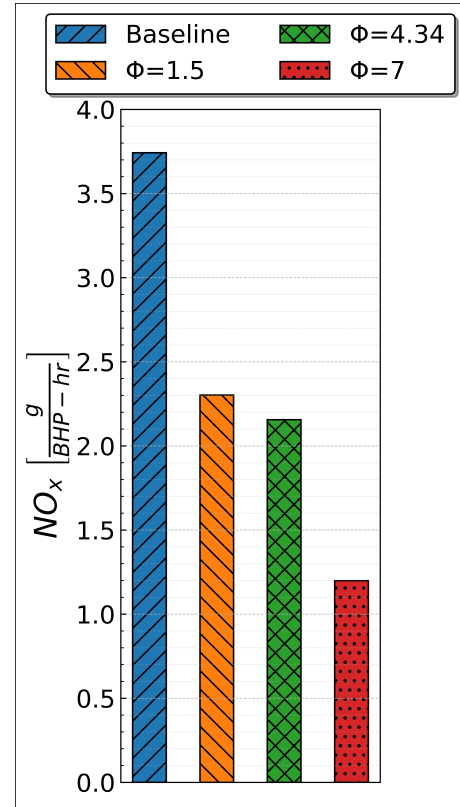


Figure 5.16: Brake specific nitric oxides emissions taken from the MCC just before EPO.

case saw a 250% increase (1.77 g/bhp-hr), $\phi=4.34$ case saw a 750% increase (5.35 g/bhp-hr), and the $\phi=7$ case saw a 711% increase (5.05 g/bhp-hr).

The brake specific nitric oxides emissions, shown in Figure 5.16, were much lower for each pre-mixed case compared to the baseline because of the reduced fuel consumption. This reduction in fuel consumption led to lower in-cylinder temperatures which led to lower nitric oxides formations and emissions.

5.3 Analyzing the Effect Premixed Injection Has with High Pressure Injection

Both the experimental testing and the high pressure injection simulations are presented below. The simulated cases mimicked an injection pressure around 150 psi (1.03 MPa) while the experimental injection pressure varied between 120-135 psi (0.827-0.930 MPa), both of these being significantly higher than the approximately 58 psi (0.4 MPa) used in the low pressure injection simulations. The simulation results will be presented first and the equivalence ratio inside the MCC and PCC will be discussed along with the trapped mass of fuel in the PCC. The MCC and PCC pressure traces will be briefly covered. Finally, an explanation for the results will be considered. The experimental results will be revealed including combustion statistics, pressure traces, AHRR's, and relevant emissions.

Table 5.4: Resulting parameters from simulated high pressure premixed injection cases.

Injected ϕ	AFR	Avg ϕ @ Spark (MCC/PCC)	PCC ϕ Std. Dev. @ Spark (σ)	PCC Trapped Fuel Mass (% to Baseline)
Baseline (fuel only)	–	0.57/0.99	0.11	100
1.1	15.9	0.51/0.69	0.05	74.5
1.5	11.6	0.51/0.86	0.08	90.8
2	8.7	0.52/1.05	0.12	110.0
2.5	7.0	0.52/1.23	0.17	127.9
3	5.8	0.52/1.31	0.22	135.5
7	2.5	0.53/2.60	0.64	248.6

The high-pressure models mimicked an injection pressure of 150 psi (1.034 MPa), an SOI of 100 °bTDC, and an injection duration of 60°CA. The injection timing and duration were arbitrarily chosen but were moved later in the cycle with the intention that more of the injected fuel would stay within the PCC volume but with enough time to promote good mixing before spark. The EOI, or duration, was chosen to be at the very latest possible timing (PCC fuel injection pressure is slightly higher than the cylinder pressure). As a first iteration of the model, the injection pressure,

SOI, and injection duration were identical for all cases. Injected equivalence ratios of 1.1, 1.5, 2, 2.5, 3, and 7 were simulated.

Table 5.4 shows the resulting MCC and PCC average equivalence ratios, the PCC ϕ standard deviation, σ , and the percentage of trapped fuel mass in the PCC. Similar behavior with the trapped mass of fuel and standard deviations are seen as the low-pressure simulations showed. The lower the ϕ injected, the lower the standard deviation of ϕ inside the PCC volume. The trapped mass of fuel in the PCC volume fell short of the baseline for the $\phi=1.1$ and $\phi=1.5$ cases at 74% and 90%, respectively. These two cases were the only simulations that produced a more homogeneous mixture in the PCC than the baseline – all others had a higher standard deviation of ϕ and more trapped fuel in the PCC.

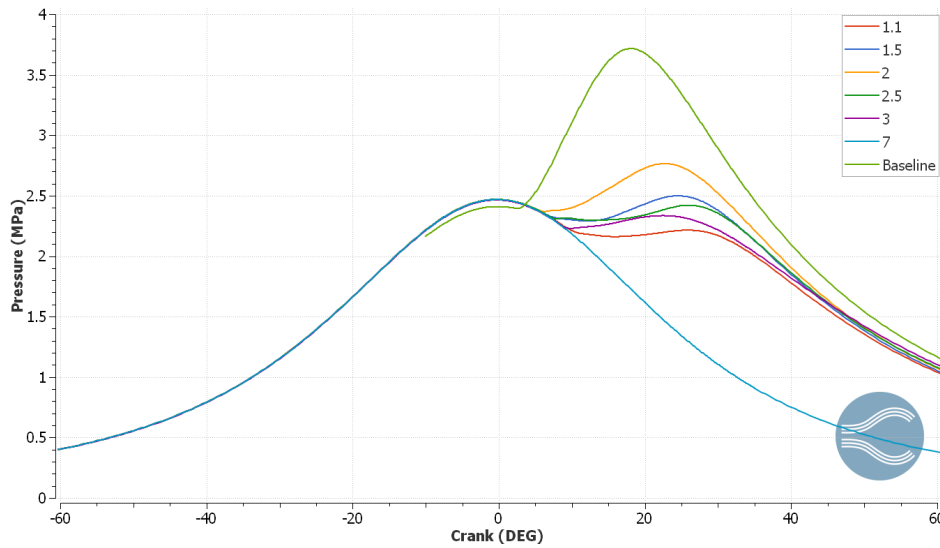


Figure 5.17: MCC pressure traces for the high pressure injection simulation cases.

Figure 5.17 shows the resulting pressure traces for the simulated cases against the baseline case. All of the test cases resulted in very weak combustion with the $\phi=7$ case being a complete misfire. Looking at Figure 5.18, the PCC pressure traces, shows similar behavior and the reason for the poor MCC combustion. Because the PCC acts as the ignition source of the MCC, when there is weak combustion or flame kernel development and growth inside the PCC it translates to the MCC having weak combustion as well.

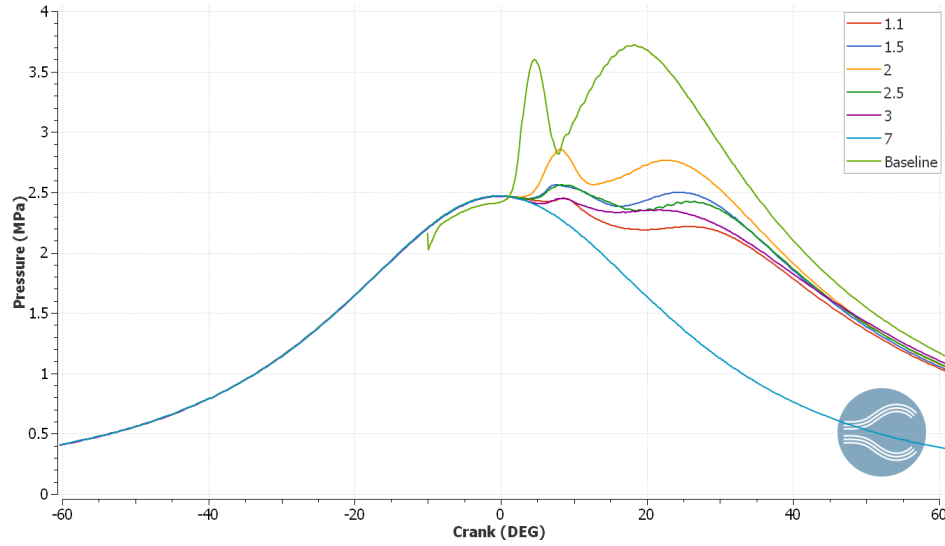


Figure 5.18: PCC pressure traces for the high pressure injection simulation cases.

Both plots show that the best performing case was the injected ϕ of 2. After PCC dilution (Table 5.4) from the piston motion, the average ϕ in the PCC is within the ideal range of 1.0-1.1, with a similar standard deviation to the baseline. All other cases did not perform as well and showed even weaker combustion. The baseline case and the $\phi=2$ case had very similar PCC conditions to each other but the baseline had much stronger combustion in the PCC. The weak combustion was found to be caused by the velocities near the spark plug at the time of ignition.

Figure 5.19 shows a single slice through the PCC body that is placed in between the spark electrodes. The PCC fuel injection line, spark plug cover, and electrodes are rendered in a semi-transparent state to show the location of each component in relation to the velocity flow field. The red arrow denotes the flow direction of the injected fuel (the flow is also at a slight downward angle, which is into the paper, of approximately 25°); the red line in front of the arrow denotes the approximate edge between the spark plug cover and the top of the PCC volume, and the red circle showcases the electrode gap, which extends into and out of the paper. There is also a small grey rectangle to the right of the electrode gap on each model, which is the spark plug's bottom electrode arm cutting through the plane.

A layer of tangential velocity vectors has been overlaid to show the general flow regime within the slice. Because the velocity vectors are tangential, they do not show the movement into or out

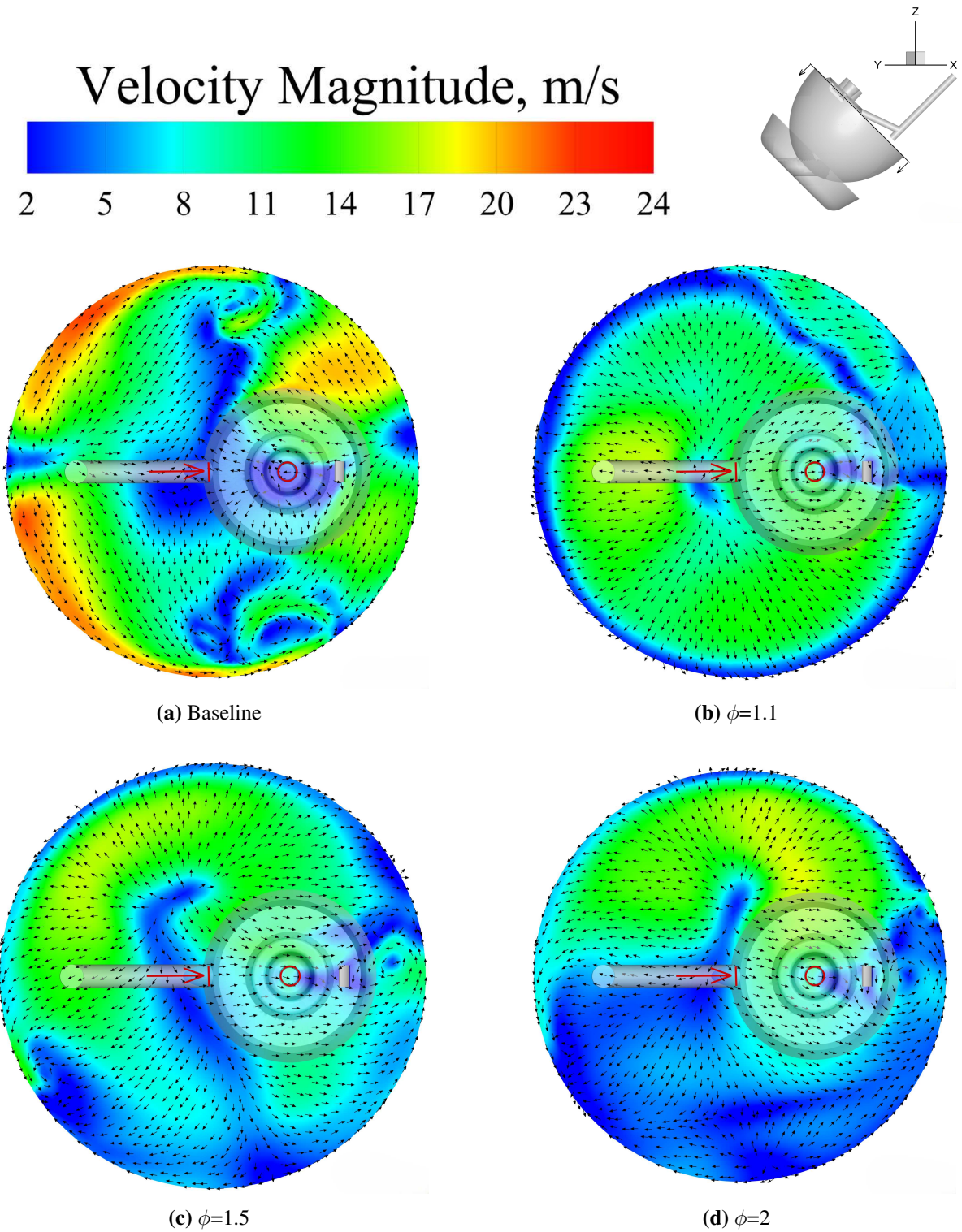
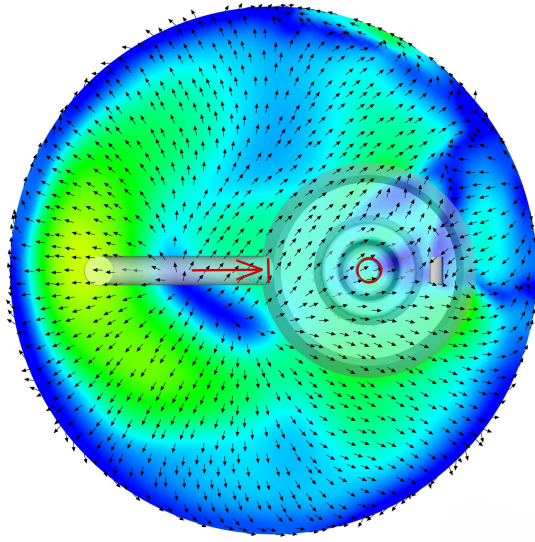
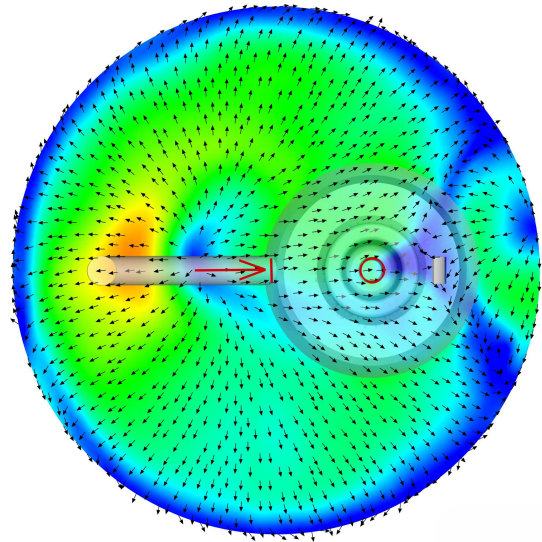


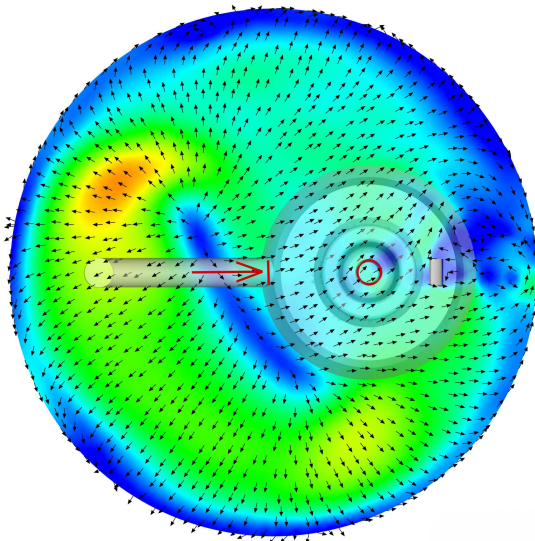
Figure 5.19: A view of a slice inside the PCC showcasing the velocity vectors going through the spark plug gap at the time of spark, -5°aTDC . The area is colored according to the magnitude of the velocity. The red arrow denotes the flow direction and location of the PCC injection line. The red circle denotes the spark plug electrode gap perimeter.



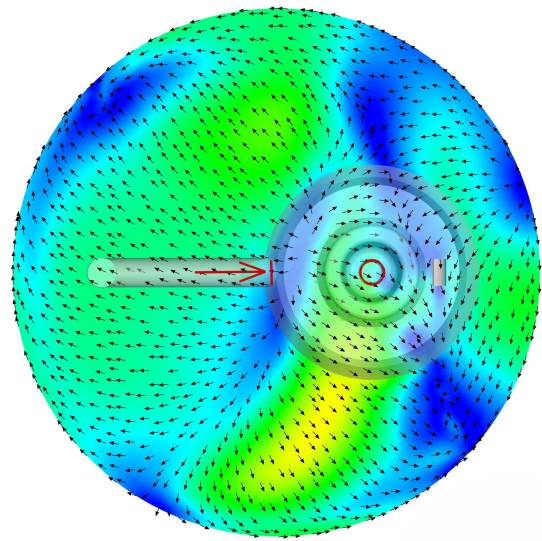
(e) $\phi=2.5$



(f) $\phi=3$



(g) $\phi=5$



(h) $\phi=7$

Figure 5.19: A view of a slice inside the PCC showcasing the velocity vectors going through the spark plug gap at the time of spark, -5°aTDC . The area is colored according to the magnitude of the velocity. The red arrow denotes the flow direction and location of the PCC injection line. The red circle denotes the spark plug electrode gap perimeter.

of the paper and are only tangential to the slice. The tumble in the PCC can be seen in Figure D.1 in Appendix D.1. The background has been colored according to the magnitude of the velocity, with blue regions being the slowest (2 m/s, 6.5 ft/s), red regions being the highest (24 m/s, 78.7 ft/s), and a full spectrum in between.

Comparing the velocity magnitude flow field of the baseline in 5.19a to the other cases (Figures 5.19b-5.19h) shows stark differences that are caused by the injected mass flow rates (mass velocities) interacting with the geometry. The baseline case shows significantly higher velocities inside the PCC at the time against the others, but all the high-velocity areas are located around the periphery of the PCC volume, and the velocity in between the electrodes is much lower, around 16.4 ft/s (5 m/s) or less. All the premixed injection cases show a local velocity around 32-50 ft/s (10-15 m/s), which is twice that of the baseline.

The flow fields themselves are also a point of interest, as all the premixed injection cases flow fields, local to the electrode, move from left to right (in relation to the figures orientation), whereas the baseline flows from right to left. The flow in the premixed cases is obviously affected by the injection, even 35 CAD after the injection ended. The flow fields not local to the electrodes are also differing. The premixed cases all have strong fields that seem to have a “source” point (which is actually just flow into or out of the page) where the flow over the whole plane extends from. The baseline has two similar “source” points as well (which is expected given the curvature of the PCC body); however, there are three areas within the plane that circle back on themselves and create eddies. The eddies imply that there is more TKE within the plane (and body) than in the premixed cases.

As it is known that turbulence helps promote flame kernel growth and propagation (to a degree) through flame wrinkling and stretching, the turbulence within the PCC of the premixed cases appears to be too low to properly promote kernel growth. The left-to-right flow also plays an important part in the flame quenching, as it pushes the newly formed and growing flame kernel into the spark plug’s electrode arm. The arm will absorb heat and further quench the kernel. These,

together, result in weak partial combustion seen in the PCC pressure traces (Figure 5.18) that ultimately extends to the MCC.

Table 5.5: Injection parameters for the high-pressure premixed injection experiment.

Boost, inHg	Injected AFR	Injected ϕ	Injection Duration, CAD
7.5	0.43	39.75	50
	0.54	31.89	50
	0.65	26.32	50
	0.94	18.23	39
12.5	0.00	inf	12
	0.18	96.27	33
	0.27	64.07	41
	0.36	48.24	45
	0.45	38.17	50
	0.54	31.85	60
	0.67	25.50	50
	0.75	22.94	60

For the experimental portion of the high-pressure injection test, two nominal boost conditions were tested: 7.5 inHg (3.6 psi, 25.4 kPa) and 12.5 inHg (6.1 psi, 42.3 kPa). At all tested points, the amount of air mixed into the PCC fuel line was adjusted, and then the ePCI duration was increased or decreased to the point where the engine's COV of peak pressure was at its minimum. Table 5.5 shows the injected AFR and ϕ along with the ePCI injection duration for each data point.

Starting with the analysis of the combustion timing, Table 5.6 shows the MFB duration and the change in CAD from the baseline case for both boost levels. At the lower boost level, the MFB durations were significantly shorter than the baseline, with the difference between the two shrinking as the injected AFR increased. Ignition delay was shortened to a minuscule 3.05 CAD from the baseline's 8.62 CAD at the lowest injected AFR of 0.43. Combustion duration, MFB 90, was just 22.13 CAD compared to the 28.58 CAD of the baseline. This indicates that the initial

Table 5.6: MFB locations and durations for the high-pressure premixed injection experiment.

Boost, inHg	Injected AFR	MFB Durations, CAD			Change in CAD from baseline		
		10	50	90	10	50	90
7.5	0.43	3.05	9.10	22.13	-5.57	-6.18	-6.45
	0.54	3.18	9.27	22.38	-5.45	-6.00	-6.20
	0.65	3.35	9.54	22.73	-5.27	-5.74	-5.85
	0.94	4.91	11.70	24.73	-3.72	-3.57	-3.85
12.5	0.00	10.10	18.18	33.15	0.66	0.52	-0.53
	0.18	10.16	18.15	33.27	0.72	0.49	-0.41
	0.27	10.39	18.46	33.64	0.95	0.81	-0.04
	0.36	10.59	18.78	34.13	1.14	1.13	0.45
	0.45	10.59	18.78	34.13	1.14	1.13	0.45
	0.54	10.74	18.92	34.27	1.30	1.26	0.59
	0.67	6.97	15.16	30.61	-2.47	-2.49	-3.07
	0.75	11.14	19.44	35.02	1.70	1.79	1.34

kernel growth and the average flame speed over the cycle time were drastically faster than the baseline, resulting in much faster combustion.

The 12.5 inHg boost data points also showed slower combustion as the injected AFR increased, but even at the lowest injected AFR of 0.18, the ignition delay and MFB 50 duration were slower than the 12.5 inHg baseline case. The overall combustion saw a duration of 33.15 CAD, just 0.53 CAD faster than the baseline. Again, this difference shrank as the injected AFR increased, and at an AFR of 0.36 and greater, combustion became slower across all MFBs.

Checking the engines overall combustion intensity by analyzing the COV of peak pressure in Figure 5.20 shows that the intensity of combustion is becoming more erratic as the AFR increases, for the high boost level at least. At the lower boost conditions, a slight improvement in COV of peak pressure is seen with the lowest AFRs, with the higher AFR injected actually producing a much higher COV than the baseline.

The COV of IMEP, seen in Figure 5.21, shows increases across all data points, low and high boost levels. With the 7.5 inHg data points showing a decrease in COV of peak pressure, it would be expected to see a decrease in COV of IMEP as well. Looking at the cycle-by-cycle IMEP of

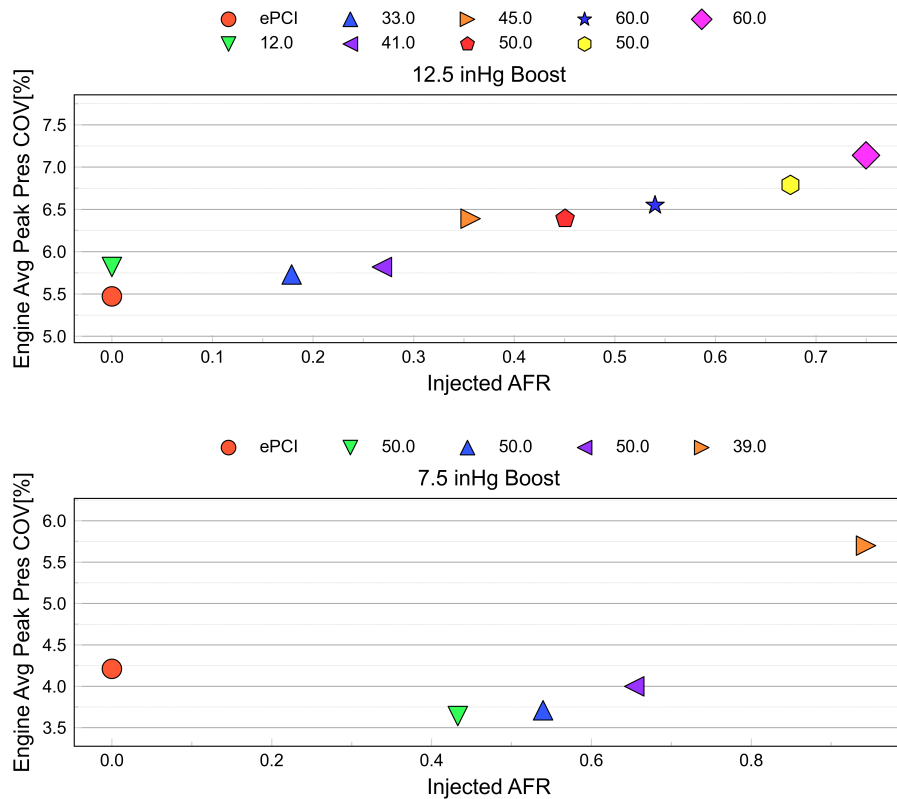


Figure 5.20: COV of peak pressure for experimental testing of premixed PCC injection.

each cylinder for the baseline case (Figure 5.23) and the lowest COV of peak pressure case (Figure 5.22) may shine light on what is actually happening. Cylinders 2 and 4 of both points have very similar groupings of their IMEPs, but cylinder 3 shows a tighter grouping for the premixed injection case—a lower local COV of IMEP. Cylinder 4, however, performs far worse for the premixed case over the baseline and is the reason for the engine average COV of IMEP dropping. This could be due to a number of factors—the engine not being tuned correctly, an issue specific to cylinder 1, or some other unknown source. However, it does show that premixed injection did improve the COV of IMEP of cylinder 3 and possibly cylinders 2 and 4.

The BSFC for the 12.5 inHg data did increase over the baseline case, but not an appreciable amount. The 7.5 inHg data saw no change.

Focusing on the engine out emissions now, the overall performance can be summed up by examining Figure 5.24. Starting with the 12.5 inHg data, there was variation in the emitted nitric oxides

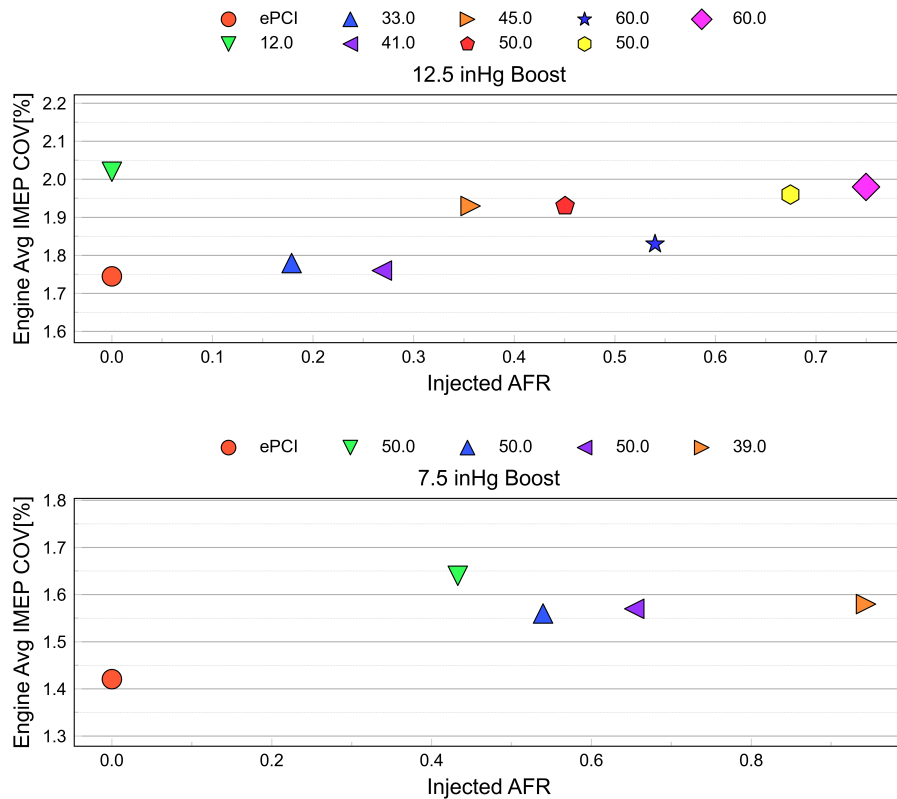


Figure 5.21: COV of IMEP for experimental testing of premixed PCC injection.

levels, more or less, than the baseline case, but the methane emissions remained higher for each point. The 7.5 inHg data showed an increase in nitric oxides across all points, with only one AFR producing about 5% less methane than the baseline. Neither, the methane and the nitric oxides, results show any kind of trend or pattern regarding injected AFR or injection duration.

5.4 Answers to Research Questions

This portion of the research intends to answer the question *How does premixing the fuel charge injected into the PCC with air affect combustion statistics and emissions?* Putting together everything described in the previous sections shows a methane reduction technique that did not produce results in line with its intended purpose. Combustion duration was increased for low boost conditions and decreased for high boost conditions—both slowing down as the injected AFR increased.

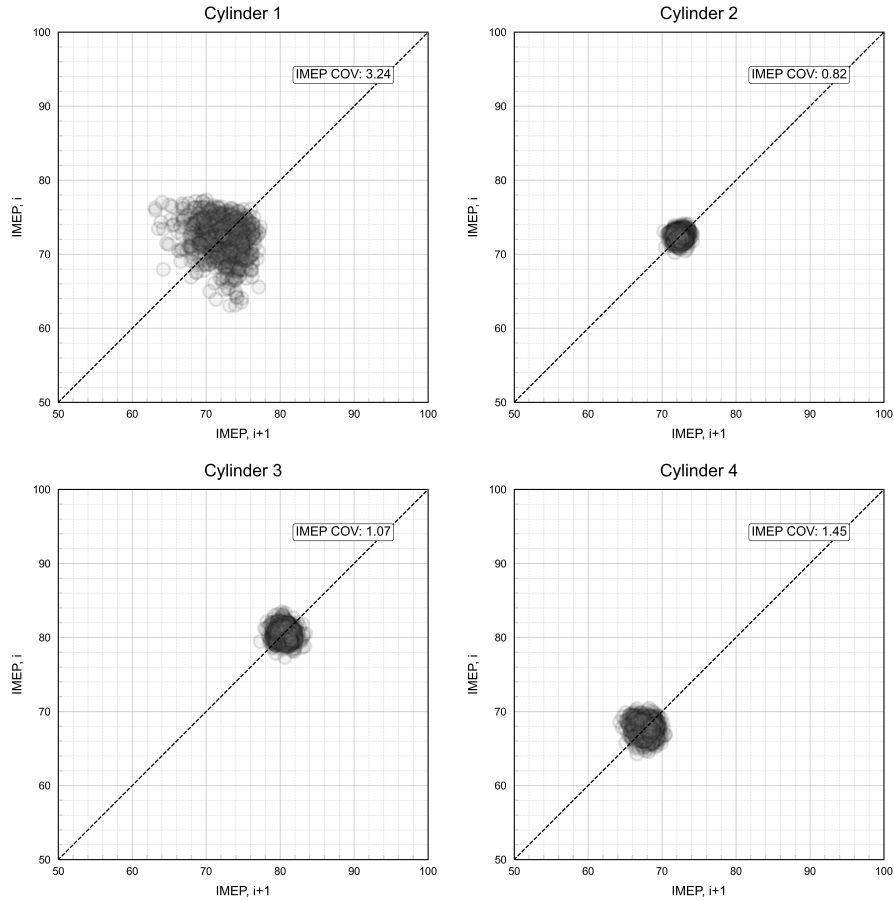


Figure 5.22: Cycle by cycle for each cylinder COV of IMEP for the 7.5 inHg boost, injected AFR of 0.43.

Overall engine stability performance dropped with both boost conditions. And engine out emissions suffered for every data point.

Combining these experimental results with the simulation results presented early in the chapter show that the flow fields inside the PCC are incredibly important and can make or break a combustion cycle. Utilizing premixed fuel and air injection required far too high of flow rates to sustain operational conditions in the PCC and ultimately did not appreciably help the stratification in it either.

For premixed injection to a viable methane reduction strategy, a PCC needs to be designed with the intention of using premixed injection—designed to utilize and/or mitigate the high mass flow rates and velocity effects.

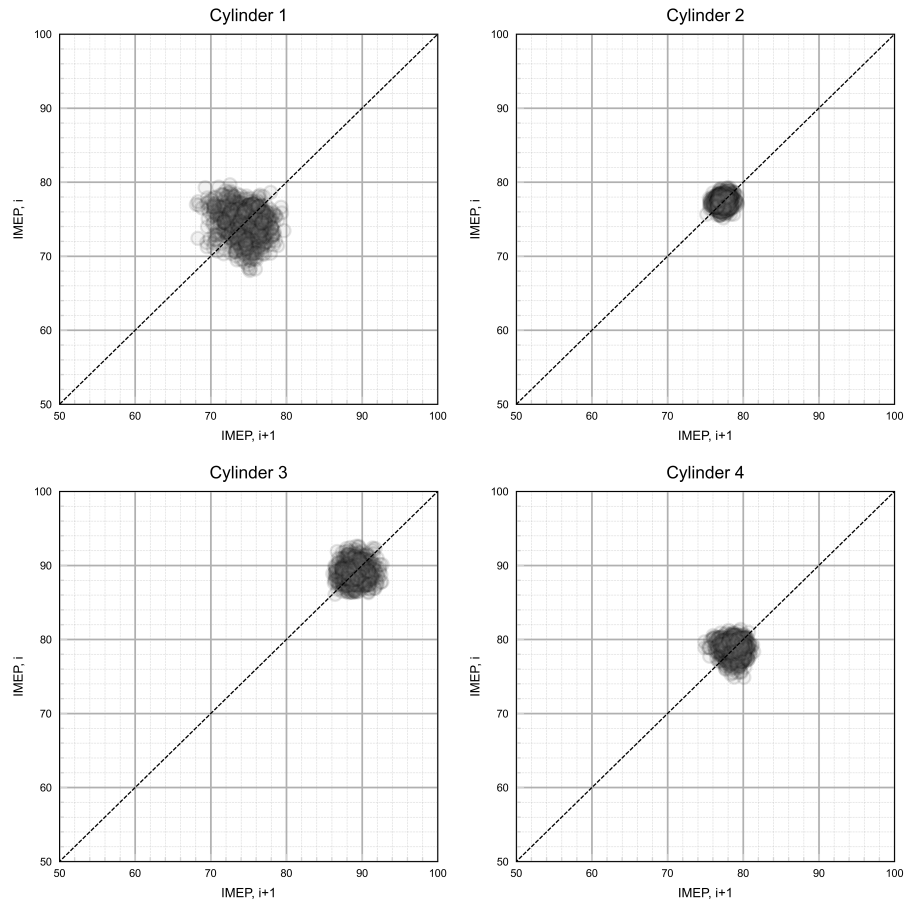


Figure 5.23: Cycle by cycle for each cylinder COV of IMEP for the 7.5 inHg boost baseline point.

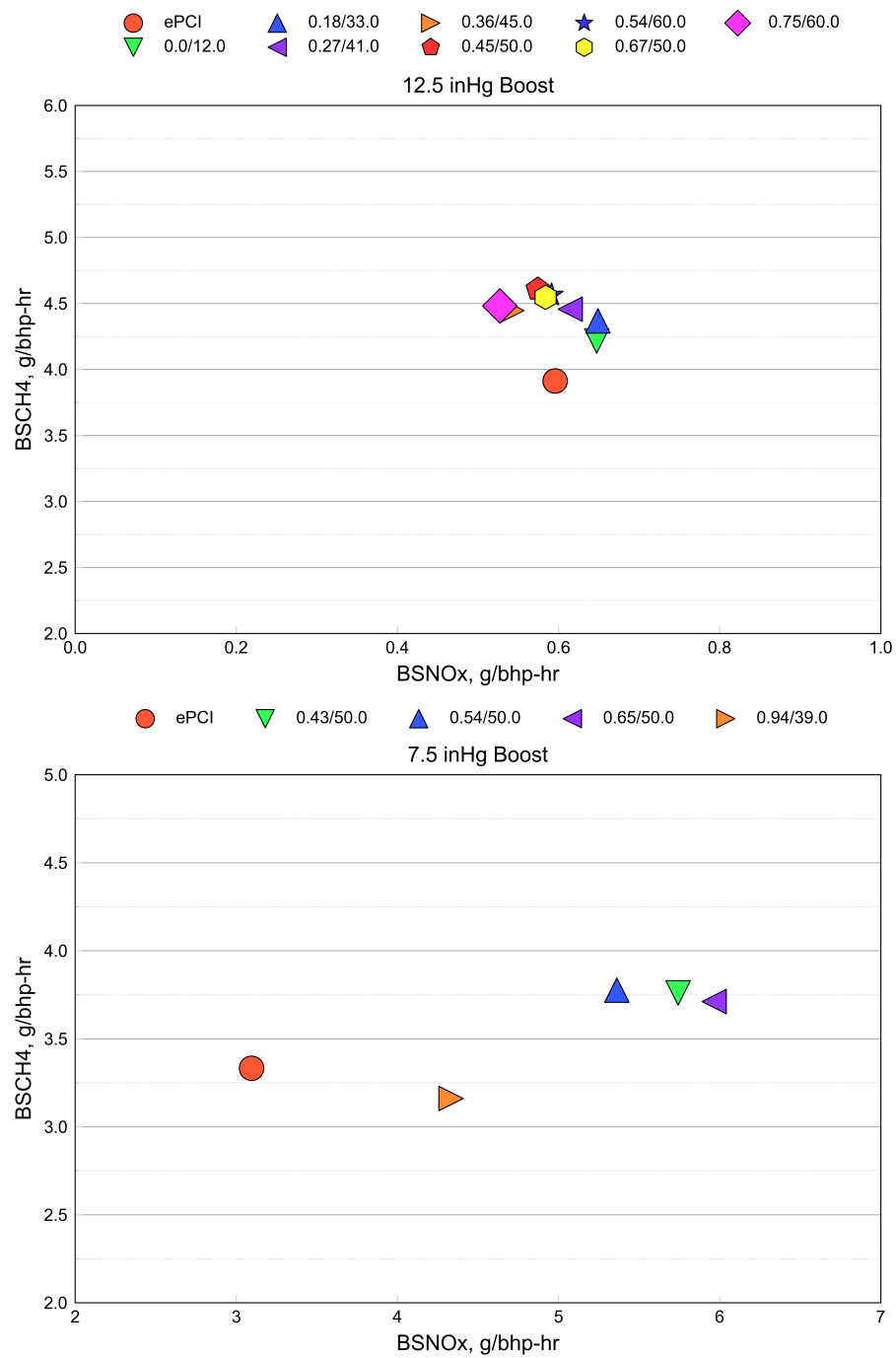


Figure 5.24: Methane and nitric oxides trade-off plot for both premixed injection data sets.

Chapter 6

Conclusion

6.1 Hydrogen/Natural Gas Blending

When the natural gas/hydrogen blended fuels were used with HPFI in both the MCC and PCC, coupled with keeping constant load/power output, there was an increase in cylinder pressure; the higher the percentage of hydrogen used the higher the peak pressure. The 41.3% hydrogen blend produced a 15% increase in the MCC peak pressure over the baseline. The location of peak pressure was shown to move forward in cycle time as the hydrogen content increased as well. The 41.3% blend had a LoPP nearly 3 degrees before the baseline. Peak pressure COVs showed improvement as well. The largest fuel consumption improvement, a nearly 1.8% decrease, came from the 41.3% hydrogen blend.

Ignition delay duration times, combustion duration times, and BSEC all saw decreases as the percent of hydrogen increased. Using the 41.3% blend, ignition delay decreased by about 1.6 degrees, combustion duration decreased by about 4.2 degrees, and the BSEC decreased by nearly 1.8%. It should be noted that the best combustion performance took place using the 43% hydrogen blend but the best BSEC was shown to take place using the 31.6% blend; this is likely due to experimental uncertainty.

THC and methane emissions showed decreases as hydrogen was added to the natural gas, with a maximum reduction of 28% coming from the 31.6% blend. carbon monoxide and carbon dioxide saw decreases as well; this was due to the carbon in the fuel being replaced with hydrogen. nitric oxides values increased, relatively linearly, as the hydrogen content increased with the 41.3 blend producing the highest output, a 70% increase over the baseline.

When the natural gas/hydrogen blends were used as the PCC fuel and the MCC used solely natural gas, there was little change seen in the combustion statistics, even at the higher hydrogen percent blends. The addition of hydrogen made little impact on the emissions as well until the

80% hydrogen blend was reached. At this point a reduction in THC and methane of around 8% was shown. carbon dioxide remained constant across all fuel blends. nitric oxides emissions increased from the onset of hydrogen addition to about 80% hydrogen. At the 90% blend nitric oxides fell, slightly, below the baseline values.

When using the blended fuels with the MGAV fueling configuration, the same trends were observed as with the HPFI fueling configuration, with both MCC and PCC fuels being blended. At a 24.0% hydrogen blend, the peak pressure increased by 5%, the LoPP moved forward in time by nearly 2 degrees, the peak pressure COV decreased by 2.3 degrees, the ignition delay decreased by -1.4 degrees, the combustion duration decreased by just over 1 degree, and the BSEC was reduced by over 2%.

The emissions exhibited similar behavior as well. THC and methane emissions saw a maximum decrease in output at the 13.4% hydrogen blend of just over 20% compared to the baseline. carbon dioxide output dropped by 10% when using the 24.0% hydrogen blend. carbon monoxide values remained constant for all blends. nitric oxides emissions also stayed relatively constant across all tested blends.

6.2 Directional PCCs

In conclusion, it was shown that utilizing CFD to guide a PCC's nozzle design is practical and can lead to improvements in engine out emissions, specifically methane. The results of the individual PCC parameter adjustments are as follows:

- Nozzle orientation plays a crucial role in combustion characteristics and emissions. Improper or unoptimized orientation can lead to high amounts of unburned methane.
- Multiple nozzles can lead to a reduced combustion rate, which can then lead to increased combustion efficiency. Many “weaker” flame-jets may be more beneficial than one “strong” flame-jet.

- **Nozzle Angle Adjustments:** Inward-angled nozzles led to higher methane emissions due to poor jet penetration, while the original orientation provided better performance.
- **PCC Volume Changes:** Increasing PCC volume resulted in lower nitric oxides emissions but slightly higher methane, while reducing volume caused excessive methane emissions due to overly aggressive jet propagation.
- **Nozzle Flow Area Variations:** Decreasing the flow area by 25% resulted in the lowest methane emissions while maintaining similar nitric oxides output, making it the most effective refinement.
- **Combined Design (Area2 Vol2):** A PCC design incorporating both the best flow area and volume adjustments performed well but was outperformed by the reduced-flow-area design in minimizing methane emissions.

When tested on the engine, the customized PCCs not only reduced the methane emissions but also reduced the COVs of IMEP and peak pressure, increasing the stability and operating limits of the engine. A reduction in BSEC, while small, was seen as well. An overview of the experimental results is as follows:

- **Boost Sweep:** The refined PCC designs consistently reduced methane emissions compared to the OEM PCC, with the nominal design achieving reductions of 22.8% to 31.1% and the expanded design achieving 19.7% to 29.2%. Higher boost pressures further improved performance.
- **4-Corner (Varying Load and Speed):**
 - At low load conditions, methane emissions were reduced by up to 46% with the nominal PCC and 39% with the expanded PCC, while nitric oxides increases were minimal.
 - At high load conditions, methane reductions were smaller, and nitric oxides emissions increased significantly, highlighting the trade-off between methane and nitric oxides control strategies.

- **Combustion Stability Improvements:** Both refined PCC designs improved combustion stability, as indicated by reduced COV in IMEP and peak pressure fluctuations.

The greatest benefits were seen when the engine was operating with high boost. Under these conditions, ultra-low nitric oxides levels were shown to vary minimally while reducing methane output significantly. At low boost operation, there were reductions in methane, but nitric oxides output significantly increased, leading to the question, how would the PCC nozzle design change for low boost operating engines?

Under low load conditions, the nominal and expanded PCCs nearly cut methane emissions in half while insignificantly increasing nitric oxides. Obviously, this is ideal performance, but nitric oxides values for the high load conditions increased radically while only a slight reduction in methane was seen. This implies that, depending on the engines' load profile, a more optimal design may be available.

6.3 Premixed Fuel and Air Injection

This premixed injection was believed to reduce the mixture stratification and increase the homogeneity of the PCC volume at the time of ignition. This decrease in stratification would lead to more stable combustion and a reduction in engine out emissions and CCVs.

The artificially generated ideal case showed some degree of improvement in brake specific emissions over the baseline case emissions. This reduction came from an increase in flame speed and a reduction in MFB duration times. However, the combustion cycle for the ideal case produced 1.3% less power than the baseline.

The full premixed low-pressure injection cases showed far less promise than the ideal case. It was found that as the AF ratio of the premixed charge approached stoichiometric, the mass flow into the PCC, needed to inject the same amount of mass of fuel as the baseline, would need to increase by approximately the AF ratio injected multiplied by the baseline flow rate. This led to very large flow rates in the leaner injected cases, causing a significant amount of the fuel intended for PCC combustion to seep into the MCC via the nozzles. So much fuel was transferred to the

MCC from the PCC in the case of an injected ϕ of 1.5 that the average ϕ in the MCC, at the time of spark, had increased compared to the baseline. The massive flow rate did improve the homogeneity of the PCC volume, but because the PCC volume was held constant, the trapped mass of fuel in the PCC at the time of spark was far less than the baseline.

The mixing within the PCC volume was found to become more stratified as the injected ϕ became richer. This was caused simply by the lessening mass transfer from the PCC to the MCC as the mass flow rates decreased. This led to higher MCC-to-PCC transfer rates of a low ER mixture that dilutes and increases stratification in the PCC volume.

The high mass flow rates needed to inject the premixed charges also drastically changed the flow fields found inside both the PCC and MCC. The change in flow fields alters not only the fuel distribution in both volumes but also the small- and large-scale turbulence dissemination, which affects flame speed and propagation as well.

All simulated cases showed very slow and poor combustion that started in the PCC and extended into the MCC. All cases produced higher methane emissions at the end of combustion and a subsequent reduction in power. Nitric oxides emissions did decrease, but only due to the reduction in fuel consumption and successive average temperature decrease.

The high-pressure electronic fuel injection model was thought to be an alternative option for premixed injection. It was believed that the ability to postpone PCC fueling until closer to TDC would help curb stratification in the PCC and help reduce the PCC-to-MCC mass transfer before ignition. Unfortunately, the strategy did not generate the intended results. All the simulated cases resulted in complete misfires or such poor combustion that the cycle would be labeled a misfire.

The high pressure used in the fueling, similarly to the low-pressure cases, caused massive alterations to the flow field directions and, more importantly, the velocity of the flow around the spark plug electrodes. The high velocities did not allow the required time needed for a spark kernel to properly grow into a fully developed, self-sustaining propagating flame. The high-pressure electronic injection was not pursued further than the initial case setups because of the poor preliminary

results shown along with the impending deadline of the project. In conclusion, the findings of the study can be summarized as follows:

- A premixed fuel and air charge injected into the PCC can decrease the stratification and increase the homogeneity of the PCC.
- The low stratification can lead to slower flame propagation through the PCC but a more stable flame in the MCC, which ultimately increased the MFB durations.
- Depending on the equivalence ratio being injected, significantly larger flow rates are needed to match the mass of fuel injected to nominal operating conditions. These large flow rates may require component changes that may include, but are not limited to, fuel injector tips, fueling lines, mass flow controllers, valves, etc.
- Without a geometric alteration to the PCC volume, matching the trapped mass of fuel to nominal operating conditions for some injected equivalence ratios is not possible. The leaner the injected mixture, the larger the PCC volume would need to be to accommodate the mass of fuel and air.
- Utilizing mechanical fuel injection check valves for the PCC requires extensive overcharging, leading to large amounts of fuel (and air) being pushed into the MCC. In the most extreme cases, this may cause a shift in the MCC equivalence ratio.
- Mass transfer from the MCC into the PCC while the piston is moving upwards is one of the major obstacles in creating a homogeneous mixture in the PCC. The later in the cycle the PCC fuel injection can be done will help curb the stratification and reduce the impact of the dilution.
- High-pressure electronic PCC fuel injectors caused an overabundance of turbulence within the PCC and around the spark plug electrodes, leading to poor, if any, flame kernel growth and combustion.

Bibliography

- [1] Global Climate NASA. Global Surface Temperature | NASA Global Climate Change. URL: <https://climate.nasa.gov/vital-signs/global-temperature?intent=121>.
- [2] Technical Summary, 2023. URL: <https://www.cambridge.org/core/books/climate-change-2021-the-physical-science-basis/technical-summary/C7CCEAD271B10F328C6E50C03A0F4F02>, doi:10.1017/9781009157896.002.
- [3] Qiancheng Ma. NASA GISS: Science Briefs: Greenhouse Gases: Refining the Role of Carbon Dioxide, January 2005. URL: https://web.archive.org/web/20050112211604/http://www.giss.nasa.gov/research/briefs/ma_01/.
- [4] Thomas R. Karl and Kevin E. Trenberth. Modern Global Climate Change. *Science*, 302(5651):1719–1723, December 2003. URL: <https://www.science.org/doi/10.1126/science.1090228>, doi:10.1126/science.1090228.
- [5] S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. AR4 Climate Change 2007: The Physical Science Basis — IPCC. URL: <https://www.ipcc.ch/report/ar4/wg1/>.
- [6] Jorge L. Sarmiento and Nicolas Gruber. Sinks for Anthropogenic Carbon. *Physics Today*, 55(8):30–36, August 2002. doi:10.1063/1.1510279.
- [7] David Archer, Michael Eby, Victor Brovkin, Andy Ridgwell, Long Cao, Uwe Mikolajewicz, Ken Caldeira, Katsumi Matsumoto, Guy Munhoven, Alvaro Montenegro, and Kathy Tokos. Atmospheric Lifetime of Fossil Fuel Carbon Dioxide. *Annual Review of Earth and Planetary Sciences*, 37(Volume 37, 2009):117–134, May 2009. URL: <https://www.annualreviews.org/content/journals/10.1146/annurev.earth.031208.100206>, doi:10.1146/annurev.earth.031208.100206.
- [8] Methane | Vital Signs. URL: <https://climate.nasa.gov/vital-signs/methane?intent=121>.

- [9] Marielle Saunois, Adrien Martinez, Benjamin Poulter, Zhen Zhang, Peter Raymond, Pierre Regnier, Joseph G. Canadell, Robert B. Jackson, Prabir K. Patra, Philippe Bousquet, Philippe Ciais, Edward J. Dlugokencky, Xin Lan, George H. Allen, David Bastviken, David J. Beerling, Dmitry A. Belikov, Donald R. Blake, Simona Castaldi, Monica Crippa, Bridget R. Deemer, Fraser Dennison, Giuseppe Etiope, Nicola Gedney, Lena Höglund-Isaksson, Meredith A. Holgerson, Peter O. Hopcroft, Gustaf Hugelius, Akihito Ito, Atul K. Jain, Rajesh Janardanan, Matthew S. Johnson, Thomas Kleinen, Paul Krummel, Ronny Lauerwald, Tingting Li, Xiangyu Liu, Kyle C. McDonald, Joe R. Melton, Jens Mühle, Jurek Müller, Fabiola Murguía-Flores, Yosuke Niwa, Sergio Noce, Shufen Pan, Robert J. Parker, Changhui Peng, Michel Ramonet, William J. Riley, Gerard Rocher-Ros, Judith A. Rosenreiter, Motoki Sasakawa, Arjo Segers, Steven J. Smith, Emily H. Stanley, Joel Thanwerdas, Hanquin Tian, Aki Tsuruta, Francesco N. Tubiello, Thomas S. Weber, Guido Van Der Werf, Doug E. Worthy, Yi Xi, Yukio Yoshida, Wenxin Zhang, Bo Zheng, Qing Zhu, Qiuhan Zhu, and Qianlai Zhuang. Global Methane Budget 2000–2020, June 2024. URL: <https://essd.copernicus.org/articles/17/1873/2025/essd-17-1873-2025-discussion.html>, doi:10.5194/essd-2024-115.
- [10] Use of natural gas - U.S. Energy Information Administration (EIA). URL: <https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php>.
- [11] General Public Portal Page. URL: <https://www.npms.phmsa.dot.gov/GeneralPublic.aspx>.
- [12] Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2022: Updates for Transmission Compressor Station Activity, 2024. URL: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.epa.gov/system/files/documents/2024-04/2024-ghgi-update_transmissionactivity_april2024.pdf&ved=2ahUKEwid8bfPnLWNAxXLFzQIHrvnE2UQFnoECBgQAQ&usg=AOvVaw0577NBV9_Vok7Ty14Aa1ca.
- [13] National Emission Standards for Hazardous Air Pollutants: Reciprocating Internal Combustion Engines and New Source Performance Standards: Internal Combustion Engines; Elec-

- tronic Reporting, August 2024. URL: https://www.federalregister.gov/documents/2024/08/30/2024-18766/national-emission-standards-for-hazardous-air-pollutants-reciprocating-internal-combustion-engines?utm_source=chatgpt.com.
- [14] OA US EPA. Waste Emissions Charge, January 2024. URL: <https://www.epa.gov/inflation-reduction-act/waste-emissions-charge>.
- [15] OAR US EPA. Subpart W – Petroleum and Natural Gas Systems, September 2014. URL: <https://www.epa.gov/ghgreporting/subpart-w-petroleum-and-natural-gas-systems>.
- [16] H2@Scale. URL: <https://www.energy.gov/eere/fuelcells/h2scale>.
- [17] Hyblend: Opportunities for hydrogen blending in natural gas pipelines. URL: <https://www.energy.gov/sites/default/files/2022-12/hyblend-tech-summary-120722.pdf>.
- [18] Kevin Topolski, Evan Reznicek, Burcin Erdener, Chris San Marchi, Joseph Ronevich, Lisa Fring, Kevin Simmons, Omar Fernandez, Bri-Mathias Hodge, and Mark Chung. Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology. Technical Report NREL/TP-5400-81704, 1893355, MainId:82477, National Renewable Energies Lab, October 2022. URL: <https://www.osti.gov/servlets/purl/1893355/>, doi:10.2172/1893355.
- [19] Mirza Jamil Yusuf. *Lean burn natural gas engines engine: modification versus hydrogen blending*. PhD thesis, University of Miami, August 1993.
- [20] G Karim, I. Wierzbza, and Y. Al-Alousi. Methane-hydrogen mixtures as fuels. *International Journal of Hydrogen Energy*, 21(7):625–631, July 1996. URL: <https://linkinghub.elsevier.com/retrieve/pii/0360319995001344>, doi:10.1016/0360-3199(95)00134-4.
- [21] Fred B. Parks. A Single-Cylinder Engine Study of Hydrogen-Rich Fuels. In *SAE International*, page 760099, February 1976. URL: <https://www.sae.org/content/760099/>, doi:10.4271/760099.

- [22] C G Bauer and T W Forest. Effect of hydrogen addition on the performance of methane-fueled vehicles. Part I: effect on S.I. engine performance. *International Journal of Hydrogen Energy*, 2001.
- [23] Fanhua Ma and Yu Wang. Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine. *International Journal of Hydrogen Energy*, 33(4):1416–1424, February 2008. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360319907007665>, doi:10.1016/j.ijhydene.2007.12.040.
- [24] S Akansu, N Kahraman, and B Ceper. Experimental study on a spark ignition engine fuelled by methane–hydrogen mixtures. *International Journal of Hydrogen Energy*, 32(17):4279–4284, December 2007. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360319907003266>, doi:10.1016/j.ijhydene.2007.05.034.
- [25] F Ma, Yu Wang, Liu Haiquan, Li Yong, Wang Junjun, and Ding Shangfen. Effects of hydrogen addition on cycle-by-cycle variations in a lean burn natural gas spark-ignition engine. *International Journal of Hydrogen Energy*, 33(2):823–831, January 2008. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360319907006404>, doi:10.1016/j.ijhydene.2007.10.043.
- [26] Yaodong Du, Xiumin Yu, Jinlong Wang, Haiming Wu, Wei Dong, and Jiaqi Gu. Research on combustion and emission characteristics of a lean burn gasoline engine with hydrogen direct-injection. *International Journal of Hydrogen Energy*, 41(4):3240–3248, January 2016. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360319915310338>, doi:10.1016/j.ijhydene.2015.12.025.
- [27] Antonio Mariani, Maria Vittoria Prati, Andrea Unich, and Biagio Morrone. Combustion analysis of a spark ignition i. c. engine fuelled alternatively with natural gas and hydrogen–natural gas blends. *International Journal of Hydrogen Energy*, 38(3):1616–1623, February 2013. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360319912024974>, doi:10.1016/j.ijhydene.2012.11.051.

- [28] Silvana Di Iorio, Paolo Sementa, and Bianca Maria Vaglieco. Experimental investigation on the combustion process in a spark ignition optically accessible engine fueled with methane/hydrogen blends. *International Journal of Hydrogen Energy*, 39(18):9809–9823, June 2014. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360319914010866>, doi:10.1016/j.ijhydene.2014.04.065.
- [29] Jianfeng Pan, Yao Lu, Mingcai Huang, Peter Otchere, Wei Chen, and Baowei Fan. Effect of different hydrogen blending ratios on combustion process of gasoline-fueled rotary engine. *Environmental Progress & Sustainable Energy*, 38(5):13200, September 2019. URL: <https://onlinelibrary.wiley.com/doi/10.1002/ep.13200>, doi:10.1002/ep.13200.
- [30] Jinhua Wang, Hao Chen, Bing Liu, and Zuohua Huang. Study of cycle-by-cycle variations of a spark ignition engine fueled with natural gas–hydrogen blends. *International Journal of Hydrogen Energy*, 33(18):4876–4883, September 2008. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360319908007635>, doi:10.1016/j.ijhydene.2008.06.062.
- [31] Jeong Park, Dong Jin Hwang, June Sung Park, Jeong Soo Kim, Sang In Keel, Han Chang Cho, Dong Soon Noh, and Tae Kwon Kim. Hydrogen utilization as a fuel: hydrogen-blending effects in flame structure and NO emission behaviour of CH₄–air flame. *International Journal of Energy Research*, 31(5):472–485, April 2007. URL: <https://onlinelibrary.wiley.com/doi/10.1002/er.1259>, doi:10.1002/er.1259.
- [32] Harry Ralph Ricardo. Internal-combustion engine, July 1918. URL: <https://patents.google.com/patent/US1271942A/en>.
- [33] Carlos Eduardo Castilla Alvarez, Giselle Elias Couto, Vinícius Rückert Roso, Arthur Braga Thiriet, and Ramon Molina Valle. A review of prechamber ignition systems as lean combustion technology for SI engines. *Applied Thermal Engineering*, 128:107–120, January 2018. URL: <https://linkinghub.elsevier.com/retrieve/pii/S1359431117302284>, doi:10.1016/j.applthermaleng.2017.08.118.

- [34] Henry K. Newhall and Ibrabim A. El-Messiri. A combustion chamber concept for control of engine exhaust air pollutant emissions. *The Combustion Insititute*, 14(1):155–158, February 1970. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0010218070800232>, doi: 10.1016/S0010-2180(70)80023-2.
- [35] Alan C. Anderson, T. N. Chen, and William Hutchins. The development and application of design criteria for precombustion chambers on natural gas fueled engines, 1984.
- [36] J. Getzlaff, J. Pape, C. Gruenig, D. Kuhnert, and R. Latsch. Investigations on Pre-Chamber Spark Plug with Pilot Injection. *SAE Transactions*, 116:2007–01–0479, April 2007. URL: <https://www.sae.org/content/2007-01-0479/>, doi:10.4271/2007-01-0479.
- [37] Xianyin Leng, Mei Wang, Zhixia He, Qian Wang, Shengli Wei, Wuqiang Long, and Chuan-gen Zhu. Impact of the pre-chamber nozzle orifice configurations on combustion and performance of a Natural Gas Engine. *Thermal Science*, 22(3):1325–1337, 2018. URL: <https://doi.org/10.2298/TSCI170912008L>, doi:10.2298/TSCI170912008L.
- [38] Ashish Shah, Per Tunestal, and Bengt Johansson. Effect of Pre-Chamber Volume and Nozzle Diameter on Pre-Chamber Ignition in Heavy Duty Natural Gas Engines. *SAE International*, pages 2015–01–0867, April 2015. URL: <https://www.sae.org/content/2015-01-0867/>, doi:10.4271/2015-01-0867.
- [39] Dean J. Simpson and Daniel B. Olsen. Precombustion Chamber Design for Emissions Reduction From Large Bore NG Engines. *Journal of Engineering for Gas Turbines and Power*, 132(12):122802, December 2010. URL: <https://asmedigitalcollection.asme.org/gasturbinespower/article/doi/10.1115/1.4001293/408746/Precombustion-Chamber-Design-for-Emissions>, doi:10.1115/1.4001293.
- [40] Greg Beshouri. A New Look at the Design and Operation of Screw-In Pre Combustion Chambers. In *Gas Machinery Conference*, 2016.

- [41] Dimitris Assanis, Nayan Engineer, Paul Neuman, and Margaret Wooldridge. Computational Development of a Dual Pre-Chamber Engine Concept for Lean Burn Combustion. In *SAE International*, pages 2016–01–2242. SAE International, October 2016. URL: <https://www.sae.org/content/2016-01-2242/>, doi:10.4271/2016-01-2242.
- [42] Kim Gi-Heon. *Computational fluid dynamics modeling of a large bore two -stroke natural gas engine*. PhD thesis, Colorado State University, 2004. URL: <https://www.proquest.com/docview/305205976?pq-origsite=primo>.
- [43] Luigi Tozzi, David Lepley, and Emmanuella Sotiropoulou. Solutions for meeting low emission requirements in large bore natural gas engines, 2013.
- [44] Justin M. Lisowski. Diagnostic techniques for precombustion chambers in large bore lean burn natural gas engines, 2007.
- [45] Daniel B. Olsen, Jessica L. Adair, and Bryan D. Willson. Precombustion Chamber Design and Performance Studies for a Large Bore Natural Gas Engine. In *ASME 2005 Internal Combustion Engine Division Spring Technical Conference*, pages 415–428, Chicago, Illinois, USA, January 2005. ASMEDC. URL: <https://asmedigitalcollection.asme.org/ICES/proceedings/ICES2005/41847/415/308639>, doi:10.1115/ICES2005-1057.
- [46] Xiang Li, Wenzheng Zhang, Zhong Huang, Dehao Ju, Li Huang, Mingzhi Feng, Xingcai Lu, and Zhen Huang. Pre-chamber turbulent jet ignition of methane/air mixtures with multiple orifices in a large bore constant volume chamber: effect of air-fuel equivalence ratio and premixed pressure. *Frontiers in Energy*, 13(3):483–493, September 2019. URL: <http://link.springer.com/10.1007/s11708-019-0631-1>, doi:10.1007/s11708-019-0631-1.
- [47] Masumeh Gholamisheeri, Bryce C Thelen, Gerald R Gentz, Indrek S Wichman, and Elisa Toulson. Rapid compression machine study of a premixed, variable inlet density and flow rate, confined turbulent jet. *Combustion and Flame*, 169:321–332, July 2016. URL: <https://doi.org/10.1016/j.combustflame.2016.05.011>.

//linkinghub.elsevier.com/retrieve/pii/S0010218016300761, doi:10.1016/j.combustflame.2016.05.001.

- [48] Daniel B. Olsen and Allan Kirkpatrick. Experimental Examination of Prechamber Heat Release in a Large Bore Natural Gas Engine. *Journal of Engineering for Gas Turbines and Power*, 2008.
- [49] Allan Kirkpatrick, Gi-Heon Kim, and Daniel Olsen. CFD Modeling of the Performance of a Prechamber for Use in a Large Bore Natural Gas Engine. In *ASME 2005 Internal Combustion Engine Division Spring Technical Conference*, pages 397–403, Chicago, Illinois, USA, January 2005. ASMEDC. URL: <https://asmedigitalcollection.asme.org/ICES/proceedings/ICES2005/41847/397/308623>, doi:10.1115/ICES2005-1049.
- [50] Mathew D. Ruter, Daniel B. Olsen, Mark V. Scotto, and Mark A. Perna. NO_x reduction from a large bore natural gas engine via reformed natural gas prechamber fueling optimization. *Fuel*, 91(1):298–306, January 2012. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0016236111003978>, doi:10.1016/j.fuel.2011.06.072.
- [51] K Evans, D Olsen, and B Willson. Fuel and ignition control methodologies for engines with articulated connecting rods. *International Journal of Engine Research*, 6(3):207–214, June 2005. URL: <https://journals.sagepub.com/doi/10.1243/146808705X7437>, doi:10.1243/146808705X7437.
- [52] Bryan Willson, Gary Hutcherson, Daniel Olsen, and Jason Holden. Evaluation of High Pressure Injection of Fuel Gas in Large-Bore Natural Gas Engines. *Gas Research Institute*, December 1999.
- [53] V. Yakhot, S. A. Orszag, S. Thangam, T. B. Gatski, and C. G. Speziale. Development of turbulence models for shear flows by a double expansion technique. *Physics of Fluids A: Fluid Dynamics*, 4(7):1510–1520, July 1992. URL: <https://pubs.aip.org/pof/article/4/7/151>

0/402677/Development-of-turbulence-models-for-shear-flows, doi:10.1063/1.8584

24.

Appendix A

Computational Fluid Dynamics

A.1 Adaptive Mesh Refinement

Table A.1: Adaptive Mesh Refinement Details

AMR Groups	Regions	Max Embedding Level	Type	Timing, °aTDC
Intake	Intake	3	Velocity, temp	-239 to -121
PCC MCC Scav	Cylinder, prechamber	3	Velocity, temp, species	-254 to -6
Injector Fueling	Injector	3	Velocity, temp, species	-116 to -94
Exhaust	Exhaust	3	Velocity, temp, species	-254 to -112
PCC Fueling	PCC Gasline	3	Velocity, temp, species	-254 to -112
PCC MCC Comb	Cylinder, prechamber	4	Velocity, temp, species	-6 to 106

A.2 Fixed Embedding

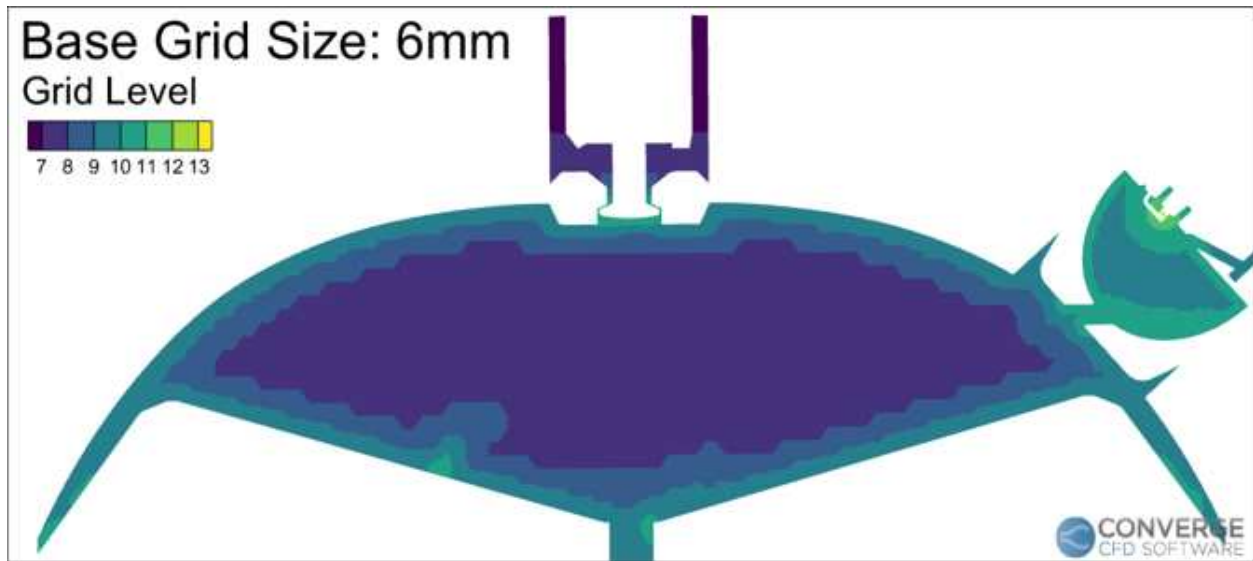
Table A.2: Fixed Embedding Details

Type	Region or Boundary ID	Scale	Embed Layers	Timing, °aTDC
Boundary	Piston	3	2	Permanent
Boundary	Injector valve seat	4	3	-116 to -94
Boundary	Injector valve top	4	3	-116 to -94
Boundary	Prechamber gas pipeline	2	2	-223 to -104
Boundary	Prechamber nozzle	4	3	Permanent
Boundary	Liner	3	2	Permanent
Boundary	Cylinder head	3	2	Permanent
Boundary	Injector valve bottom	4	2	Permanent
Boundary	Prechamber cover	3	2	Permanent
Boundary	Intake ports	2	2	-239 to -121
Boundary	Exhaust ports	2	2	-254 to -107.5
Boundary	Prechamber	4	2	Permanent
Boundary	Spark plug electrodes	4	2	Permanent
Boundary	Spark plug cover	4	2	Permanent
Boundary	Spark plug gap	4	2	Permanent
Region	Injector	3	—	-116 to -94
Region	Prechamber	2	—	-254 to -6
Region	Prechamber gasline	2	—	-224 to -103
Region	Cylinder	1	—	-6 to 106
Region	Prechamber	3	—	-6 to 106
Cylinder	*spark*	6	—	-5.5 to -4.1
Cylinder	*spark*	5	—	-6 to 0
Sphere	Prechamber gasline	3	—	-224 to -103
Sphere	*spark*	4	—	-6 to 10

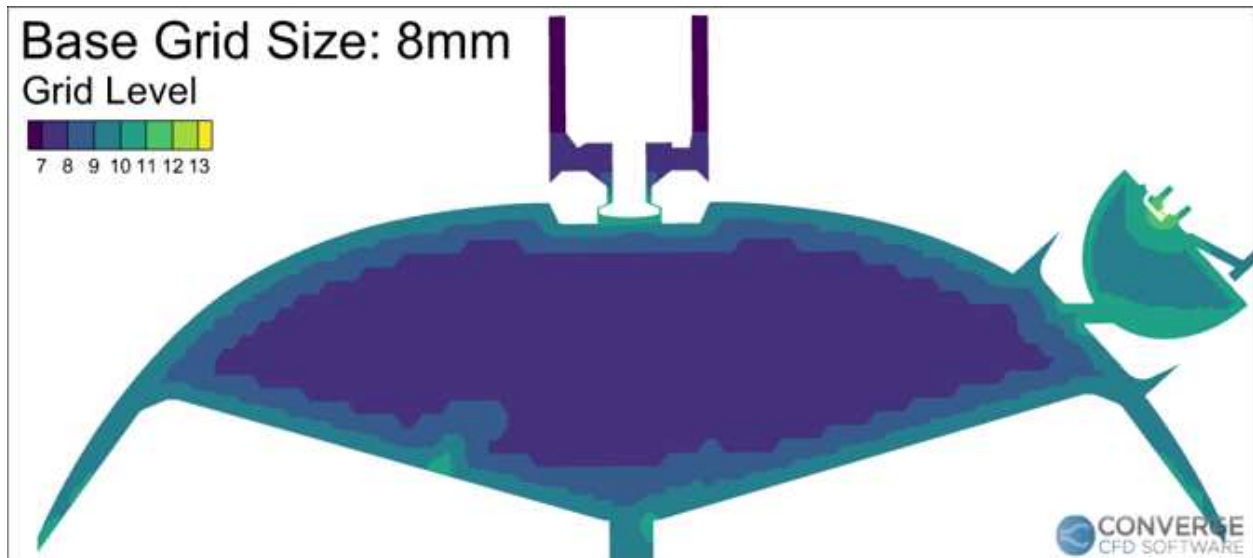
A.3 Grid Independence

Table A.3: Grid Independence Test Parameters

Base Grid Size	Total Cell Count	Min/Max Cell Size (mm)	Strategies	Average y^+ /Std Dev	Targeted Regions
8mm	~8,000,000	0.500/8 (0.250 @ spark)	AMR, Fixed Embedding	7.5/7.5	Cylinder
7mm		0.438/7 (0.218 @ spark)		7/8	PCC intake exhaust
6mm		0.375/6 (0.186 @ spark)		6.5/7	MCC injector PCC injector

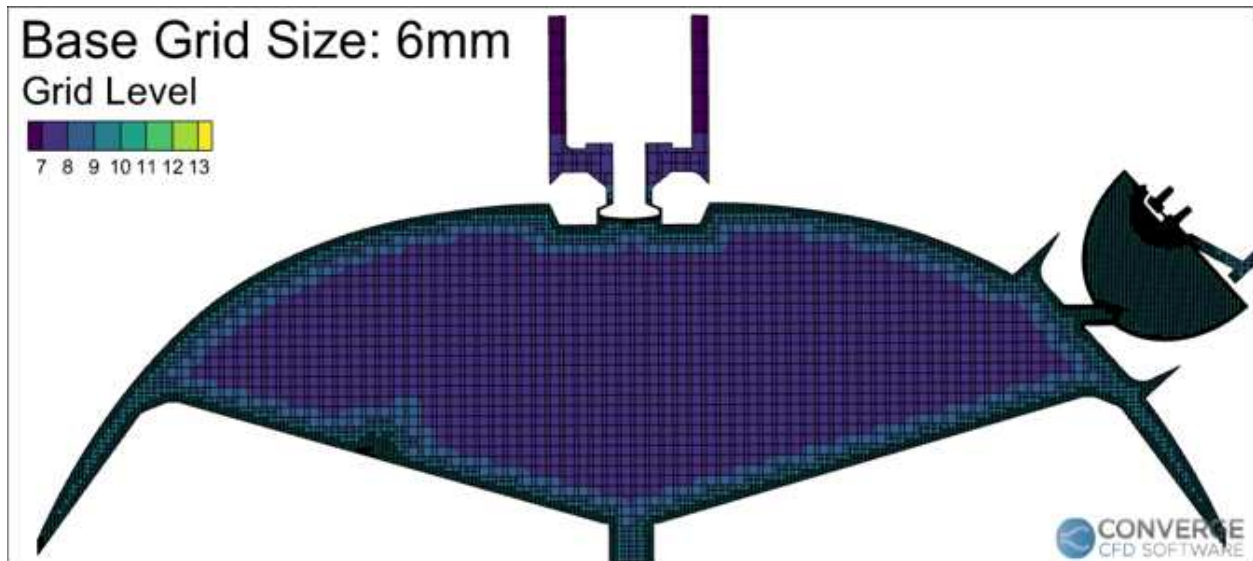


(a) 6 mm

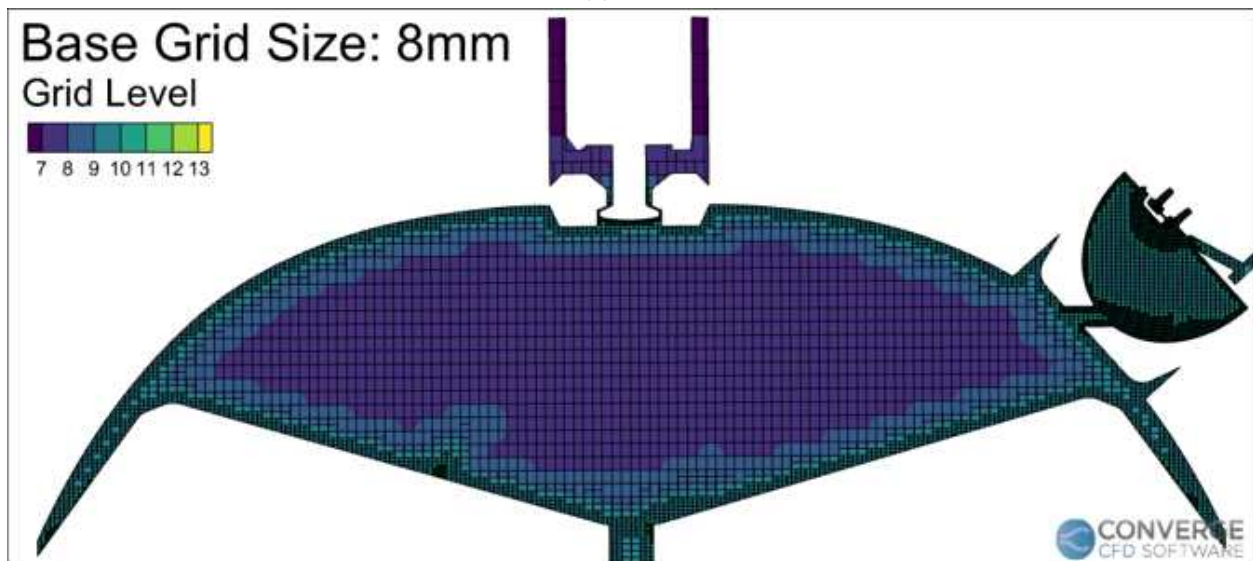


(b) 8 mm

Figure A.1: Mesh grid levels near top dead center for the 6 mm and 8 mm base grid size cases.

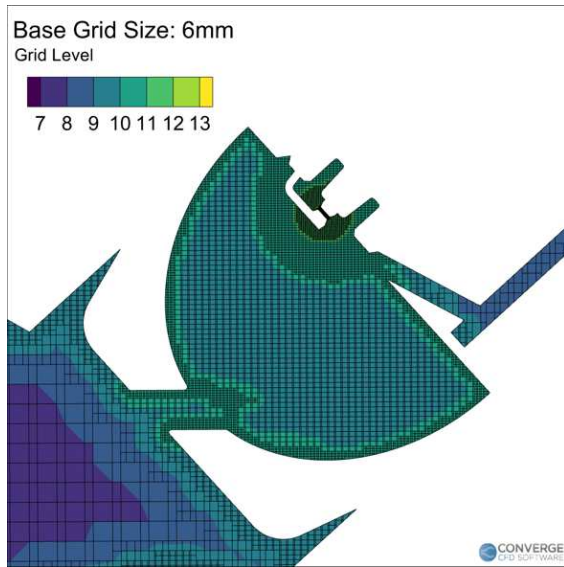


(a) 6 mm

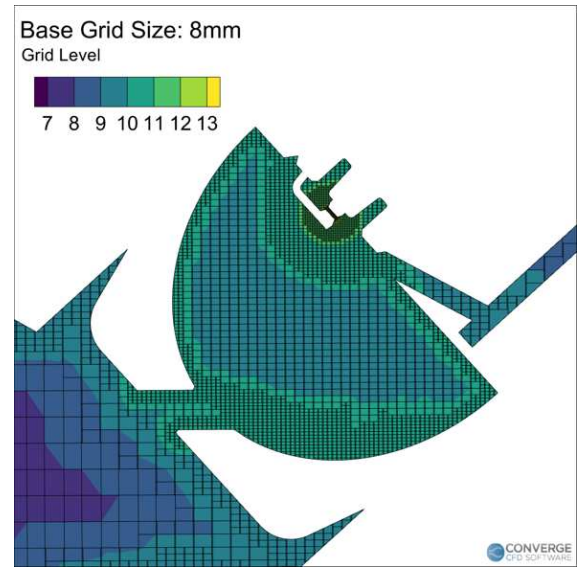


(b) 8 mm

Figure A.2: Mesh grid levels near top dead center for the 6 mm and 8 mm base grid size cases with the computational grid showing.



(a) 6 mm



(b) 8 mm

Figure A.3: Mesh grid levels of the PCC near top dead center for the 6 mm and 8 mm base grid size cases with the computational grid showing.

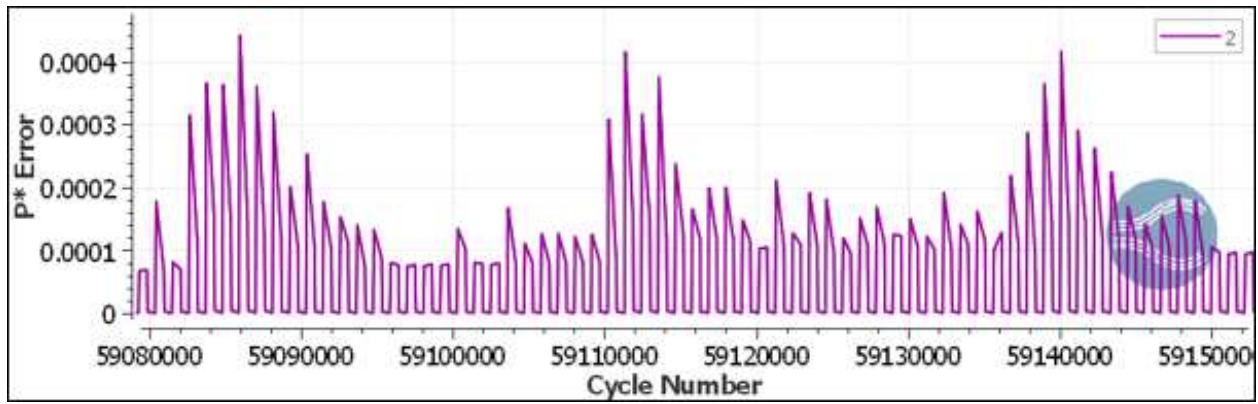


(a) 6 mm

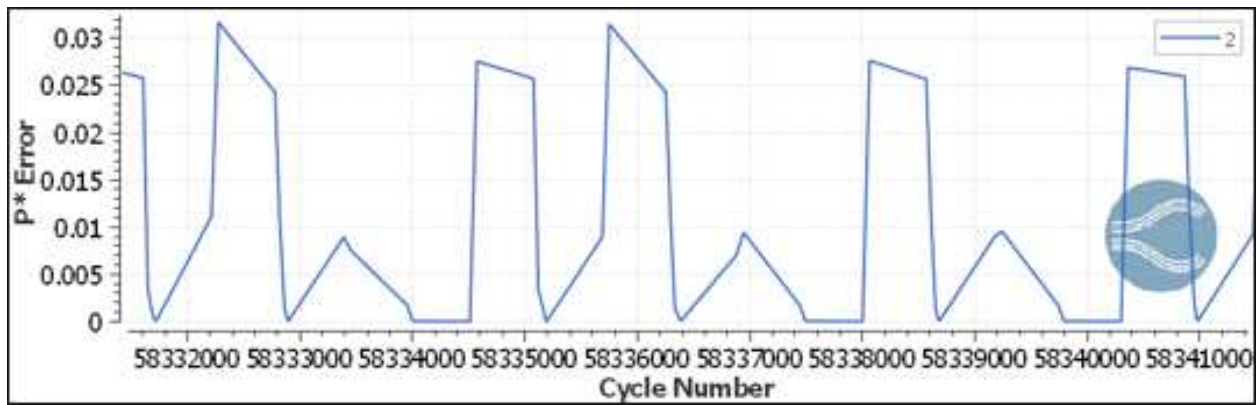


(b) 8 mm

Figure A.4: Mesh grid levels of the spark plug near top dead center for the 6 mm and 8 mm base grid size cases with the computational grid showing.

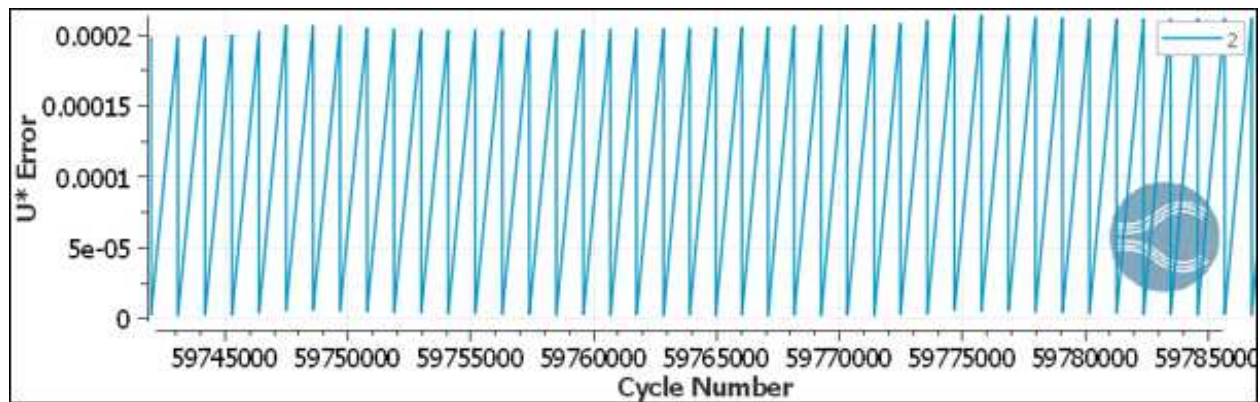


(a) 6 mm

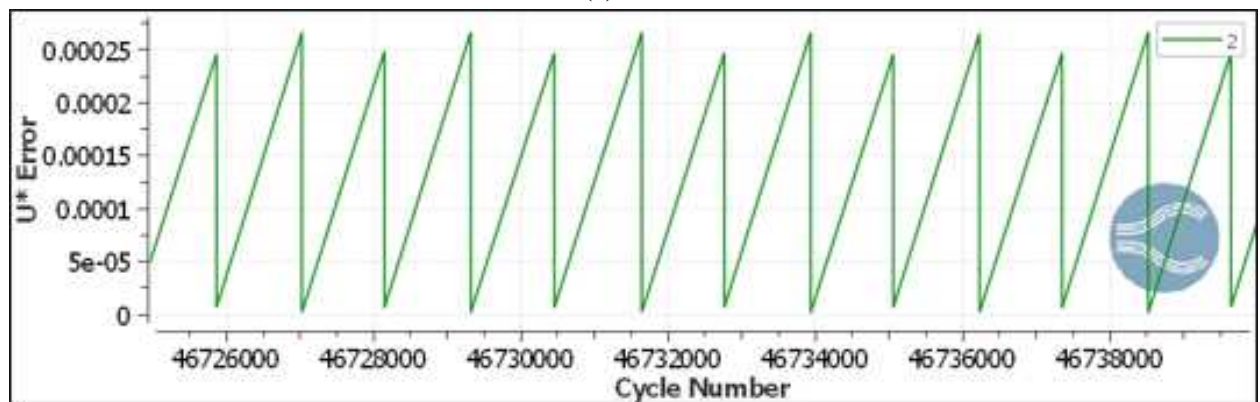


(b) 8 mm

Figure A.5: Error values of p^* for each cycle calculation

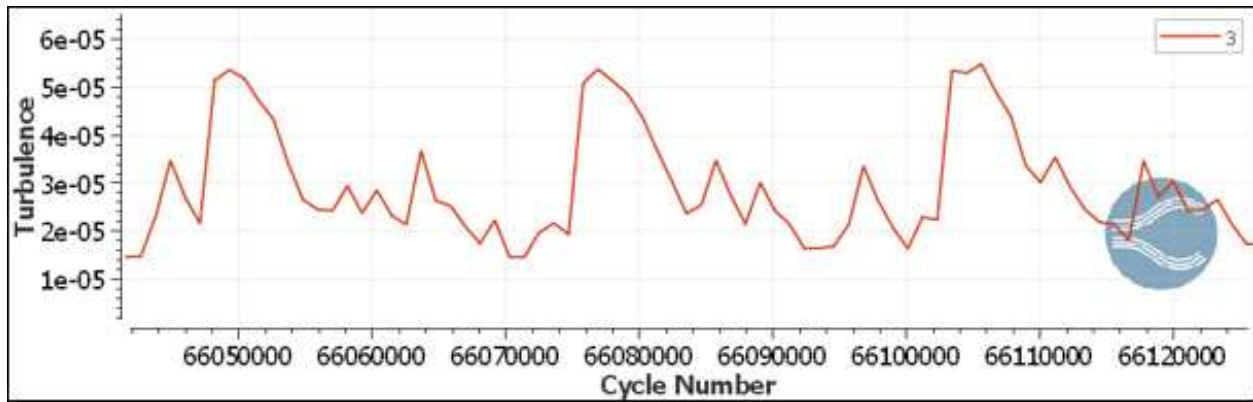


(a) 6 mm

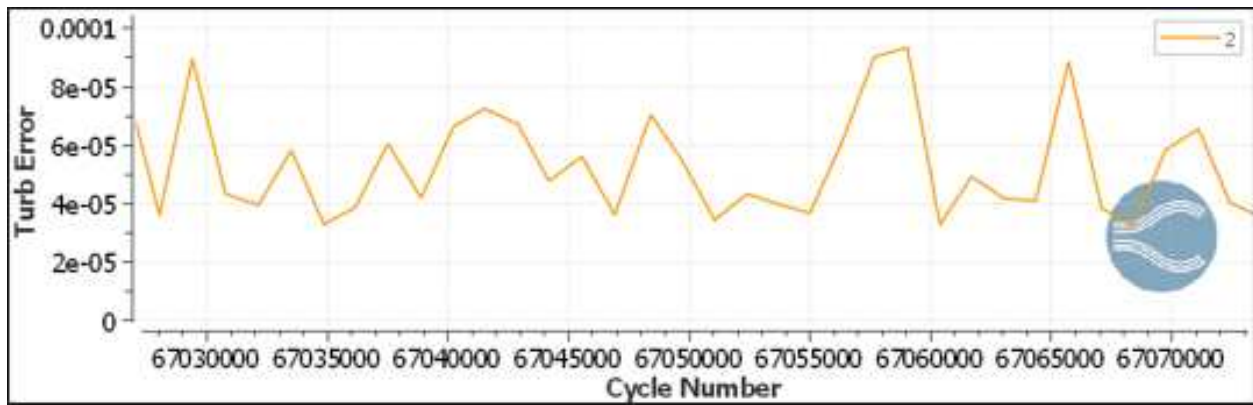


(b) 8 mm

Figure A.6: Error values of u^* for each cycle calculation



(a) 6 mm



(b) 8 mm

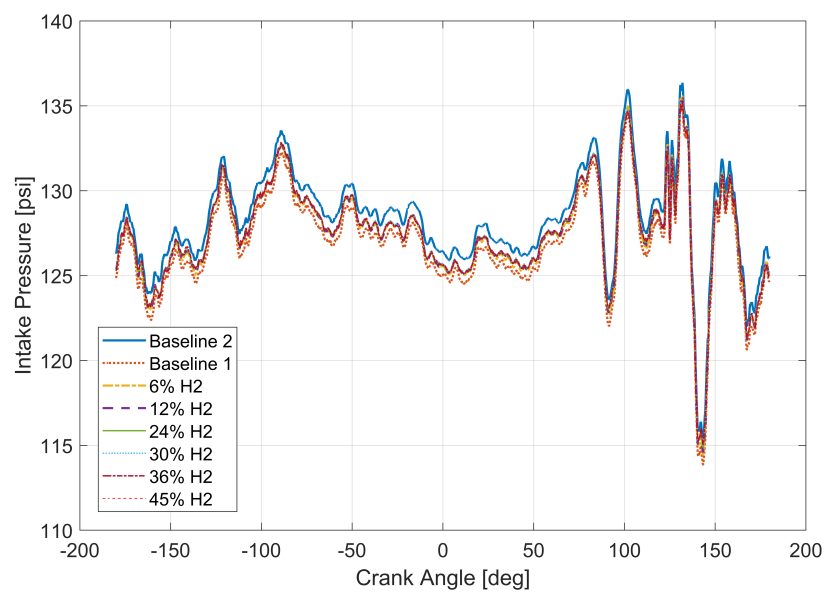
Figure A.7: Error values of the turbulence for each cycle calculation

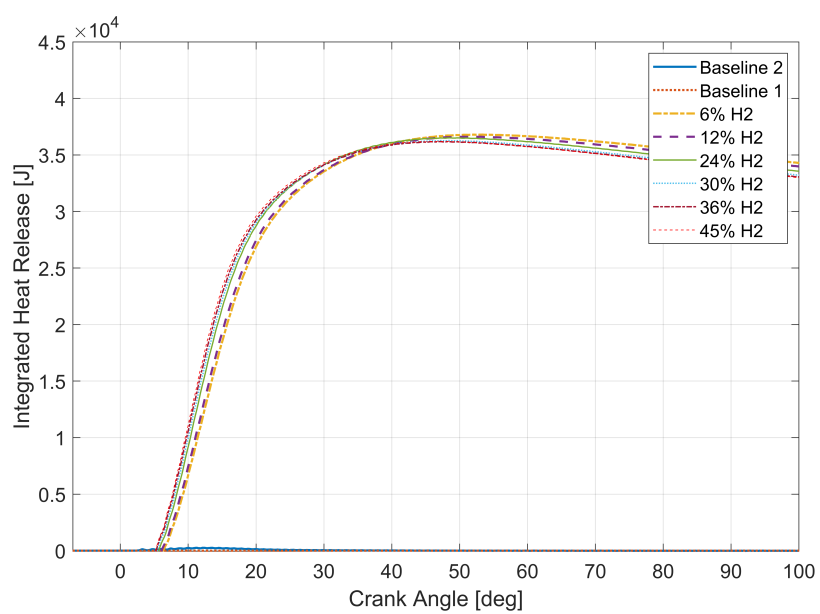
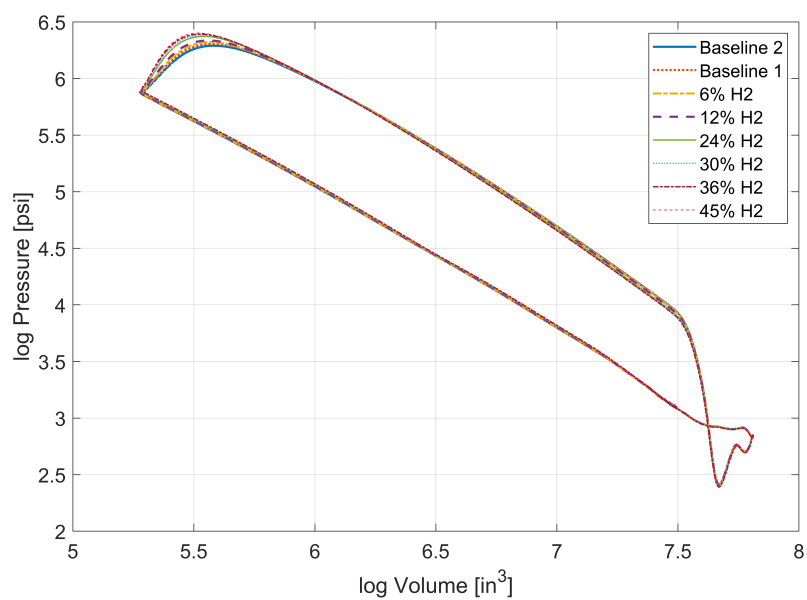
Appendix B

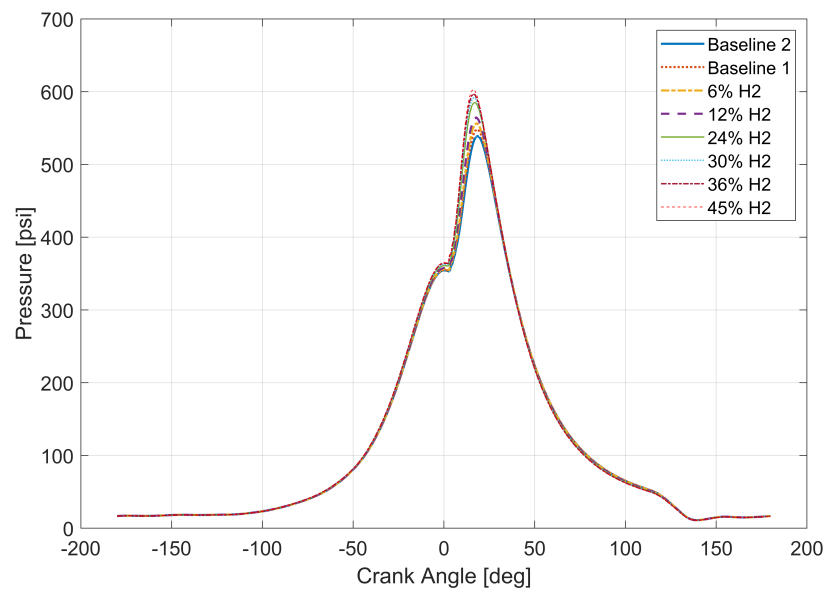
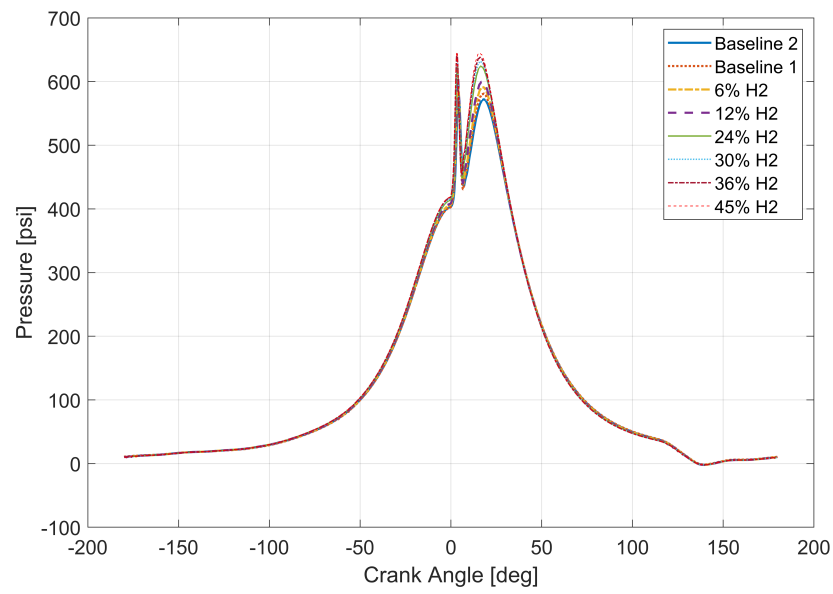
Hydrogen and Natural Gas Blending

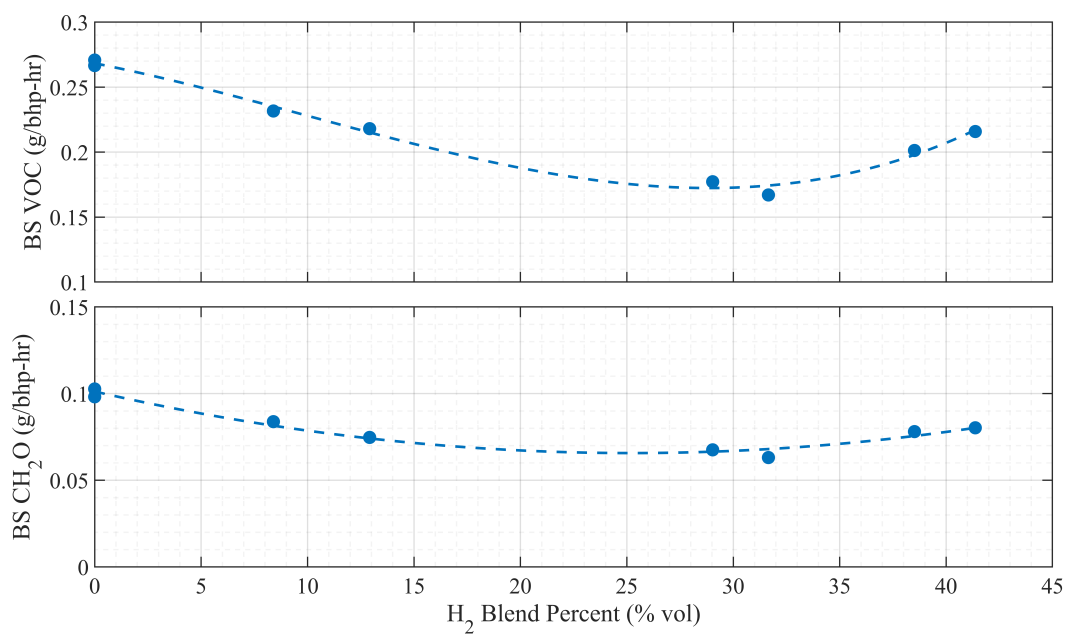
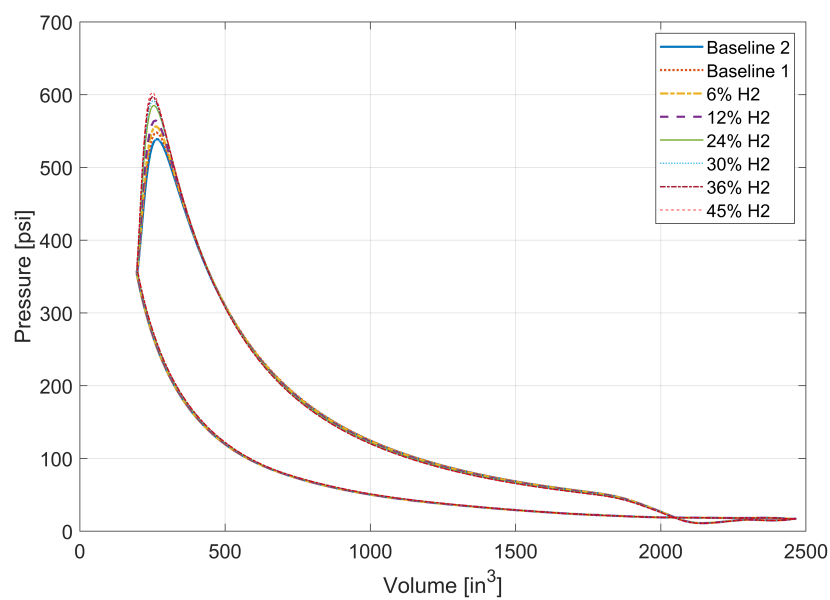
B.1 Extra Plots

HPFI - MCC/PCC Blending

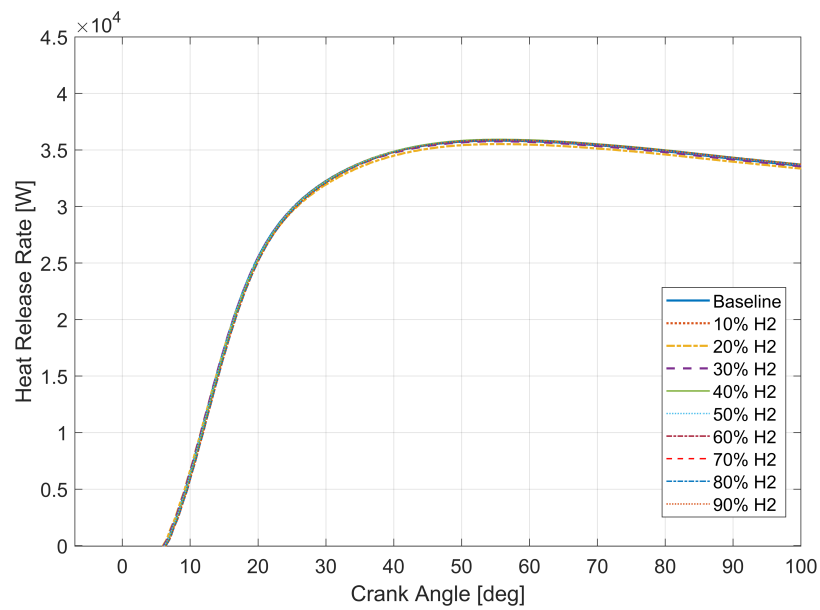
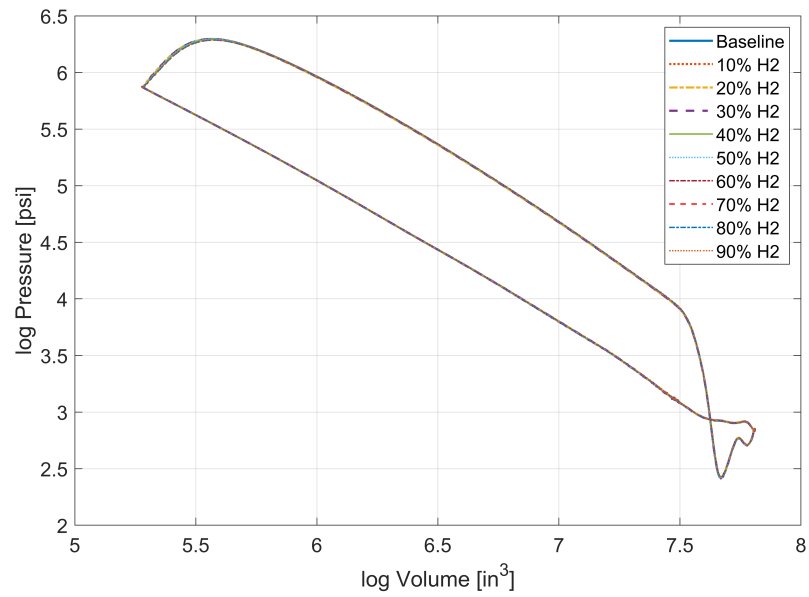


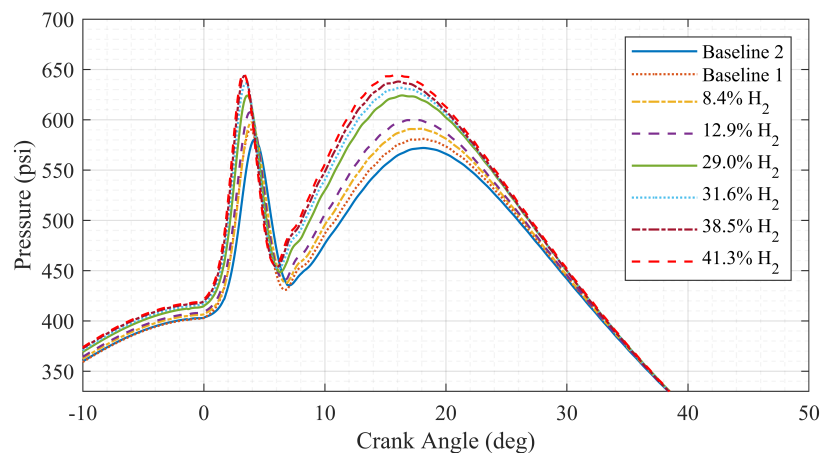
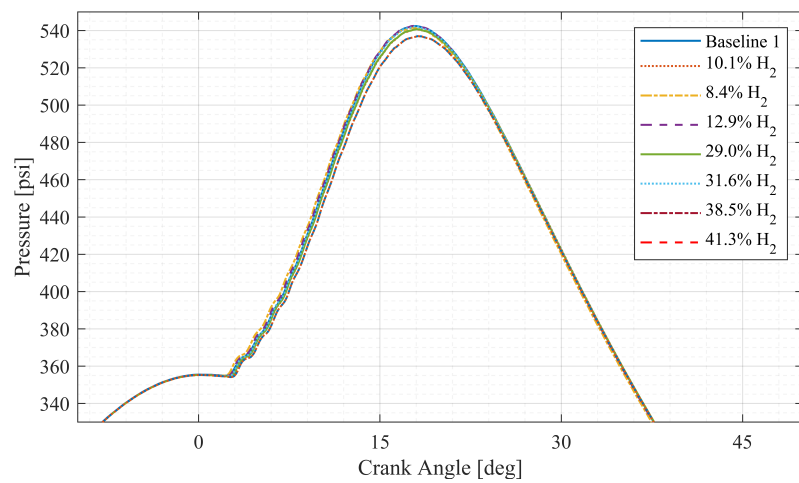
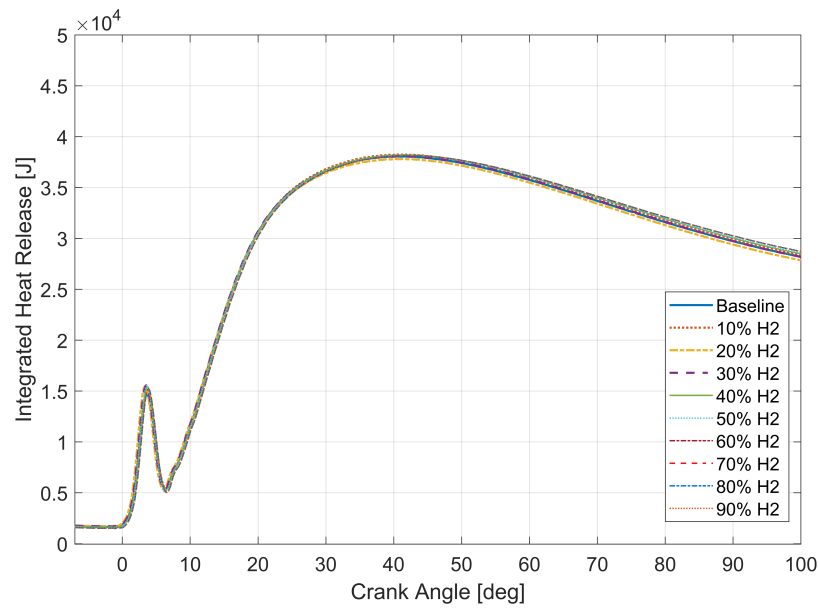


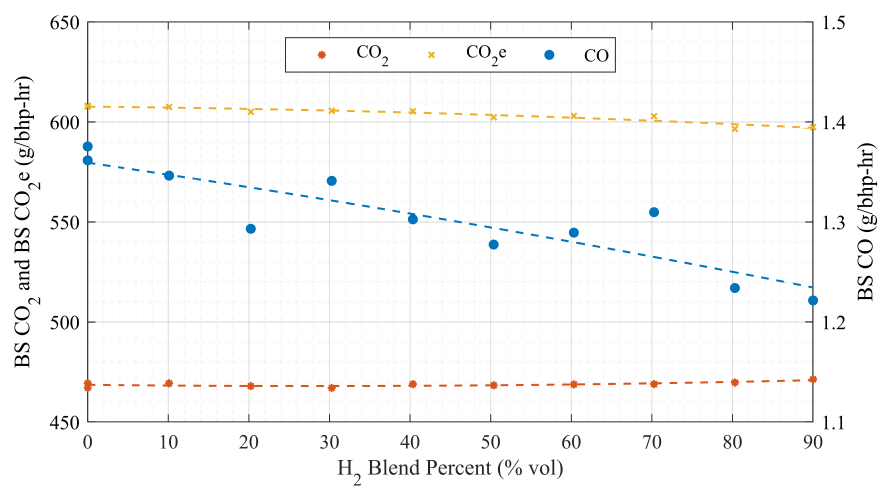
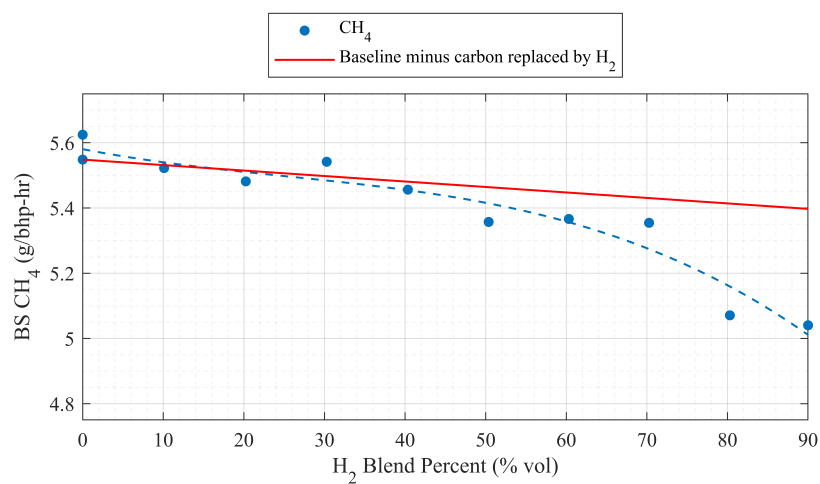
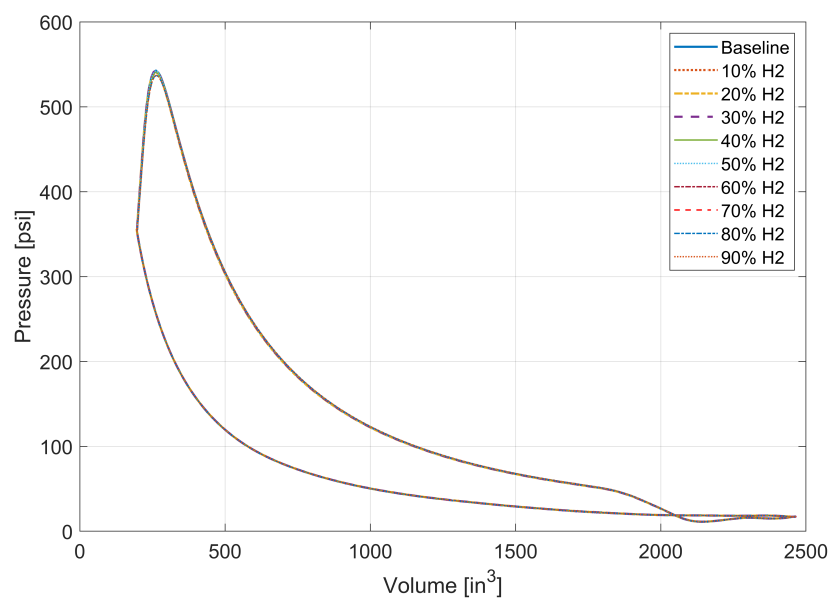




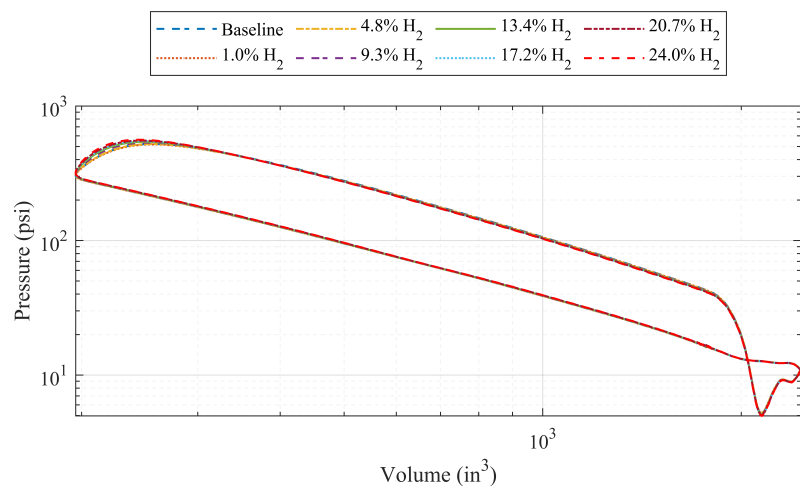
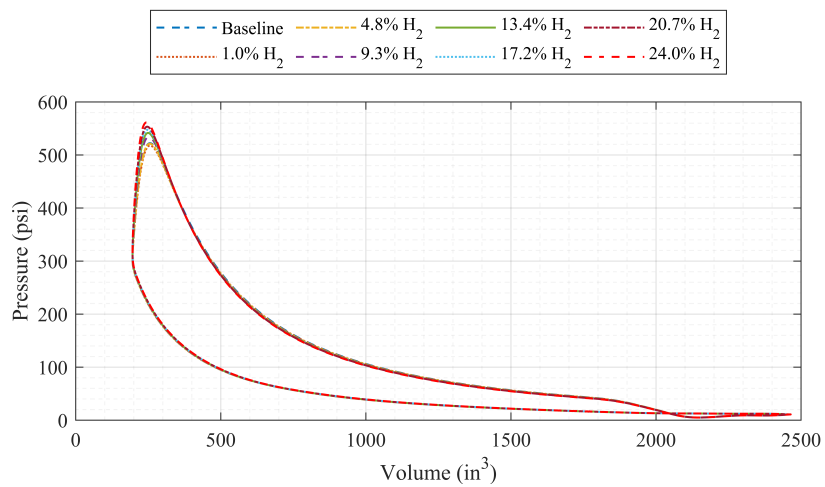
B.1.1 HPFI - PCC Blending

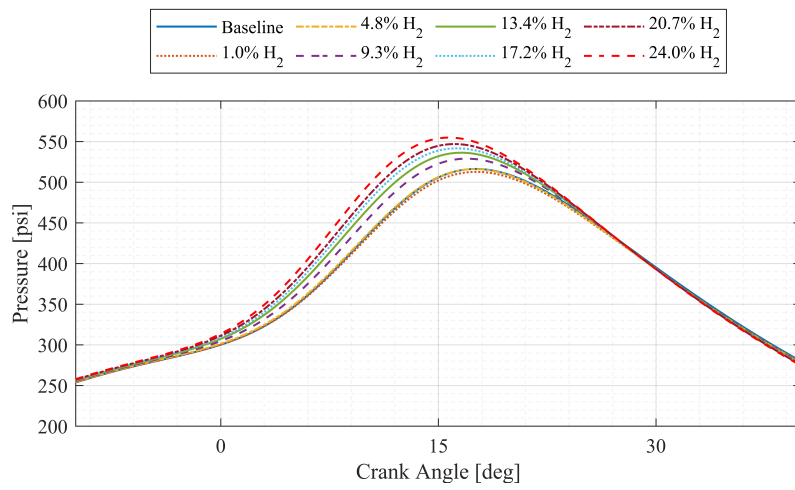
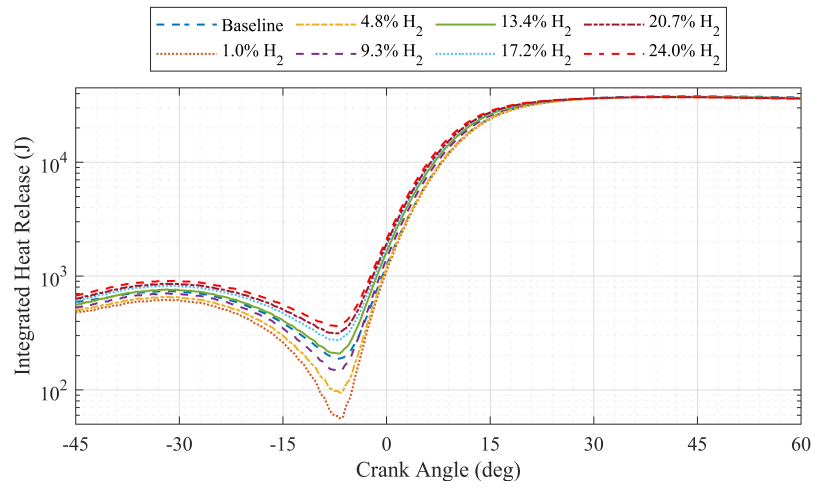
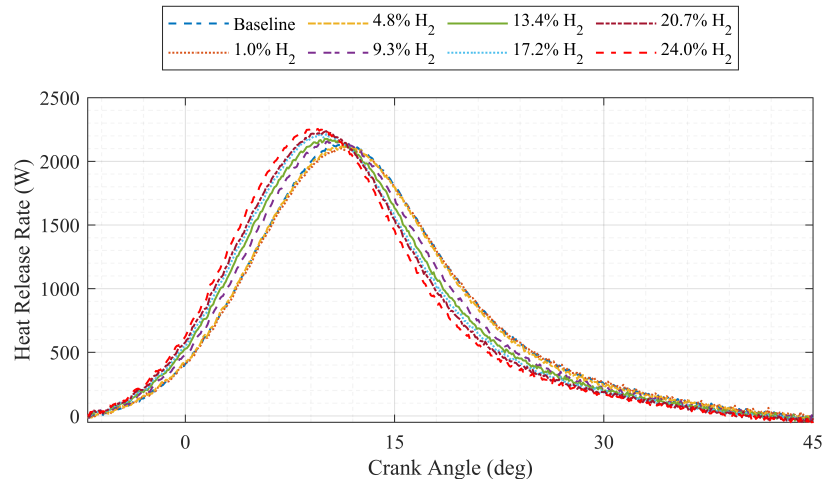


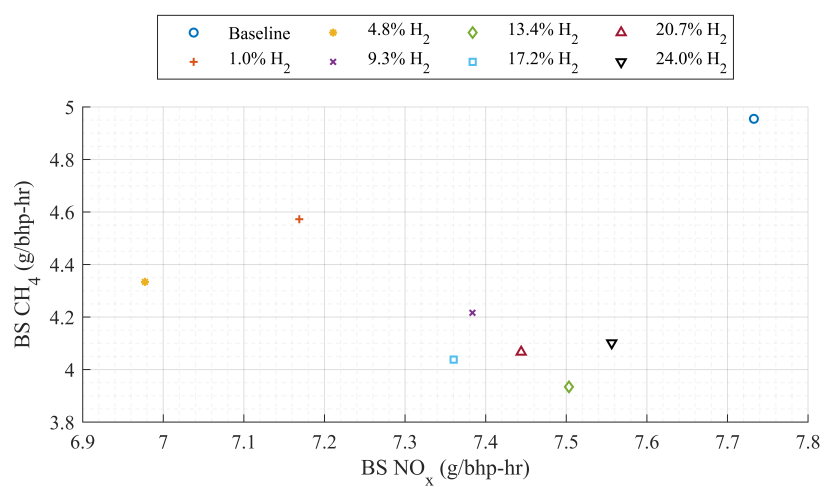
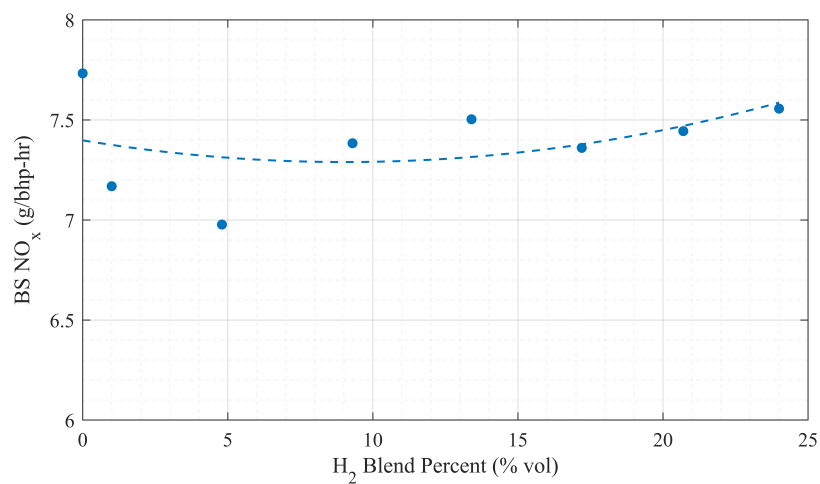
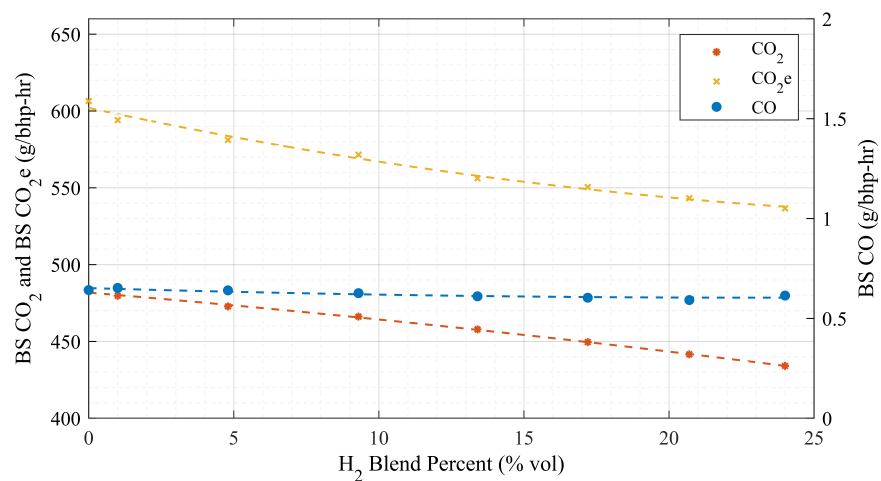


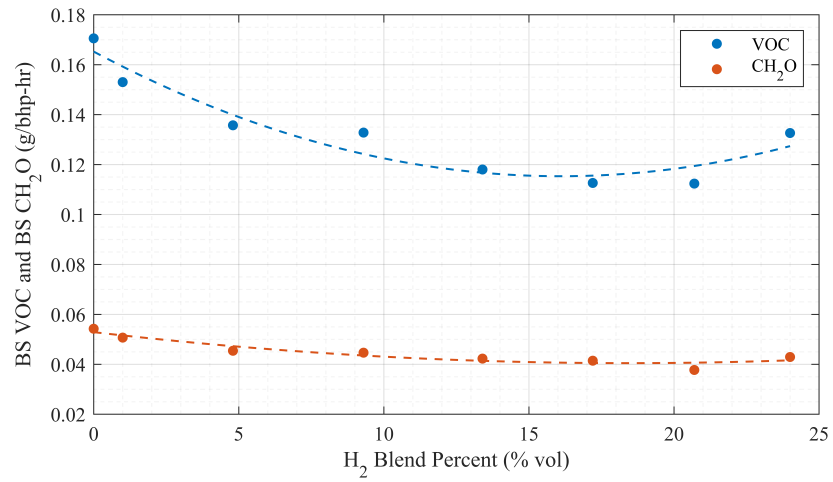


B.1.2 MGAV - Constant Spark Timing

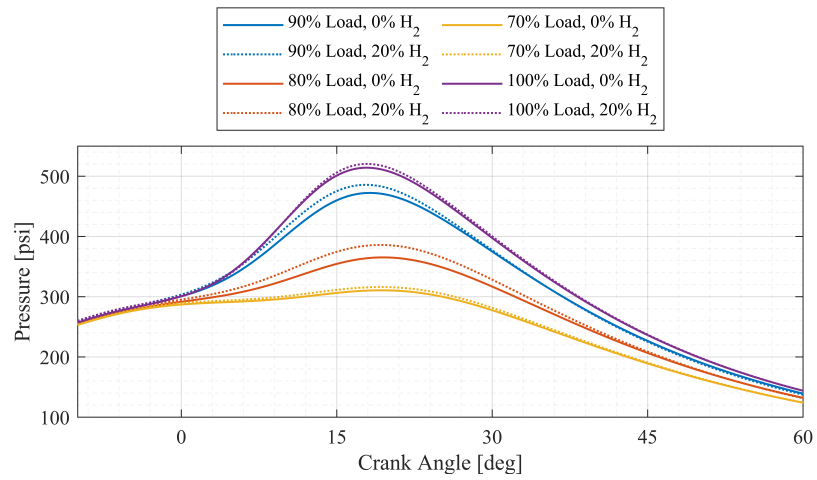


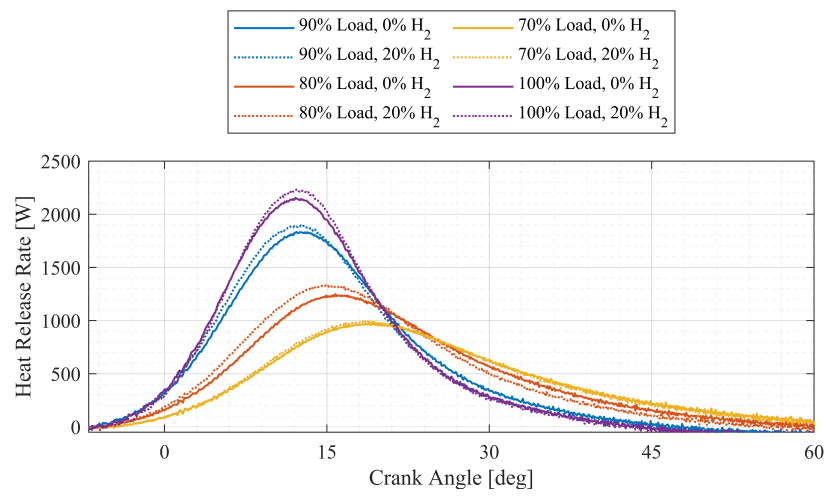
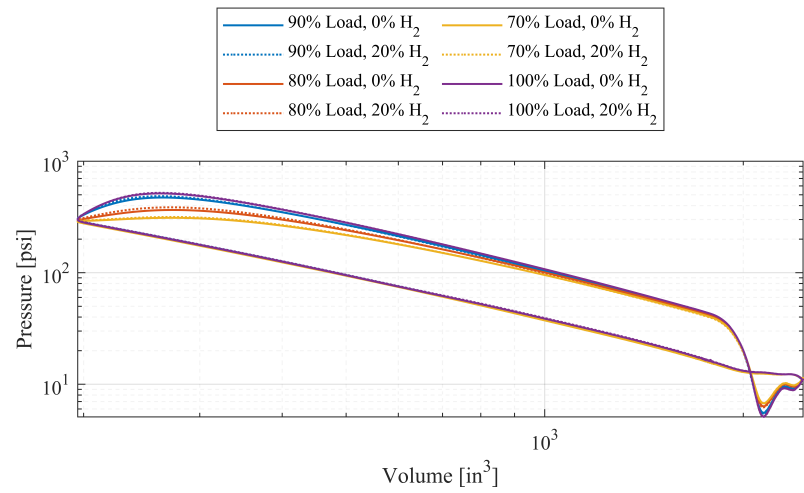
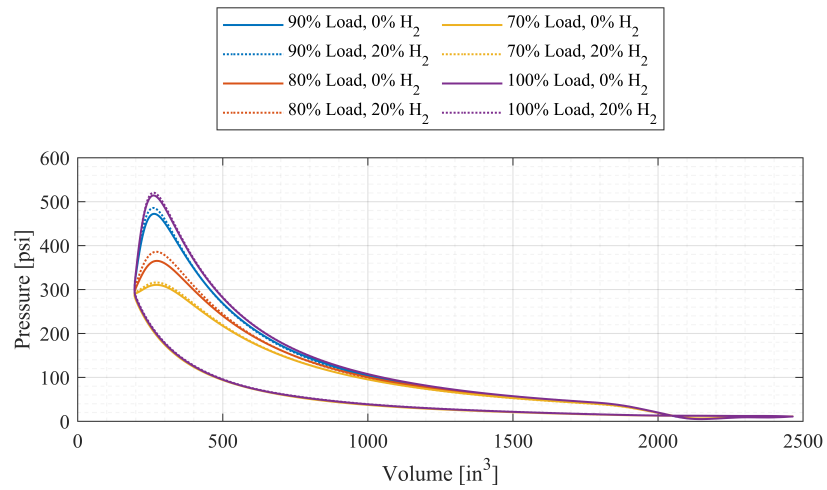






B.1.3 MGAV - Load Sweep with 20% Hydrogen





B.2 Experimental Data

HPFI - MMC/PCC Blending

Data Point Name	Base1	6% H2	12% H2	24% H2	30% H2	36% H2	45% H2	Base 2
Start Time	44929.56806	44929.60417	44929.61042	44929.61736	44929.625	44929.62986	44929.63472	44929.64583
End Time	44929.57153	44929.60764	44929.61389	44929.62083	44929.62847	44929.63333	44929.63819	44929.64931
Speed [rpm]	299.50	299.50	299.60	299.10	299.50	299.50	298.90	299.50
Torque [lb-ft]	7700.00	7712.00	7708.00	7734.00	7717.00	7708.00	7710.00	7712.00
Power [bhp]	439.10	439.80	439.80	440.50	440.10	439.60	438.80	439.80
Load [%]	99.97	100.10	100.10	100.40	100.20	100.10	100.10	100.10
Ambient Press [psia]	12.18	12.18	12.18	12.18	12.18	12.19	12.19	12.19
Ambient Temp [F]	31.24	32.18	32.42	31.36	31.56	31.51	31.81	32.01
Ambient Humidity [%]	60.93	58.15	58.22	60.41	59.82	58.30	58.77	57.81
Inlet Air Pres [in Hg]	39.80	39.80	39.81	39.80	39.80	39.80	39.80	39.80
Inlet Air Temp [F]	108.10	108.00	107.00	109.30	109.30	108.80	108.50	108.20
Inlet Air Humidity [%]	6.65	6.61	7.04	6.34	6.28	6.29	6.50	6.57
Inlet Air Flow [scfm]	2078.00	2081.00	2085.00	2087.00	2087.00	2091.00	2093.00	2077.00
IC Water Temp [F]	116.50	117.80	112.80	114.70	116.60	119.50	119.90	118.30
Exh Back Pres [in Hg]	37.30	37.30	37.30	37.30	37.30	37.30	37.30	37.30
Avg Exh Temp [F]	592.40	588.60	582.60	573.80	568.90	565.10	563.50	594.00
Fuel Flow [lb/hr], Inc. PCC Flow	175.90	174.90	171.80	165.80	162.00	158.50	156.50	177.70
Orifice Temp [F]	44.64	44.95	42.95	44.87	45.49	45.75	45.75	44.53
Eng Fuel Pres [psig]	500.10	500.00	500.10	500.60	499.90	500.10	500.40	500.10
Eng Fuel Temp [F]	56.81	56.74	56.16	55.00	52.08	50.30	50.31	55.24
JW Out Temp [F]	149.40	144.10	144.50	144.50	144.60	144.60	144.70	145.20
JW In Temp [F]	145.10	139.50	139.90	139.90	140.10	140.10	140.20	140.70
JW Flow [gpm]	479.50	481.90	482.40	482.60	483.00	484.20	483.00	483.00
THC [ppmd], analyzer down	-9.29	-9.27	-9.27	-9.27	-9.27	-9.26	-9.26	-9.26
NOx [ppmd]	20.82	25.11	24.48	32.49	31.77	33.55	35.63	21.66
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	15.18	15.21	15.27	15.38	15.44	15.49	15.54	15.16
CO2 [%d]	2.92	2.86	2.79	2.63	2.55	2.46	2.40	2.92
CO [ppmd], analyzer down	478.50	463.00	445.10	426.50	398.80	377.70	393.80	470.60
Air Flow [lb/hr]	9338.00	9352.00	9369.00	9380.00	9378.00	9397.00	9405.00	9333.00
Jacket Water Flow [gpm]	479.50	481.90	482.40	482.60	483.00	484.20	483.00	483.00
Jacket Water Valve Pos [%]	73.05	73.00	73.00	73.00	73.00	73.00	73.00	73.00
Supercharger Speed [%]	48.52	48.90	48.98	49.03	49.08	49.08	49.15	48.88
SC IC Temp Valve Pos [%]	85.50	85.20	85.20	84.12	84.13	84.13	84.18	85.02
Back Pressure Valve Pos [%]	49.71	49.87	50.04	50.40	50.59	50.61	50.55	50.90
Load Valve Pos [%]	21.59	21.95	22.08	21.98	21.82	21.86	21.79	21.89
Dyno Water Flow [gpm]	269.50	269.10	268.20	268.50	269.40	269.30	268.80	268.40
Dyno Water In [F]	69.35	69.44	69.83	69.98	69.97	70.03	70.01	70.16
Dyno Water Out [F]	82.53	82.84	83.14	83.32	83.34	83.41	83.36	83.63
Dyno Inboard Bearing [F]	108.60	109.70	109.80	109.70	109.70	109.60	109.40	109.00
Dyno Outboard Bearing [F]	133.70	136.70	136.80	136.90	136.80	136.70	136.40	135.80
Air Flow Static Pressure [kPa]	143.10	143.10	143.10	143.10	143.10	143.20	143.20	143.10
Air Flow Diff Pressure [kPa]	7.67	7.70	7.69	7.74	7.76	7.79	7.81	7.67
Air Flow Temperature [C]	44.64	44.95	42.95	44.87	45.49	45.75	45.75	44.53
Ethane Flow [lb/hr]	0.10	0.10	0.10	0.08	0.10	0.10	0.10	0.10
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.07	0.03	0.02	0.01	0.00	-0.01	-0.01	-0.02
Ethane Temperature [C]	15.42	14.81	14.75	14.59	14.41	14.27	14.14	13.95
PCC H2 Flow [lb/hr]	0.02	0.04	0.08	0.18	0.23	0.30	0.42	0.00
PCC Nat Gas Flow [lb/hr]	5.06	5.23	5.08	4.90	4.80	4.67	4.44	5.33
PCC H2 Stpt	1.00	0.04	0.08	0.18	0.24	0.30	0.42	0.00
PCC Nat Gas Stpt	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Air Manifold Pres Stpt [in Hg]	39.80	39.80	39.80	39.80	39.80	39.80	39.80	39.80
PCC 4 Temp [F]	77.30	79.49	79.72	79.89	80.07	80.16	80.21	80.33
PCC Flow [lb/hr], ignore	5.08	5.26	5.16	5.08	5.04	4.97	4.85	5.33
Sensor NOx @ 15% O2	21.46	26.02	25.67	34.71	34.35	36.62	39.17	22.24
ePCC Pressure [psig]	17.89	17.90	17.90	17.81	17.97	17.98	17.89	17.98
Fuel Flow Static P [kPa]	368.00	367.30	366.30	365.10	363.40	370.80	374.30	368.00
Fuel Flow Temp [C]	32.32	31.40	30.85	30.01	28.89	28.40	28.18	29.87
Fuel Flow Diff P [kPa]	18.11	17.41	16.56	14.66	13.61	12.45	12.04	18.14
Low Press Orifice Flow [lb/hr], not incl. of PC	179.60	176.30	171.90	162.10	156.00	151.00	149.40	180.50
Air Flow Diff 0 offset	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ign Spark #	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign Timing [deg]	-2.41	-2.41	-2.41	-2.41	-2.41	-2.41	-2.41	-2.41
Ign Offset Cyl 1 [deg]	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Ign Offset Cyl 2 [deg]	-0.44	-0.44	-0.44	-0.44	-0.44	-0.44	-0.44	-0.44
Ign Offset Cyl 3 [deg]	-0.66	-0.66	-0.66	-0.66	-0.66	-0.66	-0.66	-0.66
Ign Offset Cyl 4 [deg]	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Ign 4-20 mA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EFI Hyd Sup Pres [psig]	500.10	500.00	500.10	500.60	499.90	500.10	500.40	500.10
EFI Hyd Ret Pres [psig]	16.25	27.71	27.64	27.38	17.55	17.55	17.05	17.20
LECM RPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HP Meter Fuel Flow [lb/hr], not incl. of PCC	170.80	168.00	163.70	154.30	149.50	143.80	140.60	172.20

HPFI H2 Meter 1 Flow [g/hr]	0.03	0.56	1.07	3.04	3.35	4.39	0.09	0.04
HPFI H2 Meter 2 Flow [kg/hr]	0.08	0.18	0.14	0.14	0.12	0.17	4.86	0.08
HPFI H2 Meter 3 Flow [kg/hr]	-0.02	0.05	0.03	0.05	0.06	0.04	0.08	-0.05
HPFI H2 Meter 1 Stpt	0.00	0.57	1.18	2.61	3.36	4.30	0.00	0.00
HPFI H2 Meter 2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	5.06	0.00
HPFI H2 Meter 3 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Total Flow [kg/hr]	0.10	0.79	1.24	3.23	3.53	4.60	5.03	0.07
HPFI H2 Total Setpoint	0.00	0.57	1.18	2.61	3.36	4.30	5.06	0.00
LP Orifice Fuel Flow [lb/hr]	179.60	176.30	171.90	162.10	156.00	151.00	149.40	180.50
LPFI H2 Meter Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LPFI H2 Meter Flow [kg/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FTIR Data								
NO (350,3000) 191C	19.61	31.05	34.79	28.31	29.70	53.56	30.83	18.28
NO2 (150) 191C (1of2)	17.97	16.54	16.04	15.86	15.87	18.30	17.68	19.91
NO2 (2000) 191C (2of2)	17.34	15.03	14.49	15.43	12.23	16.33	17.81	19.67
N2O (100,200,300) 191C	0.24	0.20	0.28	0.26	0.22	0.18	0.26	0.26
NH3 (300) 191C (1of2)	0.09	0.07	0.12	0.11	0.05	0.12	0.12	0.05
NH3 (3000) 191C (2of2)	0.89	0.37	0.18	0.03	1.38	0.72	2.14	0.49
H2O% (25) 191C	6.08	6.17	6.37	6.40	6.48	6.51	6.14	6.16
CO2% (20) 191C (1of2) R4	3.08	2.99	2.86	2.73	2.59	3.10	3.00	3.13
CO (500) 191C (1of3)	122.70	106.60	98.49	89.88	84.61	94.24	104.70	126.30
CO% (1) 191C (2of3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CH4 (3000) 191C (1of2)	882.90	785.60	717.70	664.60	625.00	724.20	792.70	909.00
CH4 (20000) 191C (2of2)	900.30	802.70	734.60	676.50	646.40	744.30	800.20	921.30
Ethane (500) 191C	77.09	69.50	64.21	59.13	55.19	63.78	69.68	79.27
Ethylene (100,3000) 191C	10.03	8.53	7.55	6.30	5.87	7.56	8.67	10.89
Acetylene (1000) 191C	0.36	0.19	0.51	0.06	0.19	0.04	-0.03	0.39
Propane (200) 191C	6.42	5.96	5.67	5.02	4.63	5.29	5.70	6.61
Propylene (200,1000) 191C	1.31	0.89	0.76	0.43	0.40	0.71	0.47	0.65
Oil as octane (200) 191C	1.79	1.84	1.62	1.74	1.56	1.55	1.63	1.66
Formaldehyde (70,500) 191C	15.80	13.42	11.91	10.83	10.06	12.55	12.95	16.41
Acetaldehyde (1000) 191C	3.72	5.01	3.96	3.25	3.39	3.97	4.08	3.65
Formic Acid (100) 191C	0.46	0.40	0.43	0.43	0.37	0.39	0.38	0.54
MeOH (1000) 191C	0.76	0.53	0.25	0.27	0.36	0.41	0.69	0.76
CO% (10) 191C (3of3)	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01
CO2 low% (4) 191C (2of2)	3.03	2.91	2.81	2.67	2.55	3.02	2.94	3.06
1,3 butadiene (80) 191C	0.24	0.15	-0.10	-0.08	-0.33	0.05	0.55	-0.06
Temp (C)	190.60	190.60	190.70	190.70	190.50	190.60	190.50	190.60
Pressure (Atm)	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
NOx autorange	37.58	47.59	50.83	44.17	45.57	71.86	48.51	38.19
CO autorange	122.70	106.60	98.49	89.88	84.61	94.24	104.70	126.30
CH4 autorange	882.90	785.60	717.70	664.60	625.00	724.20	792.70	909.00
NH3 autorange	0.09	0.07	0.12	0.11	0.05	0.12	0.12	0.05
NOx autorange dry	40.01	50.72	54.29	47.19	48.73	76.87	51.68	40.70
CO autorange dry	130.60	113.60	105.20	96.02	90.47	100.80	111.60	134.60
CO2% autorange dry	3.23	3.11	3.00	2.85	2.73	3.23	3.13	3.26
N2O dry	0.25	0.21	0.30	0.27	0.24	0.19	0.27	0.28
NH3 autorange dry	0.09	0.07	0.13	0.12	0.05	0.13	0.13	0.05
FIDeq THC ppmC	1168.00	1040.00	952.60	877.70	824.50	956.60	1046.00	1202.00
FIDeq NMHC ppmC	197.10	176.10	163.20	146.70	137.00	159.90	174.20	201.80
FIDeq NMNEHC ppmC	42.91	37.09	34.75	28.41	26.63	32.35	34.82	43.28
CO2% autorange	3.03	2.91	2.81	2.67	2.55	3.02	2.94	3.06
FTIR NMHC ppmC	215.20	191.30	176.40	158.90	148.40	174.10	189.20	220.60
FTIR NMNEHC ppmC	60.98	52.36	48.01	40.61	37.98	46.54	49.80	62.02
Igram DC	3.81	3.84	3.83	3.85	3.85	3.81	3.84	3.82
Igram PP	5.96	5.96	5.95	5.95	5.96	5.93	5.95	5.93
phase Angle	90.73	90.67	90.66	90.68	90.88	90.75	90.70	90.63
laser PP	8.87	8.90	8.65	8.69	9.01	8.75	8.72	8.98
laser DC	-6.26	-6.22	-6.22	-6.24	-6.22	-6.21	-6.19	-6.17
Bad Scan counter	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Centerburst Location	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00
Linearizer Check	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNR 2500	704.60	758.00	770.00	668.20	654.60	609.60	747.40	776.90
sBeam @ 2500	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
GC Data								
METHANE [%]	88.68	80.63	88.70	88.74	88.76	88.73	88.71	88.73
ETHANE [%]	8.63	7.85	8.62	8.59	8.61	8.63	8.65	8.63
PROPANE [%]	0.61	0.52	0.57	0.56	0.54	0.54	0.53	0.53
BUTANE [%]	0.09	0.07	0.08	0.07	0.07	0.07	0.07	0.07
PENTANE [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.00	8.40	12.92	29.03	31.65	38.51	41.37	0.00

NITROGEN [%]	0.48	0.47	0.52	0.52	0.52	0.52	0.52	0.52
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.51	1.37	1.51	1.50	1.50	1.50	1.51	1.51
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LHV Actual [kJ/kg]	47430.00	47400.00	47390.00	47400.00	47410.00	47410.00	47400.00	47400.00
LHV Actual [BTU/scf]	966.20	965.10	964.80	964.40	964.30	964.40	964.30	964.10
HHV Dry [kJ/kg]	52480.00	52450.00	52440.00	52450.00	52470.00	52460.00	52450.00	52450.00
HHV Dry [BTU/scf]	1069.00	1068.00	1068.00	1067.00	1067.00	1067.00	1067.00	1067.00
Gas Density [kg/m3]	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Stioch A/F	16.28	16.45	16.56	17.06	17.17	17.46	17.59	16.28
Avg. Mol Weight	17.95	16.60	15.88	13.31	12.88	11.80	11.34	17.95
Cp [kJ/kg*K]	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
Cv [kJ/kg*K]	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
Cp/Cv	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Calculated Data								
AFR	57.52	58.58	59.96	63.03	64.83	66.36	67.44	57.35
Phi total	0.28	0.28	0.27	0.26	0.25	0.24	0.24	0.28
Air Flow [kg/hr]	4721.00	4787.00	4813.00	4885.00	4913.00	4920.00	4937.00	4761.00
Exh Flow [kg/hr]	4803.00	4869.00	4893.00	4962.00	4989.00	4994.00	5010.00	4844.00
BMEP [kPa]	477.10	477.80	477.60	479.20	478.10	477.60	477.70	477.80
thermal eff	0.30	0.30	0.31	0.32	0.33	0.34	0.34	0.30
BSFC [kJ/kW-hr]	11890.00	11810.00	11600.00	11180.00	10950.00	10720.00	10600.00	12000.00
Abs Humidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BSTHC [g/bkW-hr]	9.55	8.64	7.99	7.53	7.16	8.39	9.25	9.90
BS NOx [g/bkW-hr]	0.49	0.60	0.59	0.80	0.79	0.84	0.90	0.51
BS CO [g/bkW-hr]	1.86	1.65	1.54	1.44	1.37	1.54	1.72	1.94
THC @15%O2	1204.00	1078.00	999.10	938.40	891.30	1044.00	1151.00	1235.00
NOx @15%O2	21.46	26.02	25.68	34.74	34.35	36.62	39.22	22.25
CO @15%O2	134.60	117.70	110.30	102.70	97.80	110.00	122.80	138.30
Wet 2 Dry Scaler	1.06	1.06	1.06	1.05	1.05	1.05	1.05	1.06
15% O2 Factor	1.03	1.04	1.05	1.07	1.08	1.09	1.10	1.03
BS Calc Factor	509.60	517.90	522.50	535.10	541.50	546.40	551.30	513.50
Delivery Ratio	1.50	1.53	1.53	1.56	1.57	1.57	1.58	1.52
Scavenging Efficiency	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.78
Trapping Efficiency	0.52	0.51	0.51	0.51	0.50	0.50	0.50	0.51
Trapped AF Ratio	29.74	30.05	30.71	31.89	32.71	33.48	33.93	29.51
Trapped Equivalence Ratio	0.55	0.54	0.53	0.51	0.50	0.48	0.48	0.55
Combustion Data								
Engine Avg Peak Pressure[psi]	551.35	566.30	579.40	609.68	618.08	627.18	636.18	552.40
Engine Avg Peak Pres Std Dev[psi]	14.65	14.44	13.71	12.75	12.87	11.82	11.43	15.44
Engine Avg Peak Pres COV[%]	4.82	4.47	4.11	3.61	3.44	3.19	3.04	4.85
Engine Max Peak Pres COV Ch. #6[%]	18.41	19.22	19.76	17.57	14.94	14.19	14.01	18.05
Engine Min Peak Pres COV Ch. #7[%]	0.22	0.21	0.21	0.25	0.21	0.20	0.22	0.21
Engine Avg Peak Loc[*ATDC]	18.19	17.74	17.23	16.21	15.81	15.50	15.25	18.26
Engine Avg IMEP[psi]	82.50	82.93	82.78	83.05	82.64	82.56	82.75	82.75
Engine Avg IMEP COV[%]	2.05	1.94	1.82	2.22	1.73	1.70	1.71	2.03
Engine Max IMEP COV Ch. #6[%]	1047.00	860.30	968.40	884.80	922.40	1407.00	1110.00	695.00
Engine Min IMEP COV Ch. #8[%]	-3150.00	-3331.00	-2930.00	-2820.00	-3013.00	-3430.00	-2957.00	-3275.00
Avg. Peak Ch. #1psi	544.60	563.70	577.80	614.40	623.40	635.70	646.20	561.00
Avg. Peak Ch. #2psi	540.80	550.50	566.90	596.50	607.40	610.90	625.20	539.60
Avg. Peak Ch. #3psi	569.60	590.30	604.00	637.20	644.40	659.50	664.70	565.90
Avg. Peak Ch. #4psi	550.40	560.70	568.90	590.60	597.10	602.60	608.60	543.10
Avg. Peak Ch. #5psi	601.60	616.00	623.90	644.30	653.50	659.20	663.20	601.00
Peak Std. Dev. Ch. #1psi	25.85	24.36	22.12	21.27	20.81	19.58	19.28	25.77
Peak Std. Dev. Ch. #2psi	27.90	27.72	26.19	23.79	22.18	21.67	20.89	28.52
Peak Std. Dev. Ch. #3psi	34.71	30.34	28.03	25.03	23.14	22.64	21.32	32.33
Peak Std. Dev. Ch. #4psi	18.06	18.86	19.06	18.19	19.05	16.32	15.95	20.65
Peak Std. Dev. Ch. #5psi	18.92	21.49	20.76	19.64	23.75	18.76	18.18	23.32
Peak COV Ch. #1%	4.75	4.32	3.83	3.46	3.34	3.08	2.98	4.60
Peak COV Ch. #2%	5.16	5.04	4.62	3.99	3.65	3.55	3.34	5.28
Peak COV Ch. #3%	6.10	5.14	4.64	3.93	3.59	3.43	3.21	5.71
Peak COV Ch. #4%	3.28	3.36	3.35	3.08	3.19	2.71	2.62	3.80
Peak COV Ch. #5%	3.15	3.49	3.33	3.05	3.63	2.85	2.74	3.88
Max Peak Ch. #1psi	610.60	648.40	651.70	691.40	680.00	689.50	706.00	631.40
Max Peak Ch. #2psi	611.60	616.60	643.20	657.70	668.00	669.60	681.20	635.00
Max Peak Ch. #3psi	668.70	676.70	683.40	702.40	716.10	825.20	727.80	649.80
Max Peak Ch. #4psi	600.40	613.10	619.40	648.00	848.20	662.30	653.80	599.20
Max Peak Ch. #5psi	663.80	681.50	689.00	707.70	945.40	730.10	729.90	666.60
Max Peak Ch. #6psi	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Max Peak Ch. #7psi	136.70	137.50	137.00	138.10	137.10	136.60	136.80	137.30
Max Peak Ch. #8psi	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.21
Max Peak Ch. #9psi	196.50	200.30	201.30	206.30	200.90	200.40	196.70	219.30
Min Peak Ch. #1psi	455.90	487.30	503.70	542.20	553.60	574.90	590.30	443.00
Min Peak Ch. #2psi	424.20	381.20	462.10	513.20	528.10	533.50	545.60	436.40

Min Peak Ch. #3psi	408.40	469.10	485.40	558.60	535.60	586.60	592.60	449.20
Min Peak Ch. #4psi	492.80	473.90	499.50	530.80	544.90	543.80	549.10	467.80
Min Peak Ch. #5psi	541.60	529.70	560.80	584.80	592.80	599.50	611.80	517.10
Min Peak Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Min Peak Ch. #7psi	134.70	135.20	135.20	134.90	135.10	134.80	134.80	135.50
Min Peak Ch. #8psi	0.22	0.21	0.21	0.21	0.21	0.20	0.20	0.20
Min Peak Ch. #9psi	153.70	138.60	158.50	153.60	157.10	155.80	149.20	143.30
Avg. Peak Loc. Ch. #1psi	18.31	17.70	17.19	16.03	15.58	15.32	15.03	18.04
Avg. Peak Loc. Ch. #2psi	18.00	17.73	17.16	16.11	15.70	15.45	15.12	18.20
Avg. Peak Loc. Ch. #3psi	18.24	17.57	16.90	15.79	15.41	14.92	14.74	18.25
Avg. Peak Loc. Ch. #4psi	18.21	17.96	17.65	16.91	16.56	16.29	16.09	18.53
Avg. Peak Loc. Ch. #5psi	8.35	7.99	7.76	8.52	7.95	7.56	7.98	7.49
Peak Loc. Std. Dev Ch. #1psi	1.19	1.12	1.03	0.93	0.91	0.85	0.84	1.15
Peak Loc. Std. Dev Ch. #2psi	1.26	1.23	1.16	1.01	0.97	0.94	0.92	1.32
Peak Loc. Std. Dev Ch. #3psi	1.53	1.30	1.17	1.07	1.03	1.05	1.01	1.42
Peak Loc. Std. Dev Ch. #4psi	0.92	0.97	0.93	0.90	0.91	0.80	0.77	1.03
Peak Loc. Std. Dev Ch. #5psi	6.50	6.21	6.10	6.30	6.12	5.94	6.09	5.85
Peak Loc. COV Ch. #1%	6.51	6.31	5.99	5.83	5.82	5.53	5.56	6.40
Peak Loc. COV Ch. #2%	6.99	6.94	6.75	6.29	6.21	6.09	6.10	7.26
Peak Loc. COV Ch. #3%	8.41	7.40	6.90	6.80	6.68	7.07	6.84	7.77
Peak Loc. COV Ch. #4%	5.03	5.41	5.24	5.30	5.52	4.88	4.76	5.56
Peak Loc. COV Ch. #5%	77.82	77.73	78.63	73.95	76.98	78.66	76.25	78.18
AVG IMEP Ch. #1psi	77.32	77.77	77.47	77.79	77.36	77.34	77.40	78.85
AVG IMEP Ch. #2psi	79.18	79.35	79.72	80.08	79.94	79.30	80.01	79.70
AVG IMEP Ch. #3psi	95.26	96.37	95.96	96.46	95.88	96.50	96.42	94.67
AVG IMEP Ch. #4psi	78.24	78.23	77.97	77.85	77.36	77.11	77.18	77.77
AVG IMEP Ch. #5psi	59.37	58.11	57.71	57.73	57.41	57.20	57.53	58.14
IMEP STD DEV Ch. #1psi	2.13	2.10	2.07	2.18	2.10	2.15	2.22	2.11
IMEP STD DEV Ch. #2psi	1.18	1.09	0.91	1.12	0.68	0.61	0.60	1.17
IMEP STD DEV Ch. #3psi	1.84	1.57	1.37	1.97	1.22	1.15	1.08	1.79
IMEP STD DEV Ch. #4psi	1.57	1.61	1.58	2.04	1.60	1.57	1.62	1.64
IMEP STD DEV Ch. #5psi	3.07	2.87	2.88	2.99	2.72	2.69	2.66	3.09
IMEP COV Ch. #1%	2.76	2.70	2.67	2.81	2.71	2.78	2.87	2.68
IMEP COV Ch. #2%	1.49	1.38	1.14	1.40	0.85	0.77	0.75	1.46
IMEP COV Ch. #3%	1.93	1.63	1.43	2.04	1.27	1.19	1.12	1.89
IMEP COV Ch. #4%	2.01	2.05	2.03	2.63	2.07	2.04	2.10	2.11
IMEP COV Ch. #5%	5.17	4.95	5.00	5.19	4.74	4.70	4.63	5.32
MFB 10% Ch. #1*ATDC	6.78	6.52	6.24	5.59	5.31	5.07	4.89	6.76
MFB 10% Ch. #2*ATDC	5.81	5.71	5.42	4.92	4.69	4.50	4.31	5.97
MFB 10% Ch. #3*ATDC	6.46	6.18	5.69	5.06	4.84	4.57	4.44	6.49
MFB 10% Ch. #4*ATDC	6.90	6.76	6.53	6.11	5.88	5.75	5.65	7.18
MFB 10% Ch. #5*ATDC	2.03	2.07	1.93	1.73	1.61	1.51	1.44	2.31
MFB 50% Ch. #1*ATDC	14.97	14.20	13.57	12.17	11.71	11.32	10.99	14.53
MFB 50% Ch. #2*ATDC	14.68	14.25	13.54	12.22	11.70	11.42	10.98	14.86
MFB 50% Ch. #3*ATDC	15.83	14.98	14.20	12.72	12.29	11.71	11.48	15.92
MFB 50% Ch. #4*ATDC	14.60	14.24	13.83	12.92	12.59	12.32	12.09	14.98
MFB 50% Ch. #5*ATDC	13.88	13.52	13.16	12.41	12.11	11.86	11.66	14.24
MFB 90% Ch. #1*ATDC	28.91	27.49	26.42	23.94	23.37	22.62	22.02	27.90
MFB 90% Ch. #2*ATDC	30.24	29.40	28.08	25.88	24.94	24.62	23.64	30.48
MFB 90% Ch. #3*ATDC	37.95	36.65	35.96	33.86	33.66	32.81	32.50	38.23
MFB 90% Ch. #4*ATDC	29.00	28.19	27.40	25.78	25.33	25.00	24.53	29.38
MFB 90% Ch. #5*ATDC	24.36	23.65	22.98	21.84	21.39	21.11	20.86	24.69
Low Cycles [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #3*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #3*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Analysis Corrections for H2 Blending								
Total Fuel Flow (lb/hr)	175.90	174.90	171.80	165.80	162.00	158.50	156.50	177.70
H2 Fuel Flow (lb/hr)	0.00	1.78	2.82	7.29	8.02	10.43	11.51	0.00
H2 mass fraction (%)	0.00	1.02	1.64	4.40	4.95	6.58	7.35	0.00
H2 mole fraction (%)	0.00	8.40	12.92	29.03	31.65	38.51	41.37	0.00
Average MW (kg/kmol)	17.95	16.60	15.88	13.31	12.88	11.80	11.34	17.92
PCC H2 Mole Fraction (%)	0.00	5.61	10.91	19.27	23.81	27.34	34.51	0.00
Updated Fuel Composition Analysis								
METHANE [%]	88.68	81.23	77.24	62.98	60.67	54.56	52.01	88.73
ETHANE [%]	8.63	7.91	7.50	6.10	5.88	5.31	5.07	8.63
PROPANE [%]	0.61	0.52	0.49	0.39	0.37	0.33	0.31	0.53
BUTANE [%]	0.09	0.07	0.07	0.05	0.05	0.04	0.04	0.07
PENTANE [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.00	8.40	12.92	29.03	31.65	38.51	41.37	0.00
NITROGEN [%]	0.48	0.47	0.45	0.37	0.36	0.32	0.31	0.52
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.51	1.38	1.31	1.07	1.02	0.92	0.88	1.51
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Composition Check (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LHV (kJ/kg)	47430.00	48140.27	48580.84	50593.36	51004.89	52187.83	52738.00	47400.00
LHV (Btu/g)	44.95	45.63	46.04	47.95	48.34	49.46	49.99	44.93
Updated A/F Ratio and BS Parameter Analysis								
Carbon #	1.10	1.00	0.95	0.78	0.75	0.67	0.64	1.09
Carbon % reduction from baseline	0.00	-8.52	-13.06	-29.19	-31.82	-38.66	-41.51	-0.26
Hydrogen #	4.12	3.94	3.85	3.50	3.45	3.30	3.24	4.12
Oxygen #	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03
Nitrogen #	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
y, H/C	3.76	3.93	4.03	4.51	4.61	4.91	5.05	3.76
z, O/C	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
f, N/C	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Stoichiometric A/F Ratio	16.28	16.45	16.56	17.06	17.17	17.46	17.59	16.27
CO2 (% , dry)	2.92	2.86	2.79	2.63	2.55	2.46	2.40	2.92
O2 (% , dry)	15.18	15.21	15.27	15.38	15.44	15.49	15.54	15.16
THC (ppmd)	1243.55	1108.33	1017.44	937.67	881.60	1023.17	1114.44	1280.85
CO (ppmd)	130.64	113.60	105.19	96.02	90.47	100.80	111.55	134.59
NOx (ppmd)	20.82	25.11	24.48	32.49	31.77	33.55	35.63	21.66
CH4 (ppmd)	940.01	837.21	766.55	710.01	668.28	774.60	844.56	968.63
VOC (ppmd)	45.69	39.53	37.12	30.35	28.47	34.60	37.10	46.12
CH2O (ppmd)	16.82	14.30	12.72	11.57	10.76	13.42	13.80	17.49
U&S, H2FAC	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
U&S, a	6.82	6.99	7.18	7.66	7.89	8.14	8.31	6.80
phi, overall	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.28
A/F, overall	57.62	58.42	59.61	61.81	63.35	64.24	64.98	57.44
phi, trapped	0.55	0.55	0.54	0.55	0.54	0.54	0.54	0.55
A/F, trapped	29.79	29.97	30.53	31.28	31.97	32.41	32.68	29.55
Airflow (kg/hr)	10135.09	10218.24	10241.45	10248.56	10263.43	10182.26	10169.19	10206.28
BS THC (g/bhp-hr)	7.26	6.50	5.98	5.48	5.17	5.95	6.48	7.52
BS CO (g/bhp-hr)	1.33	1.16	1.08	0.98	0.93	1.02	1.13	1.38
BS NOx (g/bhp-hr)	0.35	0.42	0.41	0.54	0.53	0.56	0.59	0.36
reduction in BS NOx (g/bhp-hr) / H2 mole fra	0.000000	0.008766	0.004957	0.006741	0.005882	0.005486	0.005950	0.000000
BS NOx % change from baseline	0.00	21.13	18.38	56.16	53.43	60.64	70.64	4.68
BS CH4 (g/bhp-hr)	5.49	4.91	4.50	4.15	3.92	4.51	4.91	5.69
reduction in BS CH4 (g/bhp-hr) / H2 mole fra	0.000000	0.093024	0.091667	0.053098	0.055814	0.030687	0.018697	0.000000
BS CH4 % change from baseline	0.00	-10.55	-17.90	-24.41	-28.52	-17.86	-10.41	3.69
BS CH4 change from baseline incl C reduc	0.00	2.03	4.84	-4.78	-3.31	-20.80	-31.10	-3.95
BS CH4 (g/bhp-hr/C atom)	5.00	4.89	4.72	5.34	5.24	6.70	7.66	5.20
BS VOC (g/bhp-hr)	0.27	0.23	0.22	0.18	0.17	0.20	0.22	0.27
BS CH2O (g/bhp-hr)	0.10	0.08	0.07	0.07	0.06	0.08	0.08	0.10
BS CO2 (g/bhp-hr)	466.67	460.16	450.18	421.99	410.80	392.59	383.12	469.58
BS CO2e (g/bhp-hr)	603.81	582.83	562.77	525.65	508.84	505.24	505.98	611.78
BSFC (Btu/bhp-hr)	8167.02	8229.08	8157.20	8185.41	8070.19	8088.15	8084.99	8232.25
BSFC (% change from baseline 2)	-0.79	-0.04	-0.91	-0.57	-1.97	-1.75	-1.79	0.00
Ignition Delay (deg)	8.79	8.59	8.27	7.72	7.48	7.27	7.12	8.90
Combustion Duration (deg)	25.04	24.14	23.50	21.94	21.65	21.29	20.85	24.90

HPFI - PCC Blending

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LHV Actual [kJ/kg]	47514.61	48420.66	47540.00	47540.00	47540.00	47540.00	47540.00	47540.00	47540.00	47560.00	47580.00	47870.00
LHV Actual [BTU/scf]	965.70	963.60	965.70	965.70	965.70	965.70	965.30	963.80	963.30	963.30	963.10	960.80
HHV Dry [kJ/kg]	52610.00	52650.00	52610.00	52610.00	52610.00	52610.00	52610.00	52610.00	52640.00	52650.00	52990.00	
HHV Dry [BTU/scf]	1069.00	1066.00	1069.00	1069.00	1069.00	1069.00	1068.00	1067.00	1066.00	1066.00	1064.00	
Gas Density [kg/m3]	0.76	0.75	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.75	0.75	0.75
Stoich A/F	16.25	16.27	16.25	16.25	16.25	16.25	16.25	16.26	16.26	16.26	16.27	16.37
Avg. Mol Weight	17.89	16.29	17.89	13.09	11.49	9.90	8.32	6.74	5.14	3.58	17.68	
Cp [kJ/kg*K]	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.13
Cv [kJ/kg*K]	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.66	
Cp/Cv	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Calculated Data												
AFR	57.56	57.44	57.84	57.71	57.75	57.80	57.78	57.72	57.92	58.07	57.82	
Phi total	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Air Flow [kg/hr]	4748.00	4745.00	4753.00	4747.00	4746.00	4746.00	4741.00	4740.00	4752.00	4749.00	4758.00	
Exh Flow [kg/hr]	4830.00	4827.00	4835.00	4829.00	4829.00	4828.00	4823.00	4822.00	4834.00	4831.00	4840.00	
BMEP [kPa]	476.40	477.50	477.00	478.20	476.70	477.30	477.10	477.80	478.40	476.10	477.70	
thermal eff	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	
BSFC [kJ/kW-hr]	11990.00	11990.00	11930.00	11910.00	11940.00	11920.00	11920.00	11910.00	11880.00	11910.00	12020.00	
Abs Humidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BSTHC [g/bkW-hr]	9.61	9.55	9.48	9.58	9.43	9.27	9.26	9.24	8.74	8.67	9.69	
BS NOx [g/bkW-hr]	0.48	0.57	0.53	0.55	0.54	0.55	0.55	0.58	0.53	0.38	0.45	
BS CO [g/bkW-hr]	1.93	1.89	1.81	1.88	1.82	1.79	1.80	1.83	1.72	1.70	1.91	
THC @ 15%O2	1279.00	1259.00	1261.00	1275.00	1249.00	1229.00	1227.00	1225.00	1157.00	1142.00	1273.00	
NOx @ 15%O2	22.18	26.18	24.51	25.56	25.10	25.63	25.57	26.90	24.46	17.40	20.75	
CO @ 15%O2	146.90	142.40	137.90	143.10	138.20	135.70	136.80	138.80	130.30	128.20	144.00	
Wet 2 Dry Scaler	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	
15% O2 Factor	1.08	1.07	1.08	1.08	1.07	1.07	1.07	1.07	1.07	1.07	1.07	
BS Calc Factor	504.60	504.30	505.30	503.40	505.20	504.60	504.40	503.60	504.40	507.00	505.70	
Delivery Ratio	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	
Scavenging Efficiency	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	
Trapping Efficiency	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	
Trapped AF Ratio	29.71	29.64	29.84	29.75	29.80	29.80	29.83	29.78	29.84	29.96	29.79	
Trapped Equivalence Ratio	0.55	0.55	0.54	0.55	0.55	0.55	0.54	0.55	0.55	0.54	0.55	
Combustion Data												
Engine Avg Peak Pressure[psi]	554.18	559.80	566.88	563.88	561.28	564.08	560.25	563.83	561.18	554.90	553.20	
Engine Avg Peak Pres Std Dev[psi]	26.67	24.22	24.18	23.90	23.43	22.75	22.70	22.89	23.41	25.29	26.19	
Engine Avg Peak Pres COV[%]	4.80	4.32	4.25	4.23	4.17	4.02	4.05	4.05	4.17	4.55	4.73	
Engine Max Peak Pres COV Ch. #8[%]	21.74	11.31	17.39	8.78	24.91	24.46	22.42	13.71	14.73	15.56	451.30	
Engine Min Peak Pres COV Ch. #7[%]	0.21	0.20	0.20	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.00	
Engine Avg Peak Loc[*ATDC]	18.09	17.98	17.63	17.75	17.90	17.79	17.98	17.85	17.97	18.21	18.08	
Engine Avg IMEP[psi]	43.03	43.30	43.22	43.24	43.25	43.30	43.26	43.42	43.54	43.52	42.93	
Engine Avg IMEP COV[%]	973.10	-262.50	-185.70	-330.10	-851.20	-300.70	-96.33	-361.30	-350.90	-280.90	162.80	
Engine Max IMEP COV Ch. #8[%]	7853.00	625.20	681.50	696.80	685.70	516.80	551.70	601.70	592.40	629.20	5973.00	
Engine Min IMEP COV Ch. #7[%]	-114.00	-3054.00	-2415.00	-3696.00	-8389.00	-3269.00	-1479.00	-3885.00	-3804.00	-3236.00	-4636.00	
Avg. Peak Ch. #1psi	560.40	569.50	574.70	570.80	570.80	571.50	573.30	573.40	571.40	564.00	557.80	
Avg. Peak Ch. #2psi	545.50	545.60	560.60	557.60	550.30	553.20	544.50	549.60	548.10	538.60	537.90	
Avg. Peak Ch. #3psi	574.80	579.70	587.10	580.80	579.60	585.90	582.70	585.90	581.20	573.00	570.80	
Avg. Peak Ch. #4psi	536.00	544.40	545.10	546.30	544.40	545.70	540.50	546.40	544.00	544.00	546.30	
Avg. Peak Ch. #5psi	609.40	610.40	615.50	615.50	611.90	613.40	607.30	609.30	601.60	591.10	608.20	
Peak Std. Dev. Ch. #1psi	25.84	23.04	23.38	22.83	22.44	21.44	21.23	22.18	21.69	24.55	24.50	
Peak Std. Dev. Ch. #2psi	29.24	26.29	25.76	26.33	25.42	25.27	25.57	25.49	27.22	29.11	28.88	
Peak Std. Dev. Ch. #3psi	31.95	28.36	29.47	27.30	27.18	26.24	26.46	26.04	27.00	29.63	31.69	
Peak Std. Dev. Ch. #4psi	19.65	19.17	18.11	19.14	18.68	18.03	17.55	17.83	17.74	17.88	19.69	
Peak Std. Dev. Ch. #5psi	24.10	22.29	22.69	22.19	22.70	23.10	22.76	23.99	22.65	23.00	23.02	
Peak COV Ch. #1%	4.61	4.05	4.07	4.00	3.93	3.75	3.70	3.87	3.80	4.35	4.39	
Peak COV Ch. #2%	5.36	4.82	4.59	4.72	4.62	4.57	4.70	4.64	4.97	5.41	5.37	
Peak COV Ch. #3%	5.56	4.89	5.02	4.70	4.69	4.48	4.54	4.44	4.65	5.17	5.55	
Peak COV Ch. #4%	3.67	3.52	3.32	3.50	3.43	3.30	3.25	3.26	3.26	3.29	3.61	
Peak COV Ch. #5%	3.95	3.65	3.69	3.61	3.71	3.77	3.75	3.94	3.77	3.89	3.79	
Max Peak Ch. #1psi	625.90	644.80	638.80	644.20	633.80	637.70	645.60	630.50	630.40	634.90	633.90	
Max Peak Ch. #2psi	640.10	608.10	640.80	646.00	618.90	623.20	615.00	625.70	621.60	616.20	616.40	
Max Peak Ch. #3psi	658.10	661.40	685.00	669.40	661.00	670.40	666.90	667.60	653.30	660.70	655.50	
Max Peak Ch. #4psi	597.90	604.30	597.20	596.40	610.60	594.30	587.10	597.30	600.00	599.10	602.20	
Max Peak Ch. #5psi	673.00	673.20	694.90	683.30	684.30	674.20	671.80	694.40	672.70	682.00	682.40	
Min Peak Ch. #1psi	465.30	491.60	488.30	493.00	487.90	507.80	507.50	487.90	475.70	477.40	476.70	
Min Peak Ch. #2psi	428.50	444.30	469.30	470.80	465.30	460.90	454.50	471.50	446.00	431.40	389.40	
Min Peak Ch. #3psi	415.20	466.10	484.00	487.00	475.20	504.90	467.10	510.00	499.90	469.80	456.10	
Min Peak Ch. #4psi	451.60	485.10	481.60	480.70	472.30	483.40	471.50	481.40	491.90	478.10	484.20	
Min Peak Ch. #5psi	521.20	525.20	540.80	541.40	544.40	547.10	545.80	532.60	537.20	522.10	538.00	
Avg. Peak Loc. Ch. #1psi	18.09	17.76	17.52	17.61	17.73	17.63	17.76	17.64	17.75	18.05	17.93	
Avg. Peak Loc. Ch. #2psi	18.04	18.05	17.51	17.67	17.91	17.82	18.01	17.86	18.02	18.37	18.17	
Avg. Peak Loc. Ch. #3psi	18.16	18.05	17.69	17.81	17.93	17.74	17.93	17.78	17.94	18.24	18.26	
Avg. Peak Loc. Ch. #4psi	18.07	18.07	17.79	17.91	18.01	17.95	18.21	18.11	18.15	18.18	17.96	
Avg. Peak Loc. Ch. #5psi	4.46	5.34	4.36	4.64	5.11	5.23	5.42	5.89	6.64	8.94	5.83	
Peak Loc. Std. Dev Ch. #1psi	1.13	1.06	1.06	1.04	1.03	0.97	0.97	0.98	1.02	1.05	1.14	
Peak Loc. Std. Dev Ch. #2psi	1.34	1.18	1.15	1.13	1.08	1.08	1.07	1.05	1.16	1.21	1.34	
Peak Loc. Std. Dev Ch. #3psi	1.36	1.28	1.22	1.13	1.10	1.09	1.08	1.03	1.11	1.21	1.38	
Peak Loc. Std. Dev Ch. #4psi	0.93	0.94	0.92	0.93	0.90	0.89	0.90	0.92	0.90	0.90	0.97	
Peak Loc. Std. Dev Ch. #5psi	3.32	4.40	3.51	3.72	4.12	4.39	4.36	4.95	5.65	6.85	5.00	
Peak Loc. COV Ch. #1%	6.27	5.99	6.04	5.92	5.81	5.50	5.49	5.55	5.74	5.80	6.35	
Peak Loc. COV Ch. #2%	7.40	6.51	6.56	6.39	6.05	6.06	5.93	5.88	6.43	6.61	7.38	
Peak Loc. COV Ch. #3%	7.48	7.09	6.90	6.34	6.15	6.15	6.04	5.78	6.18	6.63	7.58	
Peak Loc. COV Ch. #4%	5.16	5.19	5.16	5.21	5.00	4.96	4.93	5.11	4.97	4.96	5.39	
Peak Loc. COV Ch. #5%	74.46	82.49	80.40	80.10	80.70	83.92	80.39	84.08	85.03	76.57	85.73	
AVG IMEP Ch. #1psi	78.67	78.62	78.59	78.31	78.22	78.01	78.39	78.25	78.32	78.28	77.55	
AVG IMEP Ch. #2psi	80.21	79.85	80.62	80.58	80.12	80.26	79.44	79.66	80.06	79.53	78.95	
AVG IMEP Ch. #3psi	96.08	96.06	96.18	95.49	95.42	95.82	95.81	95.85	95.48	95.14	95.20	
AVG IMEP Ch. #4psi	75.32	76.50	75.94	76.33	76.59	76.50	76.42	77.04	77.21	77.32	76.45	
AVG IMEP Ch. #5psi	57.20	58.74	57.89	58.55	59.06	59.25	59.55	60.09	60.86	61.55	58.48	
IMEP STD DEV Ch. #1psi	2.08	2.10	2.13	2.12	2.16	2.21	2.20	2.17	2.12	2.10	2.11	
IMEP STD DEV Ch. #2psi	1.19	1.12	1.02	1.03	1.08	1.02	1.07	1.04	1.05	1.19	1.22	
IMEP STD DEV Ch. #3psi	1.76	1.52	1.67	1.57	1.51	1.45	1.49	1.44	1.47	1.51	1.66	
IMEP STD DEV Ch. #4psi	1.65	1.58	1.66	1.63	1.54	1.64	1.55	1.53				

AVG NMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
MFB 10% Ch. #1*ATDC	6.76	6.58	6.35	6.48	6.59	6.52	6.70	6.65	6.74	6.98	6.56	
MFB 10% Ch. #2*ATDC	5.96	6.03	5.60	5.77	5.98	5.94	6.13	6.05	6.16	6.41	5.99	
MFB 10% Ch. #3*ATDC	6.55	6.56	6.22	6.30	6.46	6.35	6.55	6.51	6.58	6.86	6.63	
MFB 10% Ch. #4*ATDC	6.53	6.64	6.29	6.43	6.62	6.53	6.80	6.74	6.83	6.91	6.56	
MFB 10% Ch. #5*ATDC	1.65	1.83	1.49	1.67	1.85	1.77	1.99	1.95	1.95	1.91	1.75	
MFB 50% Ch. #1*ATDC	14.56	14.17	13.89	14.03	14.11	13.99	14.09	14.02	14.15	14.50	14.43	
MFB 50% Ch. #2*ATDC	14.69	14.68	14.01	14.17	14.49	14.35	14.67	14.44	14.59	15.04	14.88	
MFB 50% Ch. #3*ATDC	15.71	15.50	15.09	15.28	15.40	15.14	15.34	15.18	15.37	15.75	15.82	
MFB 50% Ch. #4*ATDC	14.68	14.55	14.29	14.36	14.54	14.44	14.74	14.57	14.69	14.72	14.41	
MFB 50% Ch. #5*ATDC	13.93	13.86	13.60	13.69	13.86	13.78	14.07	13.93	14.04	14.10	13.72	
MFB 90% Ch. #1*ATDC	27.89	27.23	26.88	27.06	26.98	26.85	26.81	26.79	26.98	27.45	27.88	
MFB 90% Ch. #2*ATDC	30.24	30.02	29.06	29.18	29.68	29.37	29.98	29.65	29.91	30.55	30.49	
MFB 90% Ch. #3*ATDC	37.64	37.32	36.69	37.05	37.29	36.83	37.10	36.85	37.10	37.37	37.57	
MFB 90% Ch. #4*ATDC	29.68	29.26	29.21	29.17	29.43	29.36	29.68	29.38	29.78	29.86	29.14	
MFB 90% Ch. #5*ATDC	24.79	24.65	24.43	24.48	24.76	24.77	25.04	24.88	25.29	25.47	24.51	
Low Cycles [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Low Cycles [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Low Cycles [%] Ch. #3*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Low Cycles [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Low Cycles [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Misfires [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Misfires [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Misfires [%] Ch. #3*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Misfires [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Misfires [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Analysis Corrections for H2 Blending												
Total Fuel Flow (lb/hr)	176.50	176.90	176.10	176.30	176.30	176.20	176.30	176.60	176.70	176.40	176.20	
PCC Nat Gas Flow [lb/hr]	5.34	5.10	4.93	4.76	4.58	4.28	3.94	3.51	2.88	1.91	5.27	
PCC H2 Fuel Flow (lb/hr)	0.00	0.06	0.14	0.23	0.35	0.49	0.67	0.93	1.32	1.97	0.00	
H2 mass fraction (%)	0.00000000	1.24996852	2.77969579	4.66458283	7.08153200	10.26151878	14.62224247	21.03247894	31.46869793	50.68281371	0.00000000	
H2 mole fraction (%)	0.00	10.10	24.67	30.28	40.35	50.37	60.32	70.27	80.30	90.12	0.00	
Average MW (kg/kmol)	17.89	17.89	17.89	17.89	17.89	17.89	17.89	17.89	17.89	17.89	17.89	
PCC H2 Mole Fraction (%)	0.00	10.10	20.24	30.28	40.35	50.37	60.32	70.27	80.30	90.12	0.00	
Updated Fuel Composition Analysis												
METHANE [%]	88.89	79.91	70.89	61.97	53.02	44.11	35.27	26.42	17.51	8.78	89.93	
ETHANE [%]	8.48	7.63	6.77	5.91	5.06	4.21	3.37	2.52	1.67	0.84	7.96	
PROPANE [%]	0.64	0.57	0.51	0.44	0.38	0.32	0.25	0.19	0.13	0.06	0.41	
BUTANE [%]	0.07	0.06	0.05	0.05	0.04	0.03	0.03	0.02	0.01	0.01	0.05	
PENTANE [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
HYDROGEN [%]	0.00	10.10	20.24	30.28	40.35	50.37	60.32	70.28	80.30	90.12	0.00	
NITROGEN [%]	0.55	0.49	0.44	0.38	0.33	0.27	0.22	0.16	0.11	0.05	0.49	
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
CARBON DIOXIDE [%]	1.37	1.23	1.09	0.95	0.81	0.68	0.54	0.41	0.27	0.13	1.14	
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Total Composition Check (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
LHV (kJ/kg)	47514.61	47514.61	47514.61	47514.61	47514.61	47514.61	47514.61	47514.61	47514.61	47514.61	47514.61	
LHV (Btu/g)	45.03	45.03	45.03	45.03	45.03	45.03	45.03	45.03	45.03	45.03	45.03	
Updated A/F Ratio and BS Parameter Analysis												
Carbon #	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	
Hydrogen #	4.12	4.12	4.12	4.12	4.12	4.12	4.12	4.12	4.12	4.12	4.12	
Oxygen #	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	
Nitrogen #	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
y, H/C	3.77	3.77	3.77	3.77	3.77	3.77	3.77	3.77	3.77	3.77	3.77	
z, O/C	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	
f, N/C	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
Stoichiometric A/F Ratio	16.32	16.32	16.32	16.32	16.32	16.32	16.32	16.32	16.32	16.32	16.32	
CO2 (% dry)	2.96	2.96	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.94	2.95	
O2 (% dry)	15.42	15.37	15.43	15.41	15.41	15.40	15.40	15.39	15.39	15.39	15.37	
THC (ppmd)	1263.59	1256.92	1245.52	1261.66	1237.95	1218.42	1217.60	1217.66	1149.76	1134.91	1270.60	
CO (ppmd)	136.47											

BS CO (g/bhp-hr)	1.38	1.35	1.29	1.34	1.30	1.28	1.29	1.31	1.23	1.22	1.36
BS NOx (g/bhp-hr)	0.34	0.41	0.38	0.39	0.39	0.40	0.40	0.42	0.38	0.27	0.32
reduction in BS NOX (g/bhp-hr) / H2 mole frac (%)	0.00	0.0065	0.0018	0.0017	0.0012	0.0011	0.0009	0.0011	0.0005	-0.0008	0.00
BS NOx (g/bhp-hr change from baseline 1)	0.00	0.07	0.04	0.05	0.05	0.06	0.05	0.08	0.04	-0.07	-0.02
BS NOx (% change from baseline 1)	0.00	16.10	9.66	13.29	12.16	13.92	13.87	18.22	10.40	-25.17	-5.90
BS CH4 (g/bhp-hr)	5.55	5.52	5.48	5.54	5.46	5.36	5.37	5.35	5.07	5.04	5.62
reduction in BS CH4 (g/bhp-hr) / H2 mole frac (%)	0.00	0.0026	0.0033	0.0002	0.0023	0.0038	0.0030	0.0028	0.0059	0.0056	0.00
BS CH4 (change from baseline 1)	0.00	-0.47	-1.20	-0.12	-1.66	-3.44	-3.28	-3.49	-8.60	-9.15	1.37
BS CH4 (g/bhp-hr/C atom)	5.07	5.05	5.01	5.06	4.98	4.89	4.90	4.89	4.63	4.60	
BS VOC (g/bhp-hr)	0.25	0.24	0.26	0.25	0.24	0.25	0.23	0.24	0.23	0.24	0.24
BS CH2O (g/bhp-hr)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10
BS CO2 (g/bhp-hr)	469.38	469.41	467.95	467.03	468.94	468.35	468.84	468.97	469.72	471.37	467.12
BS CO2 (change from baseline 1)	0.00	0.01	-0.30	-0.50	-0.09	-0.22	-0.11	-0.09	0.07	0.43	-0.48
BS CO2c (g/bhp-hr)	608.08	607.46	604.99	605.57	605.34	602.29	603.00	602.83	596.50	597.38	607.73
BS CO2c (change from baseline 1)	0.00	-0.10	-0.51	-0.41	-0.45	-0.95	-0.84	-0.86	-1.91	-1.76	-0.06
BSFC (Btu/bhp-hr)	8222.61	8220.61	8192.76	8181.56	8207.67	8191.81	8200.20	8202.94	8196.40	8221.70	8186.22
Ignition Delay (deg)	8.86	8.37	8.47	8.16	8.11	8.03	8.02	7.97	8.06	8.27	8.79
Combustion Duration (deg)	24.91	24.51	24.34	24.37	24.43	24.27	24.35	24.18	24.36	24.52	24.84

MGAV - LPP18 Blending

Data Point Name	Base	1% H2 LPP18	5% H2 LPP18	10% H2 LPP18	15% H2 LPP18	20% H2 LPP18	25% H2 LPP18	30% H2 LPP18
Engine Data								
Start Time	44932.40903	44932.49028	44932.50069	44932.50972	44932.52014	44932.53056	44932.54167	44932.55139
End Time	44932.4125	44932.49375	44932.50417	44932.51319	44932.52361	44932.53403	44932.54514	44932.55486
Speed [rpm]	299.40	299.70	299.60	299.50	299.70	299.70	299.70	299.70
Torque [lb-ft]	7703.00	7694.00	7690.00	7688.00	7684.00	7673.00	7682.00	7701.00
Power [bhp]	439.20	439.00	438.70	438.50	438.40	437.80	438.40	439.40
Load [%]	100.00	99.88	99.83	99.80	99.75	99.61	99.73	99.97
Ambient Press [psia]	12.26	12.25	12.25	12.25	12.25	12.25	12.25	12.25
Ambient Temp [F]	36.96	46.64	47.50	47.83	48.53	49.37	48.98	48.54
Ambient Humidity [%]	51.24	40.15	37.30	35.65	32.27	31.42	31.02	30.58
Inlet Air Pres [in Hg]	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50
Inlet Air Temp [F]	109.40	108.80	109.50	108.10	107.60	108.40	109.10	109.70
Inlet Air Humidity [%]	5.23	6.47	5.97	6.15	5.89	5.71	5.34	4.97
Inlet Air Flow [scfm]	1878.00	1879.00	1880.00	1881.00	1882.00	1880.00	1879.00	1876.00
IC Water Temp [F]	116.40	111.30	115.50	115.90	113.90	110.70	113.30	116.40
Exh Back Pres [in Hg]	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Exh Cyl 1 Temp [F]	604.00	603.90	602.70	602.20	603.30	603.40	603.50	604.00
Exh Cyl 2 Temp [F]	637.90	636.50	635.80	635.40	635.90	635.60	636.90	636.70
Exh Cyl 3 Temp [F]	554.30	557.20	556.00	556.40	556.00	555.20	555.10	554.50
Exh Cyl 4 Temp [F]	640.20	639.70	639.00	639.40	638.60	638.30	639.00	639.10
Avg Exh Temp [F]	609.10	609.40	608.40	608.30	608.50	608.40	608.60	608.60
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	180.00	180.20	180.20	181.10	182.50	183.20	184.40	185.40
Sensor NOx [ppm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor Lambda	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orifice Temp [F]	45.15	43.20	44.87	43.60	42.80	42.67	43.69	45.12
Eng Fuel Pres [psig]	21.45	21.07	21.72	21.39	21.58	21.64	21.15	21.68
Eng Fuel Temp [F]	82.98	80.67	80.83	81.04	80.95	80.94	81.08	81.18
JW Out Temp [F]	145.20	147.60	148.60	149.30	149.60	148.90	147.40	147.10
JW In Temp [F]	140.20	142.40	144.00	144.00	144.90	144.90	142.50	142.80
JW Flow [gpm]	485.20	490.40	488.60	490.20	489.40	491.00	490.20	491.90
Lube Press [psig]	33.36	34.20	33.61	29.93	33.40	32.22	34.86	33.92
Lube In Temp [F]	149.20	149.90	150.90	150.90	151.50	151.20	149.80	149.80
Lube Out Temp [F]	159.60	161.50	161.80	162.00	162.00	161.90	161.40	161.20
Thrust 1 Temp [F]	158.80	160.80	160.80	160.90	160.80	161.00	160.70	160.40
Thrust 2 Temp [F]	158.40	161.00	160.80	161.00	161.00	161.10	161.00	160.60
Main 2A Temp [F]	159.60	161.40	161.30	161.40	161.40	161.50	161.30	160.90
Main 2B Temp [F]	159.10	160.80	160.70	160.80	160.70	160.80	160.60	160.20
Main 3A Temp [F]	160.40	162.30	162.20	162.30	162.20	162.40	162.20	161.90
Main 3B Temp [F]	160.40	162.40	162.20	162.40	162.30	162.50	162.30	161.90
Main 4A Temp [F]	156.20	158.10	157.90	158.00	158.00	158.10	157.90	157.50
Main 4B Temp [F]	156.10	158.00	157.80	158.00	157.90	158.00	157.90	157.50
THC [ppmd]	-9.20	-9.29	-9.30	-9.30	-9.30	-9.30	-9.30	-9.31
NOx [ppmd]	500.00	451.80	450.50	443.90	439.20	445.50	447.50	447.70
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	14.72	14.73	14.74	14.74	14.74	14.74	14.73	14.74
CO2 [%d]	3.26	3.23	3.23	3.22	3.22	3.22	3.21	3.22
CO [ppmd]	442.00	459.20	462.20	455.60	448.80	461.60	477.20	447.50
AFR Left	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AFR Right	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Flow [lb/hr]	8438.00	8443.00	8448.00	8452.00	8458.00	8447.00	8441.00	8430.00
Piezo 1 [F]	267.40	271.00	272.10	272.50	272.30	272.60	272.10	272.60
Piezo 2 [F]	275.30	277.90	279.10	279.80	279.20	279.40	278.80	279.20
Piezo 3 [F]	259.30	264.20	264.90	264.60	264.40	265.00	264.70	264.80
Piezo 4 [F]	279.80	282.00	282.20	282.20	282.20	282.70	282.60	282.90
Jacket Water Flow [gpm]	485.20	490.40	488.60	490.20	489.40	491.00	490.20	491.90
Jacket Water Valve Pos [%]	73.00	70.36	70.00	70.13	70.02	73.00	73.00	73.00
Supercharger Speed [%]	40.72	41.70	41.75	41.93	41.99	42.06	42.02	41.99
SC IC Temp Valve Pos [%]	85.20	83.94	84.11	85.31	85.31	84.20	83.95	83.73
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	40.76	40.84	40.82	40.85	40.82	40.92	41.06	41.20
Load Valve Pos [%]	21.41	21.00	21.00	21.00	21.00	21.00	21.00	21.00
Dyno Water Flow [gpm]	269.20	269.70	269.50	269.30	269.10	269.30	269.20	269.20
Dyno Water In [F]	74.38	79.84	80.61	80.84	81.65	82.42	82.45	82.72
Dyno Water Out [F]	87.31	92.70	93.80	93.49	94.78	95.21	95.42	95.83
Dyno Inboard Bearing [F]	108.60	114.80	115.10	115.00	115.00	115.20	115.10	115.40
Dyno Outboard Bearing [F]	124.20	140.20	140.80	141.00	141.40	141.90	142.40	142.80
Air Flow Static Pressure [kPa]	118.30	118.30	118.30	118.30	118.30	118.30	118.30	118.30
Air Flow Diff Pressure [kPa]	7.72	7.68	7.73	7.71	7.70	7.68	7.69	7.70
Air Flow Temperature [C]	45.15	43.20	44.87	43.60	42.80	42.67	43.69	45.12
Ethane Flow [lb/hr]	0.10	0.10	0.08	0.10	0.10	0.06	0.10	0.10
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.11	0.07	0.07	0.06	0.06	0.07	0.07	0.08
Ethane Temperature [C]	16.02	15.48	15.51	15.38	15.49	15.69	15.87	16.07
PCC H2 Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC H2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spare	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Manifold Pres Stpt [in Hg]	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50
PCC 4 Temp [F]	56.23	57.46	57.54	57.67	57.74	57.77	57.85	57.94
NOx Correction Step	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Averaging Time [s]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Feedback Time [s]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor NOx @ 15% O2	476.40	431.70	431.20	425.50	420.50	426.40	428.20	428.90
ePCC Pressure [psig]	2.88	2.27	2.25	2.18	2.17	2.15	2.10	2.07
Fuel Flow Static P [kPa]	322.50	320.40	320.40	320.40	320.50	320.60	320.60	320.60
Fuel Flow Temp [C]	29.10	28.93	28.85	28.92	28.92	29.08	29.27	29.39

Fuel Flow Diff P [kPa]	20.73	20.68	20.61	20.58	20.64	20.56	20.60	20.57
Low Press Orifice Flow [lb/hr]	179.90	179.40	179.20	179.10	179.30	179.00	179.10	178.90
Air Flow Diff 0 offset	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ign Spark #	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign Timing [deg]	-9.42	-9.42	-9.42	-9.42	-9.42	-9.42	-9.42	-9.42
Ign Offset Cyl 1 [deg]	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Ign Offset Cyl 2 [deg]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign Offset Cyl 3 [deg]	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Ign Offset Cyl 4 [deg]	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10
Ign 4-20 mA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EFI Hyd Sup Pres [psig]	5.18	5.21	5.20	5.20	5.19	5.31	5.29	5.29
EFI Hyd Ret Pres [psig]	16.98	18.19	17.39	24.52	27.11	17.31	17.25	18.03
LECM RPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOI Cylinder 1 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 2 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 3 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 4 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 1 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Global Duration [usec]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cylinder 1 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
LECM Fuel Temp [deg F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LECM Fuel Pres [psia]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HP Meter Fuel Flow [lb/hr]	1.56	1.57	1.57	1.58	1.57	1.57	1.57	1.57
SC 1C Coolant Out [C]	46.78	44.13	46.48	46.38	45.25	43.83	45.23	46.94
SC 1C Coolant In [C]	46.87	44.03	46.39	46.61	45.48	43.73	45.19	46.87
SC 1C Air 1 [C]	47.25	44.43	46.89	45.53	44.38	43.79	45.21	47.31
SC 1C Air 2 [C]	43.41	49.40	50.00	50.23	50.72	51.25	51.26	51.16
SC 1D Pres Diff	367.30	367.00	370.70	369.90	369.60	367.80	369.90	369.00
HPFI H2 Meter 1 Flow [g/hr]	0.02	0.02	0.02	0.01	0.02	0.02	0.03	0.01
HPFI H2 Meter 2 Flow [kg/hr]	0.08	0.09	0.08	0.09	0.07	0.07	0.08	0.09
HPFI H2 Meter 3 Flow [kg/hr]	-0.02	-0.02	-0.02	-0.03	-0.02	-0.03	-0.02	-0.04
HPFI H2 Meter 1 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 3 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Total Flow [kg/hr]	0.08	0.08	0.08	0.07	0.07	0.06	0.09	0.06
HPFI H2 Total Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LP Orifice Fuel Flow [lb/hr]	179.90	179.40	179.20	179.10	179.30	179.00	179.10	178.90
LPFI H2 Meter Setpoint	0.00	0.10	0.46	0.94	1.43	1.91	2.41	2.91
LPFI H2 Meter Flow [kg/hr]	0.00	0.33	0.46	0.94	1.42	1.91	2.41	2.92
FTIR Data								
NO (350,3000) 191C	407.40	480.00	420.50	466.30	487.70	430.70	475.90	446.40
NO2 (150) 191C (1of2)	15.26	16.70	16.38	16.55	17.48	16.66	16.12	16.07
NO2 (2000) 191C (2of2)	11.66	15.84	13.75	14.84	15.54	12.50	14.81	13.88
N2O (100,200,300) 191C	0.32	0.29	0.26	0.18	0.25	0.31	0.24	0.26
NH3 (300) 191C (1of2)	0.02	0.04	0.13	0.03	0.02	0.08	0.06	0.05
NH3 (3000) 191C (2of2)	0.39	0.06	0.72	1.05	1.34	0.27	0.66	-0.01
H2O% (25) 191C	6.57	6.73	6.68	6.67	6.63	6.62	6.69	6.62
CO2% (20) 191C (1of2) R4	3.32	3.40	3.34	3.37	3.37	3.36	3.40	3.38
CO (500) 191C (1of3)	63.69	64.34	64.66	65.16	62.81	62.82	62.30	63.02
CO% (1) 191C (2of3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CH4 (3000) 191C (1of2)	858.40	798.40	795.30	785.30	804.90	772.60	794.90	801.30
CH4 (20000) 191C (2of2)	873.60	811.00	809.70	797.60	811.60	782.90	803.20	810.80
Ethane (500) 191C	70.42	65.05	64.72	65.00	66.74	63.74	65.91	65.84
Ethylene (100,3000) 191C	5.53	5.60	5.26	5.05	5.22	5.46	5.13	5.18
Acetylene (1000) 191C	0.20	0.11	0.26	0.02	-0.07	0.34	0.12	0.12
Propane (200) 191C	4.92	4.44	4.37	4.38	4.73	4.04	4.66	4.65
Propylene (200,1000) 191C	1.33	0.94	0.62	1.38	1.00	0.82	1.10	1.05
Oil as octane (200) 191C	2.03	2.35	2.18	2.21	2.21	2.25	2.29	2.34
Formaldehyde (70,500) 191C	10.06	9.93	9.82	9.32	9.68	10.00	9.64	9.67
Acetaldehyde (1000) 191C	3.97	3.33	3.74	3.99	3.71	4.31	3.77	4.10
Formic Acid (100) 191C	0.39	0.28	0.32	0.39	0.34	0.36	0.38	0.38
MeOH (1000) 191C	0.12	0.35	0.27	0.40	0.15	0.09	0.37	0.24
CO% (10) 191C (3of3)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2 low% (4) 191C (2of2)	3.27	3.33	3.31	3.30	3.30	3.29	3.34	3.30
1,3 butadiene (80) 191C	0.06	-0.21	-0.05	-0.33	0.24	0.13	-0.07	-0.53
Temp (C)	190.60	190.70	190.60	190.50	190.60	190.50	190.60	190.50
Pressure (Atm)	0.97	0.97	0.97	0.97	0.98	0.98	0.97	0.97
NOx autorange	422.70	496.70	436.90	482.90	505.10	447.40	492.00	462.50
CO autorange	63.69	64.34	64.66	65.16	62.81	62.82	62.30	63.02
CH4 autorange	858.40	798.40	795.30	785.30	804.90	772.60	794.90	801.30
NH3 autorange	0.02	0.04	0.13	0.03	0.02	0.08	0.06	0.05
NOx autorange dry	452.40	532.60	468.20	517.40	541.00	479.10	527.30	495.20
CO autorange dry	68.17	68.99	69.29	69.81	67.27	67.27	66.77	67.48
CO2% autorange dry	3.50	3.57	3.54	3.53	3.54	3.53	3.58	3.53
N2O dry	0.34	0.32	0.28	0.20	0.27	0.34	0.26	0.28
NH3 autorange dry	0.02	0.04	0.14	0.03	0.02	0.08	0.06	0.05
FIDeq THC ppmC	1115.00	1035.00	1030.00	1021.00	1046.00	1003.00	1033.00	1040.00
FIDeq NMHC ppmC	170.40	157.00	154.90	156.70	160.30	153.10	159.00	158.80
FIDeq NMNEHC ppmC	29.55	26.90	25.48	26.71	26.76	25.66	27.14	27.07
CO2% autorange	3.27	3.33	3.31	3.30	3.30	3.29	3.34	3.30
FTIR NMHC ppmC	181.60	168.20	165.90	167.50	171.10	164.10	170.00	169.70
FTIR NMNEHC ppmC	40.79	38.11	36.40	37.51	37.63	36.64	38.16	37.98
Igram DC	3.77	3.72	3.73	3.73	3.72	3.73	3.72	3.72
Igram PP	6.02	5.99	6.00	5.99	5.99	6.00	5.99	5.99
phase Angle	89.76	90.47	90.59	90.45	90.55	90.36	90.53	90.66
laser PP	8.76	8.62	8.66	8.73	8.82	8.83	8.86	9.04

laser DC	-6.09	-6.20	-6.24	-6.23	-6.25	-6.24	-6.25	-6.27
Bad Scan counter	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Centerburst Location	1129.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00
Linearizer Check	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNR 2500	693.50	708.70	762.20	808.60	746.20	731.10	683.00	785.70
sBeam @ 2500	1.36	1.35	1.35	1.35	1.35	1.35	1.35	1.35
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GC Data								
METHANE [%]	89.91	89.98	89.98	89.95	89.95	89.92	89.93	89.93
ETHANE [%]	7.81	7.81	7.81	7.83	7.84	7.87	7.86	7.85
PROPANE [%]	0.50	0.43	0.43	0.43	0.42	0.42	0.42	0.42
BUTANE [%]	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05
PENTANE [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NITROGEN [%]	0.50	0.48	0.48	0.49	0.49	0.49	0.49	0.49
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.22	1.24	1.24	1.25	1.24	1.24	1.25	1.25
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LHV Actual [kJ/kg]	47780.00	47770.00	47770.00	47750.00	47760.00	47750.00	47750.00	47740.00
LHV Actual [BTU/scf]	960.30	959.10	959.10	959.10	959.10	959.20	959.00	958.90
HHV Dry [kJ/kg]	52880.00	52870.00	52870.00	52860.00	52870.00	52860.00	52850.00	52850.00
HHV Dry [BTU/scf]	1063.00	1062.00	1062.00	1062.00	1062.00	1062.00	1062.00	1061.00
Gas Density [kg/m3]	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Stioch A/F	16.34	16.34	16.34	16.33	16.34	16.33	16.33	16.33
Avg. Mol Weight	17.71	17.15	17.61	15.93	15.61	15.01	14.45	13.94
Cp [kJ/kg*K]	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13
Cv [kJ/kg*K]	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Cp/Cv	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Calculated Data								
AFR	52.60	53.03	53.15	53.23	53.19	53.23	53.34	53.22
Phi total	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Air Flow [kg/hr]	4294.00	4334.00	4345.00	4374.00	4402.00	4424.00	4462.00	4475.00
Exh Flow [kg/hr]	4375.00	4416.00	4427.00	4456.00	4485.00	4507.00	4546.00	4559.00
BMEP [kPa]	477.30	476.70	476.40	476.30	476.10	475.40	476.00	477.10
thermal eff	0.30	0.30	0.30	0.30	0.30	0.30	0.29	0.29
BSFC [kJ/kW-hr]	11910.00	11920.00	11930.00	12000.00	12090.00	12160.00	12220.00	12250.00
Abs Humidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BSTHC [g/bkW-hr]	8.18	7.68	7.67	7.66	7.90	7.62	7.93	7.97
BS NOx [g/bkW-hr]	10.52	9.62	9.62	9.55	9.52	9.71	9.85	9.84
BS CO [g/bkW-hr]	0.87	0.89	0.90	0.91	0.89	0.89	0.89	0.90
THC @15%O2	1063.00	989.20	985.80	978.20	1001.00	960.20	988.70	996.50
NOx @15%O2	477.00	431.70	431.20	425.50	420.50	426.40	428.20	428.90
CO @15%O2	65.04	65.92	66.33	66.92	64.40	64.40	63.88	64.65
Wet 2 Dry Scalar	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
15% O2 Factor	0.95	0.96	0.96	0.96	0.96	0.96	0.96	0.96
BS Calc Factor	457.10	462.70	464.30	467.70	471.00	473.80	478.20	477.70
Delivery Ratio	1.68	1.69	1.70	1.71	1.72	1.73	1.74	1.75
Scavenging Efficiency	0.81	0.82	0.82	0.82	0.82	0.82	0.83	0.83
Trapping Efficiency	0.48	0.48	0.48	0.48	0.48	0.48	0.47	0.47
Trapped AF Ratio	25.47	25.57	25.57	25.53	25.43	25.35	25.25	25.13
Trapped Equivalence Ratio	0.64	0.64	0.64	0.64	0.64	0.64	0.65	0.65
Combustion Data								
Engine Avg Peak Pressure[psi]	533.15	525.55	526.58	525.33	524.30	526.10	525.73	525.08
Engine Avg Peak Pres Std Dev[psi]	27.24	27.51	26.42	26.58	27.50	27.16	26.40	26.64
Engine Avg Peak Pres COV[%]	9.13	9.34	9.02	9.15	9.40	9.18	9.09	9.10
Engine Max Peak Pres COV Ch. #6[%]	28.04	22.87	21.73	21.97	23.21	23.95	24.32	25.27
Engine Min Peak Pres COV Ch. #8[%]	0.27	0.20	0.20	0.19	0.20	0.21	0.20	0.21
Engine Avg Peak Loc[*ATDC]	17.89	18.16	18.09	18.18	18.19	18.09	18.14	18.12
Engine Avg IMEP[psi]	80.63	80.29	80.23	80.07	80.17	80.13	80.15	79.99
Engine Avg IMEP COV[%]	74.22	41.84	40.21	51.06	55.09	57.28	65.59	80.30
Engine Max IMEP COV Ch. #9[%]	463.80	398.40	391.90	473.00	518.30	477.10	493.30	478.80
Engine Min IMEP COV Ch. #8[%]	-93.88	-95.00	-94.70	-94.53	-94.89	-94.93	-95.62	-95.54
Avg. Peak Ch. #1psi	539.40	533.70	533.90	534.30	533.00	533.70	532.50	531.80
Avg. Peak Ch. #2psi	533.40	521.90	525.50	526.60	525.50	524.30	522.40	524.20
Avg. Peak Ch. #3psi	528.90	526.60	526.80	520.30	522.30	525.60	524.20	521.60
Avg. Peak Ch. #4psi	530.90	520.00	520.10	520.10	516.40	520.80	523.80	522.70
Avg. Peak Ch. #5psi	524.60	511.20	511.20	511.50	507.80	513.30	516.80	516.40
Avg. Peak Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Avg. Peak Ch. #7psi	109.50	110.20	110.30	110.30	110.50	110.50	110.50	110.60
Avg. Peak Ch. #8psi	1.13	1.14	1.14	1.14	1.14	1.14	1.14	1.14
Avg. Peak Ch. #9psi	110.80	110.80	110.90	111.10	111.20	111.60	111.80	112.10
Peak Std. Dev. Ch. #1psi	41.79	39.89	40.68	40.02	41.83	41.34	41.24	40.10
Peak Std. Dev. Ch. #2psi	43.00	47.37	41.70	43.31	44.69	44.19	44.95	43.90
Peak Std. Dev. Ch. #3psi	59.23	57.41	59.46	61.56	59.79	56.27	58.51	58.18
Peak Std. Dev. Ch. #4psi	50.48	51.51	48.01	47.17	50.64	51.34	46.38	48.72
Peak Std. Dev. Ch. #5psi	49.77	50.53	47.06	46.30	49.67	50.46	45.65	48.01
Peak Std. Dev. Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak Std. Dev. Ch. #7psi	0.35	0.29	0.29	0.28	0.30	0.31	0.29	0.30
Peak Std. Dev. Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak Std. Dev. Ch. #9psi	0.59	0.54	0.53	0.53	0.55	0.53	0.54	0.52
Peak COV Ch. #1%	7.75	7.48	7.62	7.49	7.85	7.75	7.75	7.54
Peak COV Ch. #2%	8.06	9.08	7.94	8.23	8.51	8.43	8.60	8.38
Peak COV Ch. #3%	11.20	10.90	11.29	11.83	11.45	10.70	11.16	11.15
Peak COV Ch. #4%	9.51	9.91	9.23	9.07	9.81	9.86	8.86	9.32
Peak COV Ch. #5%	9.49	9.88	9.21	9.05	9.78	9.83	8.83	9.30

Peak COV Ch. #6%	28.04	22.87	21.73	21.97	23.21	23.95	24.32	25.27
Peak COV Ch. #7%	0.32	0.27	0.26	0.25	0.27	0.28	0.26	0.27
Peak COV Ch. #8%	0.27	0.20	0.20	0.19	0.20	0.21	0.20	0.21
Peak COV Ch. #9%	0.53	0.49	0.48	0.47	0.49	0.48	0.48	0.46
Max Peak Ch. #1psi	647.90	637.50	639.00	645.90	640.20	629.50	638.50	631.80
Max Peak Ch. #2psi	645.50	645.10	636.90	631.40	640.50	640.10	637.90	638.20
Max Peak Ch. #3psi	664.00	663.30	672.10	643.70	658.80	654.60	641.50	655.10
Max Peak Ch. #4psi	644.90	641.40	640.50	636.20	646.70	627.30	628.50	633.80
Max Peak Ch. #5psi	636.90	630.80	628.80	625.60	635.70	617.80	620.10	626.20
Max Peak Ch. #6psi	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Max Peak Ch. #7psi	111.00	111.50	111.50	112.50	112.20	112.90	111.80	112.80
Max Peak Ch. #8psi	1.15	1.14	1.14	1.15	1.15	1.16	1.15	1.16
Max Peak Ch. #9psi	112.50	112.20	112.30	112.60	112.60	113.20	113.40	113.90
Min Peak Ch. #1psi	289.70	371.80	354.20	387.00	288.70	339.70	345.50	370.60
Min Peak Ch. #2psi	341.60	288.30	286.20	326.70	287.50	286.30	287.60	302.50
Min Peak Ch. #3psi	289.10	290.20	289.10	288.70	287.90	289.30	288.50	288.60
Min Peak Ch. #4psi	290.00	289.60	291.30	290.90	290.80	287.80	289.00	288.00
Min Peak Ch. #5psi	287.40	285.50	287.20	287.10	286.90	284.50	285.90	285.40
Min Peak Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Min Peak Ch. #7psi	108.60	109.40	109.50	109.50	109.50	109.80	108.60	108.70
Min Peak Ch. #8psi	1.12	1.13	1.13	1.13	1.13	1.13	1.12	1.12
Min Peak Ch. #9psi	108.10	107.90	108.20	109.00	108.40	108.90	109.00	109.50
Avg. Peak Loc. Ch. #1psi	18.09	18.23	18.16	18.25	18.24	18.26	18.33	18.29
Avg. Peak Loc. Ch. #2psi	17.51	17.91	17.73	17.76	17.77	17.79	17.90	17.77
Avg. Peak Loc. Ch. #3psi	18.52	18.71	18.75	18.96	18.88	18.75	18.75	18.85
Avg. Peak Loc. Ch. #4psi	17.45	17.78	17.73	17.74	17.85	17.56	17.59	17.56
Avg. Peak Loc. Ch. #5psi	17.87	18.19	18.12	18.14	18.25	17.95	17.99	17.97
Avg. Peak Loc. Ch. #6psi	-25.08	-30.04	-25.37	-28.94	-23.43	-32.03	-32.00	-34.49
Avg. Peak Loc. Ch. #7psi	131.40	131.30	131.10	130.80	131.10	131.10	131.20	130.80
Avg. Peak Loc. Ch. #8psi	131.60	131.50	131.40	131.10	131.30	131.10	131.30	130.90
Avg. Peak Loc. Ch. #9psi	134.50	134.70	134.60	134.70	134.70	134.70	134.70	134.70
Peak Loc. Std. Dev Ch. #1psi	2.12	1.99	2.01	1.99	2.15	2.09	2.10	1.98
Peak Loc. Std. Dev Ch. #2psi	2.17	2.49	2.22	2.25	2.38	2.39	2.48	2.31
Peak Loc. Std. Dev Ch. #3psi	3.19	2.93	3.10	3.43	3.20	2.96	3.17	3.16
Peak Loc. Std. Dev Ch. #4psi	2.58	2.66	2.43	2.46	2.58	2.74	2.46	2.55
Peak Loc. Std. Dev Ch. #5psi	2.58	2.66	2.42	2.43	2.56	2.73	2.45	2.54
Peak Loc. Std. Dev Ch. #6psi	107.40	97.69	93.23	92.55	99.64	106.20	106.80	101.20
Peak Loc. Std. Dev Ch. #7psi	2.58	3.03	3.76	4.85	4.22	4.11	3.77	4.95
Peak Loc. Std. Dev Ch. #8psi	3.54	3.74	4.28	5.25	4.74	5.24	4.74	5.71
Peak Loc. Std. Dev Ch. #9psi	1.60	1.50	1.53	1.15	1.13	1.49	1.50	1.13
Peak Loc. COV Ch. #1%	11.71	10.92	11.06	10.90	11.77	11.44	11.47	10.84
Peak Loc. COV Ch. #2%	12.38	13.91	12.55	12.65	13.40	13.45	13.85	13.02
Peak Loc. COV Ch. #3%	17.24	15.64	16.54	18.09	16.96	15.76	16.92	16.78
Peak Loc. COV Ch. #4%	14.81	14.94	13.73	13.84	14.46	15.63	13.98	14.50
Peak Loc. COV Ch. #5%	14.45	14.61	13.37	13.40	14.03	15.21	13.60	14.12
Peak Loc. COV Ch. #6%	-428.40	-325.30	-367.50	-319.80	-425.20	-331.70	-333.60	-293.30
Peak Loc. COV Ch. #7%	1.96	2.31	2.86	3.71	3.22	3.13	2.88	3.78
Peak Loc. COV Ch. #8%	2.69	2.84	3.26	4.01	3.61	3.99	3.61	4.36
Peak Loc. COV Ch. #9%	1.19	1.12	1.14	0.86	0.84	1.11	1.11	0.84
AVG IMEP Ch. #1psi	76.99	76.73	76.65	76.58	76.67	76.57	76.63	76.51
AVG IMEP Ch. #2psi	79.98	79.28	79.29	79.31	79.35	79.19	79.18	79.14
AVG IMEP Ch. #3psi	90.54	90.71	90.64	90.15	90.43	90.59	90.33	90.11
AVG IMEP Ch. #4psi	75.02	74.44	74.32	74.22	74.21	74.17	74.44	74.18
AVG IMEP Ch. #5psi	74.59	73.65	73.51	73.47	73.44	73.56	73.92	73.75
AVG IMEP Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AVG IMEP Ch. #7psi	-0.68	-0.68	-0.68	-0.68	-0.68	-0.68	-0.68	-0.68
AVG IMEP Ch. #8psi	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
AVG IMEP Ch. #9psi	0.14	0.42	0.44	0.40	0.42	0.30	0.24	0.15
IMEP STD DEV Ch. #1psi	2.10	2.10	1.93	2.04	2.09	1.88	1.97	2.02
IMEP STD DEV Ch. #2psi	1.18	1.32	1.12	1.12	1.29	1.20	1.41	1.17
IMEP STD DEV Ch. #3psi	4.06	2.81	2.93	3.51	3.24	2.95	4.49	4.33
IMEP STD DEV Ch. #4psi	1.75	1.54	1.52	1.57	1.59	2.08	1.59	1.74
IMEP STD DEV Ch. #5psi	1.76	1.55	1.53	1.58	1.60	2.10	1.60	1.75
IMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IMEP STD DEV Ch. #7psi	0.60	0.61	0.61	0.61	0.61	0.61	0.61	0.61
IMEP STD DEV Ch. #8psi	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
IMEP STD DEV Ch. #9psi	0.63	0.63	0.63	0.63	0.63	0.63	0.64	0.64
IMEP COV Ch. #1%	2.72	2.74	2.52	2.66	2.73	2.45	2.57	2.64
IMEP COV Ch. #2%	1.47	1.67	1.41	1.41	1.63	1.52	1.78	1.48
IMEP COV Ch. #3%	4.48	3.10	3.23	3.89	3.58	3.26	4.97	4.81
IMEP COV Ch. #4%	2.33	2.07	2.05	2.12	2.15	2.81	2.14	2.35
IMEP COV Ch. #5%	2.36	2.11	2.08	2.15	2.18	2.85	2.17	2.37
IMEP COV Ch. #6%	373.30	398.40	391.90	473.00	518.30	477.10	493.30	478.80
IMEP COV Ch. #7%	-88.56	-89.15	-88.87	-88.78	-89.08	-89.37	-90.15	-90.17
IMEP COV Ch. #8%	-93.88	-95.00	-94.70	-94.53	-94.89	-94.93	-95.62	-95.54
IMEP COV Ch. #9%	463.80	150.60	142.30	157.70	149.20	209.80	269.10	415.90
AVG NMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #7psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #9psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

NMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #7psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #9psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
MFB 10% Ch. #1*ATDC	5.43	5.58	5.52	5.55	5.59	5.61	5.60	5.61	5.61	5.61
MFB 10% Ch. #2*ATDC	4.06	4.31	4.20	4.17	4.22	4.24	4.28	4.24	4.24	4.24
MFB 10% Ch. #3*ATDC	5.58	5.66	5.62	5.83	5.75	5.74	5.76	5.76	5.76	5.76
MFB 10% Ch. #4*ATDC	3.85	4.01	4.05	4.05	4.12	3.97	3.98	3.98	3.98	3.98
MFB 10% Ch. #5*ATDC	4.15	4.31	4.35	4.34	4.42	4.26	4.28	4.28	4.28	4.28
MFB 10% Ch. #6*ATDC	35.05	35.15	35.16	35.18	35.23	35.25	35.21	35.17	35.17	35.17
MFB 10% Ch. #7*ATDC	35.54	35.55	35.55	35.55	35.55	35.54	35.54	35.54	35.54	35.54
MFB 10% Ch. #8*ATDC	35.53	35.56	35.55	35.55	35.55	35.55	35.55	35.55	35.55	35.55
MFB 10% Ch. #9*ATDC	35.55	35.36	35.34	35.37	35.36	35.45	35.50	35.55	35.55	35.55
MFB 50% Ch. #1*ATDC	13.19	13.39	13.29	13.33	13.40	13.39	13.41	13.41	13.41	13.41
MFB 50% Ch. #2*ATDC	12.51	12.96	12.78	12.79	12.80	12.85	12.94	12.81	12.81	12.81
MFB 50% Ch. #3*ATDC	14.44	14.58	14.53	14.82	14.76	14.62	14.65	14.74	14.74	14.74
MFB 50% Ch. #4*ATDC	12.36	12.74	12.72	12.74	12.89	12.61	12.57	12.55	12.55	12.55
MFB 50% Ch. #5*ATDC	12.76	13.14	13.12	13.14	13.28	13.01	12.97	12.95	12.95	12.95
MFB 50% Ch. #6*ATDC	87.12	87.01	87.09	87.18	87.32	86.89	87.19	87.21	87.21	87.21
MFB 50% Ch. #7*ATDC	84.66	84.75	84.76	84.76	84.76	84.76	84.76	84.76	84.76	84.76
MFB 50% Ch. #8*ATDC	84.69	84.82	84.81	84.82	84.82	84.81	84.80	84.79	84.79	84.79
MFB 50% Ch. #9*ATDC	85.28	85.38	85.39	85.37	85.38	85.35	85.34	85.33	85.33	85.33
MFB 90% Ch. #1*ATDC	23.27	23.60	23.56	23.44	23.68	23.54	23.67	23.64	23.64	23.64
MFB 90% Ch. #2*ATDC	23.98	24.90	24.33	24.21	24.48	24.49	24.66	24.53	24.53	24.53
MFB 90% Ch. #3*ATDC	31.16	31.21	31.22	31.71	31.67	31.23	31.51	31.39	31.39	31.39
MFB 90% Ch. #4*ATDC	23.91	24.66	24.42	24.36	24.83	24.50	24.18	24.24	24.24	24.24
MFB 90% Ch. #5*ATDC	24.28	25.03	24.80	24.73	25.19	24.85	24.54	24.59	24.59	24.59
MFB 90% Ch. #6*ATDC	144.70	144.90	145.00	144.40	144.90	144.40	145.20	144.50	144.50	144.50
MFB 90% Ch. #7*ATDC	131.40	131.60	131.60	131.60	131.60	131.60	131.60	131.60	131.60	131.60
MFB 90% Ch. #8*ATDC	131.80	132.20	133.20	133.20	133.20	132.20	133.20	132.20	132.20	132.20
MFB 90% Ch. #9*ATDC	131.80	132.10	132.10	132.10	132.10	132.10	132.00	132.00	132.00	132.00
Low Cycles [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #3*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #6*ATDC	6.60	5.90	5.70	6.30	5.90	3.80	4.60	6.30	6.30	6.30
Low Cycles [%] Ch. #7*ATDC	0.00	0.00	0.00	-0.10	-0.10	-0.30	-0.30	0.00	0.00	0.00
Low Cycles [%] Ch. #8*ATDC	0.00	0.00	0.00	-0.10	-0.10	-0.30	-0.40	0.00	0.00	0.00
Low Cycles [%] Ch. #9*ATDC	8.40	0.40	0.00	0.40	0.30	1.60	3.00	8.30	8.30	8.30
Misfires [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #3*ATDC	0.10	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.10	0.10
Misfires [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #6*ATDC	28.40	29.20	30.20	32.00	32.40	34.40	33.20	33.40	33.40	33.40
Misfires [%] Ch. #7*ATDC	99.90	100.00	100.00	100.00	100.00	100.00	99.90	99.80	99.80	99.80
Misfires [%] Ch. #8*ATDC	99.90	100.00	100.00	100.00	100.00	100.00	99.90	99.80	99.80	99.80
Misfires [%] Ch. #9*ATDC	4.30	0.10	0.10	0.10	0.20	0.20	0.70	3.70	3.70	3.70
Analysis Corrections for H2 Blending										
Total Fuel Flow (lb/hr)	180.00	180.20	180.20	181.10	182.50	183.20	184.40	185.40	185.40	185.40
H2 Fuel Flow (lb/hr)	0.00	0.72	1.02	2.07	3.13	4.22	5.31	6.43	6.43	6.43
H2 mass fraction (%)	0.000	0.401113	0.568023	1.142213	1.716901	2.302527	2.880631	3.466889	3.466889	3.466889
H2 mole fraction (%)	0.0	3.4	5.0	9.0	13.3	17.1	20.7	24.0	24.0	24.0
Average MW (kg/kmol)	17.71	17.15	16.91	16.28	15.61	15.01	14.45	13.94	13.94	13.94
PCC H2 Mole Fraction (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Updated Fuel Composition Analysis										
METHANE [%]	89.91	86.91	85.51	81.83	77.99	74.51	71.35	68.38	68.38	68.38
ETHANE [%]	7.81	7.54	7.42	7.12	6.80	6.52	6.23	5.97	5.97	5.97
PROPANE [%]	0.50	0.42	0.41	0.39	0.37	0.35	0.33	0.32	0.32	0.32
BUTANE [%]	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.03

PENTANE [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.000	3.413	4.962	9.027	13.292	17.141	20.655	23.967
NITROGEN [%]	0.50	0.46	0.46	0.44	0.43	0.41	0.39	0.37
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.22	1.20	1.18	1.14	1.07	1.03	0.99	0.95
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Composition Check (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LHV (kJ/kg)	47780	48060	48180	48575	49000	49414	49831	50245
LHV (Btu/g)	45.29	45.55	45.67	46.04	46.44	46.83	47.23	47.62
<u>Updated A/F Ratio and BS Parameter Analysis</u>								
Carbon #	1.09	1.05	1.03	0.99	0.94	0.90	0.86	0.82
Hydrogen #	4.11	4.04	4.00	3.92	3.83	3.75	3.67	3.60
Oxygen #	0.0243	0.0240	0.0236	0.0227	0.0215	0.0206	0.0198	0.0191
Nitrogen #	0.01005	0.00923	0.00917	0.00889	0.00854	0.00819	0.00784	0.00746
y, H/C	3.789	3.856	3.887	3.973	4.074	4.172	4.271	4.372
z, O/C	0.02243	0.02296	0.02290	0.02303	0.02287	0.02294	0.02302	0.02313
f, N/C	0.009262	0.008818	0.008903	0.009020	0.009093	0.009123	0.009120	0.009059
Stoichiometric A/F Ratio	16.40	16.47	16.51	16.60	16.71	16.81	16.91	17.02
CO2 (% dry)	3.26	3.23	3.23	3.22	3.22	3.22	3.21	3.22
O2 (% dry)	14.72	14.73	14.74	14.74	14.74	14.74	14.73	14.74
THC (ppmd)	1193	1110	1104	1094	1120	1074	1107	1114
CO (ppmd)	68.2	69.0	69.3	69.8	67.3	67.3	66.8	67.5
NOx (ppmd)	500.00	451.80	450.50	443.90	439.20	445.50	447.50	447.70
CH4 (ppmd)	919	856	852	841	862	827	852	858
VOC (ppmd)	31.6	28.8	27.3	28.6	28.7	27.5	29.1	29.0
Formaldehyde, CH2O (ppmd)	10.8	10.6	10.5	10.0	10.4	10.7	10.3	10.4
U&S, H2FAC	0.003695	0.003806	0.003854	0.003969	0.003921	0.004015	0.004080	0.004221
U&S, a	6.218	6.289	6.310	6.339	6.359	6.390	6.425	6.435
phi, overall	0.3114	0.3105	0.3107	0.3127	0.3156	0.3180	0.3200	0.3234
A/F, overall	52.69	53.06	53.13	53.08	52.94	52.87	52.85	52.61
phi, trapped	0.6429	0.6440	0.6459	0.6519	0.6601	0.6675	0.6762	0.6851
A/F, trapped	25.52	25.58	25.56	25.46	25.31	25.18	25.01	24.84
Airflow (kg/hr)	9484	9562	9575	9614	9662	9686	9745	9753
BS THC (g/bhp-hr)	6.44	6.04	6.01	5.97	6.12	5.87	6.06	6.06
BS CO (g/bhp-hr)	0.64	0.66	0.66	0.66	0.64	0.64	0.64	0.64
BS NOx (g/bhp-hr)	7.733	7.046	7.033	6.942	6.879	6.977	7.029	6.985
reduction in BS NOx (g/bhp-hr) / H2 mole frac (%)	0.000	-0.201	-0.141	-0.088	-0.064	-0.044	-0.034	-0.031
BS NOx (change from baseline)	0.000	-8.881	-9.052	-10.230	-11.046	-9.776	-9.101	-9.677
BS CH4 (g/bhp-hr)	4.955	4.655	4.639	4.588	4.708	4.518	4.666	4.668
reduction in BS CH4 (g/bhp-hr) / H2 mole frac (%)	0.000	0.088	0.064	0.041	0.019	0.025	0.014	0.012
BS CH4 (g/bhp-hr/C atom)	4.566	4.448	4.505	4.654	5.010	5.031	5.427	5.666
BS VOC (g/bhp-hr)	0.171	0.157	0.149	0.156	0.157	0.150	0.159	0.158
BS CH2O (g/bhp-hr)	0.058	0.058	0.057	0.054	0.057	0.058	0.057	0.056
BS CO2 (g/bhp-hr)	483	482	482	482	482	483	482	480
BS CO2e (g/bhp-hr)	606	599	598	597	600	596	598	597
BSFC (Btu/bhp-hr)	8417	8480	8507	8623	8768	8888	9009	9113
BSFC (% change from baseline)	0.00	0.74	1.06	2.45	4.17	5.59	7.04	8.26
Ignition Delay (deg)	13.72	13.88	13.83	13.89	13.91	13.87	13.89	13.87
Combustion Duration (deg)	20.8	21.2	21.0	21.0	21.2	21.1	21.1	21.1

MGAV - FixedT Blending

Data Point Name	Base	1% H2 Fixed T	5% H2 Fixed T	10% H2 Fixed T	15% H2 Fixed T	20% H2 Fixed T	25% H2 Fixed T	30% H2 Fixed T
Engine Data								
Start Time	44932.40903	44932.58264	44932.58958	44932.59792	44932.60556	44932.61528	44932.62431	44932.63125
End Time	44932.4125	44932.58611	44932.59306	44932.60139	44932.60903	44932.61875	44932.62778	44932.63472
Speed [rpm]	299.40	299.70	299.70	299.70	299.70	299.70	299.60	299.60
Torque [lb-ft]	7703.00	7709.00	7694.00	7699.00	7717.00	7702.00	7718.00	7712.00
Power [bhp]	439.20	439.80	439.10	439.30	440.30	439.50	440.20	439.90
Load [%]	100.00	100.10	99.89	99.95	100.20	99.99	100.20	100.10
Ambient Press [psia]	12.26	12.25	12.25	12.25	12.26	12.26	12.26	12.26
Ambient Temp [F]	36.96	51.83	51.54	51.53	51.03	49.83	49.14	48.98
Ambient Humidity [%]	51.24	27.46	28.39	28.93	29.56	29.69	31.50	31.65
Inlet Air Pres [in Hg]	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50
Inlet Air Temp [F]	109.40	109.10	109.50	108.60	109.70	108.50	108.70	108.00
Inlet Air Humidity [%]	5.23	5.26	5.26	5.63	5.31	5.38	5.59	5.73
Inlet Air Flow [scfm]	1878.00	1877.00	1877.00	1879.00	1877.00	1882.00	1882.00	1884.00
IC Water Temp [F]	116.40	119.90	114.90	117.60	116.70	121.60	112.60	117.60
Exh Back Pres [in Hg]	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Exh Cyl1 Temp [F]	604.00	604.20	599.60	597.90	595.80	592.00	589.50	587.70
Exh Cyl2 Temp [F]	637.90	636.30	632.80	631.30	629.50	624.80	620.70	620.70
Exh Cyl3 Temp [F]	554.30	555.70	551.60	547.70	544.70	542.10	540.10	538.80
Exh Cyl4 Temp [F]	640.20	639.30	634.50	632.70	630.20	626.20	624.30	620.70
Avg Exh Temp [F]	609.10	608.90	604.60	602.40	600.10	596.30	594.20	592.00
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	180.00	179.10	176.80	175.30	173.30	171.10	169.50	167.70
Sensor NOx [ppm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor Lambda	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orifice Temp [F]	45.15	45.48	44.56	44.22	45.26	45.68	43.31	44.23
Eng Fuel Pres [psig]	21.45	21.58	21.98	21.68	21.67	22.38	22.50	22.50
Eng Fuel Temp [F]	82.98	82.05	82.30	82.49	82.71	84.29	86.19	86.90
JW Out Temp [F]	145.20	145.30	144.80	144.90	144.80	143.70	143.20	143.20
JW In Temp [F]	140.20	140.70	140.50	140.00	139.60	139.10	138.50	138.20
JW Flow [gpm]	485.20	493.00	492.10	492.00	492.60	490.80	491.60	492.00
Lube Press [psig]	33.36	34.11	31.82	33.63	35.23	34.43	31.71	31.10
Lube In Temp [F]	149.20	148.20	148.00	147.60	147.30	146.90	146.50	146.30
Lube Out Temp [F]	159.60	160.00	159.70	159.40	159.30	159.10	158.70	158.50
Thrust 1 Temp [F]	158.80	159.50	159.20	158.90	158.60	158.40	158.00	157.80
Thrust 2 Temp [F]	158.40	159.90	159.50	159.20	158.90	158.60	158.30	158.10
Main 2A Temp [F]	159.60	160.00	159.60	159.30	159.00	158.70	158.40	158.10
Main 2B Temp [F]	159.10	159.30	158.90	158.60	158.30	158.10	157.70	157.50
Main 3A Temp [F]	160.40	161.00	160.70	160.40	160.20	159.90	159.60	159.40
Main 3B Temp [F]	160.40	161.10	160.70	160.40	160.20	159.90	159.60	159.40
Main 4A Temp [F]	156.20	156.60	156.20	155.90	155.70	155.40	155.00	154.80
Main 4B Temp [F]	156.10	156.60	156.20	155.90	155.60	155.30	155.00	154.70
THC [ppmd]	-9.20	-9.30	-9.30	-9.29	-9.29	-9.30	-9.29	-9.30
NOx [ppmd]	500.00	459.70	444.40	472.00	480.50	470.80	477.50	482.40
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	14.72	14.73	14.76	14.80	14.84	14.88	14.89	14.94
CO2 [%d]	3.26	3.22	3.15	3.12	3.07	3.01	2.96	2.90
CO [ppmd]	442.00	455.80	445.50	448.70	427.20	454.60	420.30	413.30
AFR Left	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AFR Right	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Flow [lb/hr]	8438.00	8435.00	8436.00	8443.00	8435.00	8457.00	8457.00	8467.00
Piezo 1 [F]	267.40	272.50	272.80	274.00	274.10	274.20	274.90	275.10
Piezo 2 [F]	275.30	280.00	280.30	282.00	282.10	282.30	283.00	284.00
Piezo 3 [F]	259.30	265.50	265.50	267.20	267.60	269.10	270.00	270.70
Piezo 4 [F]	279.80	283.40	283.60	285.00	285.70	287.10	288.00	288.30
Jacket Water Flow [gpm]	485.20	493.00	492.10	492.00	492.60	490.80	491.60	492.00
Jacket Water Valve Pos [%]	73.00	73.00	73.00	73.00	73.00	73.00	73.00	73.00
Supercharger Speed [%]	40.72	42.09	42.18	42.11	42.09	42.02	42.03	42.04
SC IC Temp Valve Pos [%]	85.20	84.70	83.65	85.07	83.67	84.75	84.08	85.21
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	40.76	41.17	41.26	41.38	41.22	41.19	41.20	41.27
Load Valve Pos [%]	21.41	21.23	21.05	20.99	21.05	20.87	20.70	20.56
Dyno Water Flow [gpm]	269.20	270.30	270.60	270.80	270.80	270.50	270.60	270.50
Dyno Water In [F]	74.38	83.24	83.19	82.98	82.84	82.25	81.80	81.63
Dyno Water Out [F]	87.31	96.32	96.15	95.64	95.79	95.33	94.49	94.21
Dyno Inboard Bearing [F]	108.60	115.00	114.90	114.70	114.40	113.90	113.90	113.70
Dyno Outboard Bearing [F]	124.20	143.30	143.30	143.30	143.20	143.10	143.00	143.00
Air Flow Static Pressure [kPa]	118.30	118.30	118.30	118.30	118.30	118.30	118.30	118.40
Air Flow Diff Pressure [kPa]	7.72	7.72	7.70	7.71	7.72	7.77	7.72	7.75
Air Flow Temperature [C]	45.15	45.48	44.56	44.22	45.26	45.68	43.31	44.23
Ethane Flow [lb/hr]	0.10	0.10	0.10	0.09	0.10	0.10	0.08	0.09
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.11	0.09	0.09	0.08	0.07	0.05	0.04	0.03
Ethane Temperature [C]	16.02	16.44	16.53	16.49	16.40	16.01	15.86	15.76
PCC H2 Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC H2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spare	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Manifold Pres Stpt [in Hg]	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50
PCC 4 Temp [F]	56.23	58.28	58.36	58.45	58.56	58.70	58.81	58.83
NOx Correction Step	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Averaging Time [s]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Feedback Time [s]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor NOx @ 15% O2	476.40	439.50	427.10	456.10	467.60	461.50	468.70	477.30
ePCC Pressure [psig]	2.88	1.97	1.95	1.91	1.86	1.82	1.78	1.77
Fuel Flow Static P [kPa]	322.50	320.50	319.80	319.30	318.60	318.00	317.50	320.10
Fuel Flow Temp [C]	29.10	29.69	29.58	29.36	29.22	28.91	28.56	28.47
Fuel Flow Diff P [kPa]	20.73	20.59	19.90	19.34	18.69	17.98	17.43	16.69
Low Press Orifice Flow [lb/hr]	179.90	178.90	175.80	173.30	170.30	167.10	164.60	161.90
Air Flow Diff 0 offset	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ign Spark #	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Ign Timing [deg]	-9.42	-9.42	-9.42	-9.42	-9.42	-9.42	-9.42	-9.42	-9.42
Ign Offset Cyl 1 [deg]	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
Ign Offset Cyl 2 [deg]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign Offset Cyl 3 [deg]	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Ign Offset Cyl 4 [deg]	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10	-1.10
Ign 4-20 mA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EFI Hyd Sup Pres [psig]	5.18	5.27	5.18	5.20	5.20	5.23	5.24	5.24	5.24
EFI Hyd Ret Pres [psig]	16.98	16.62	16.63	22.68	21.33	24.19	26.29	21.93	21.93
LECM RPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOI Cylinder 1 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 2 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 3 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 4 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 1 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Global Duration [usec]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cylinder 1 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
LECM Fuel Temp [deg F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LECM Fuel Pres [psia]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HP Meter Fuel Flow [lb/hr]	1.56	1.57	1.57	1.57	1.57	1.58	1.58	1.58	1.58
SC IC Coolant Out [C]	46.78	48.72	46.16	47.23	47.17	49.56	44.83	47.35	47.35
SC IC Coolant In [C]	46.87	48.81	46.04	47.54	47.07	49.76	44.77	47.53	47.53
SC IC Air 1 [C]	47.25	48.20	46.41	46.28	47.50	48.80	44.69	46.59	46.59
SC IC Air 2 [C]	43.41	52.55	52.65	52.59	52.51	51.92	51.60	51.43	51.43
SC ID Pres Diff	367.30	371.70	372.80	370.70	370.60	376.70	367.90	371.20	371.20
HPFI H2 Meter 1 Flow [g/hr]	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.00	0.00
HPFI H2 Meter 2 Flow [kg/hr]	0.08	0.09	0.09	0.08	0.07	0.10	0.10	0.07	0.07
HPFI H2 Meter 3 Flow [kg/hr]	-0.02	-0.01	-0.04	-0.04	-0.02	-0.03	-0.02	-0.02	-0.02
HPFI H2 Meter 1 Stp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 2 Stp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 3 Stp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Total Flow [kg/hr]	0.08	0.10	0.07	0.04	0.06	0.09	0.09	0.06	0.06
HPFI H2 Total Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LP Orifice Fuel Flow [lb/hr]	179.90	178.90	175.80	173.30	170.30	167.10	164.60	161.90	161.90
LPFI H2 Meter Setpoint	0.00	0.09	0.46	0.91	1.36	1.79	2.22	2.63	2.63
LPFI H2 Meter Flow [kg/hr]	0.00	0.09	0.46	0.91	1.36	1.79	2.22	2.63	2.63
FTIR Data									
NO (350,3000) 191C	407.40	440.50	477.50	467.40	495.40	464.50	508.90	477.00	477.00
NO2 (150) 191C (1oF2)	15.26	16.77	17.41	17.48	17.10	17.61	17.73	17.32	17.32
NO2 (2000) 191C (2oF2)	11.66	15.38	16.38	17.11	16.16	18.96	19.14	16.75	16.75
N2O (100,200,300) 191C	0.32	0.21	0.27	0.38	0.31	0.26	0.32	0.25	0.25
NH3 (300) 191C (1oF2)	0.02	0.03	-0.02	0.05	0.03	0.06	0.00	0.07	0.07
NH3 (3000) 191C (2oF2)	0.39	1.40	0.25	0.17	-0.03	0.50	1.31	-0.12	-0.12
H2O% (25) 191C	6.57	6.69	6.71	6.81	6.81	6.89	6.89	6.81	6.81
CO2% (20) 191C (1oF2) R4	3.32	3.31	3.27	3.23	3.17	3.12	3.03	3.16	3.16
CO (500) 191C (1oF3)	63.69	64.13	62.50	61.28	59.85	59.03	58.06	60.02	60.02
CO% (1) 191C (2oF3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CH4 (3000) 191C (1oF2)	858.40	784.60	738.50	720.30	673.30	689.70	696.60	699.70	699.70
CH4 (20000) 191C (2oF2)	873.60	794.30	742.50	717.10	674.40	686.40	683.30	697.60	697.60
Ethane (500) 191C	70.42	65.03	61.69	60.96	57.36	58.36	59.33	59.24	59.24
Ethylene (100,3000) 191C	5.53	5.05	4.54	4.48	4.10	3.80	3.58	4.43	4.43
Acetylene (1000) 191C	0.20	-0.26	-0.17	0.39	0.31	0.11	-0.01	0.63	0.63
Propane (200) 191C	4.92	4.56	3.93	3.53	2.96	2.95	3.21	3.36	3.36
Propylene (200,1000) 191C	1.33	1.26	1.10	0.93	0.98	1.02	0.99	0.92	0.92
Oil as octane (200) 191C	2.03	2.28	2.27	2.09	1.88	1.87	1.93	1.99	1.99
Formaldehyde (70,500) 191C	10.06	9.32	8.30	8.19	7.77	7.60	6.94	7.86	7.86
Acetaldehyde (1000) 191C	3.97	3.93	4.28	2.79	2.24	2.93	3.61	3.02	3.02
Formic Acid (100) 191C	0.39	0.36	0.27	0.25	0.24	0.27	0.26	0.36	0.36
MeOH (1000) 191C	0.12	0.47	0.43	0.34	0.34	0.31	0.61	0.51	0.51
CO% (10) 191C (3oF3)	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01
CO2 low% (4) 191C (2oF2)	3.27	3.24	3.18	3.13	3.09	3.05	2.98	3.08	3.08
1,3 butadiene (80) 191C	0.06	-0.44	-0.10	-0.09	-0.07	-0.20	-0.39	-0.07	-0.07
Temp (C)	190.60	190.60	190.60	190.60	190.50	190.60	190.60	190.60	190.60
Pressure (Atm)	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
NOx autorange	422.70	457.30	494.90	484.90	512.50	482.10	526.70	494.30	494.30
CO autorange	63.69	64.13	62.50	61.28	59.85	59.03	58.06	60.02	60.02
CH4 autorange	858.40	784.60	738.50	720.30	673.30	689.70	696.60	699.70	699.70
NH3 autorange	0.02	0.03	-0.02	0.05	0.03	0.06	0.00	0.07	0.07
NOx autorange dry	452.40	490.10	530.50	520.30	549.90	517.70	565.60	530.50	530.50
CO autorange dry	68.17	68.72	67.00	65.76	64.22	63.39	62.35	64.41	64.41
CO2% autorange dry	3.50	3.48	3.40	3.36	3.32	3.28	3.20	3.30	3.30
N2O dry	0.34	0.23	0.29	0.41	0.34	0.28	0.35	0.27	0.27
NH3 autorange dry	0.02	0.03	-0.02	0.05	0.04	0.07	0.00	0.08	0.08
FIDeq THC ppmC	1115.00	1019.00	958.80	936.90	875.50	894.70	904.20	910.80	910.80
FIDeq NMHC ppmC	170.40	156.30	146.50	144.60	134.90	136.00	137.90	141.10	141.10
FIDeq NMNEHC ppmC	29.55	26.26	23.13	22.69	20.20	19.24	19.25	22.63	22.63
CO2% autorange	3.27	3.24	3.18	3.13	3.09	3.05	2.98	3.08	3.08
FTIR NMHC ppmC	181.60	167.30	156.20	153.80	143.70	144.60	146.20	150.20	150.20
FTIR NMNEHC ppmC	40.79	37.21	32.83	31.89	28.98	27.91	27.57	31.68	31.68
Igram DC	3.77	3.72	3.73	3.71	3.72	3.72	3.72	3.71	3.71
Igram PP	6.02	5.96	5.96	5.96	5.96	5.96	5.96	5.96	5.96
phase Angle	89.76	90.35	90.47	90.42	90.62	90.29	90.44	90.44	90.44
laser PP	8.76	9.04	9.03	8.90	8.83	8.95	8.95	8.89	8.89
laser DC	-6.09	-6.28	-6.28	-6.27	-6.27	-6.27	-6.29	-6.26	-6.26
Bad Scan counter	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Centerburst Location	1129.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00
Linearizer Check	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNR 2500	693.50	626.30	731.00	649.30	738.10	706.30	703.60	723.60	723.60
sBeam @ 2500	1.36	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

GC Data								
METHANE [%]	89.91	89.87	89.83	89.79	89.82	89.79	89.74	89.76
ETHANE [%]	7.81	7.90	7.94	7.99	7.97	7.98	8.01	8.00
PROPANE [%]	0.50	0.41	0.42	0.42	0.42	0.42	0.43	0.42
BUTANE [%]	0.06	0.05	0.05	0.04	0.05	0.05	0.04	0.04
PENTANE [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NITROGEN [%]	0.50	0.48	0.48	0.48	0.48	0.48	0.48	0.48
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.22	1.28	1.28	1.28	1.27	1.28	1.30	1.30
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LHV Actual [kJ/kg]	47780.00	47720.00	47710.00	47720.00	47730.00	47720.00	47700.00	47700.00
LHV Actual [BTU/scf]	960.30	959.00	959.30	959.70	959.60	959.70	959.90	959.70
HHV Dry [kJ/kg]	52880.00	52820.00	52810.00	52820.00	52830.00	52820.00	52800.00	52790.00
HHV Dry [BTU/scf]	1063.00	1062.00	1062.00	1062.00	1062.00	1062.00	1062.00	1062.00
Gas Density [kg/m3]	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Stioch A/F	16.34	16.32	16.32	16.32	16.32	16.32	16.31	16.31
Avg. Mol Weight	17.71	17.55	16.96	16.26	15.62	15.02	14.48	13.96
Cp [kJ/kg*K]	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13
Cv [kJ/kg*K]	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
Cp/Cv	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Calculated Data								
AFR	52.60	53.22	54.18	54.71	55.54	56.37	56.94	57.94
Phi total	0.31	0.31	0.30	0.30	0.29	0.29	0.29	0.28
Air Flow [kg/hr]	4294.00	4323.00	4346.00	4351.00	4366.00	4374.00	4377.00	4406.00
Exh Flow [kg/hr]	4375.00	4405.00	4426.00	4431.00	4444.00	4451.00	4454.00	4483.00
BMEP [kPa]	477.30	477.60	476.70	477.00	478.10	477.20	478.20	477.80
thermal eff	0.30	0.30	0.31	0.31	0.32	0.32	0.32	0.33
BSFC [kJ/kW-hr]	11910.00	11820.00	11690.00	11590.00	11430.00	11300.00	11170.00	11060.00
Abs Humidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BSTHC [g/bkW-hr]	8.18	7.55	7.18	7.04	6.60	6.79	6.89	7.02
BS NOx [g/bkW-hr]	10.52	9.76	9.55	10.16	10.39	10.25	10.43	10.66
BS CO [g/bkW-hr]	0.87	0.89	0.88	0.86	0.85	0.84	0.83	0.87
THC @15%O2	1063.00	974.60	921.60	905.50	851.90	876.90	887.50	901.20
NOx @15%O2	477.00	439.50	427.10	456.20	467.60	461.50	468.70	477.30
CO @15%O2	65.04	65.71	64.40	63.55	62.49	62.14	61.20	63.74
Wet 2 Dry Scaler	1.07	1.07	1.06	1.06	1.06	1.06	1.06	1.06
15% O2 Factor	0.95	0.96	0.96	0.97	0.97	0.98	0.98	0.99
BS Calc Factor	457.10	461.40	467.00	468.00	469.80	473.40	474.80	480.20
Delivery Ratio	1.68	1.69	1.70	1.70	1.71	1.71	1.71	1.72
Scavenging Efficiency	0.81	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Trapping Efficiency	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Trapped AF Ratio	25.47	25.69	26.06	26.32	26.63	27.03	27.28	27.67
Trapped Equivalence Ratio	0.64	0.64	0.63	0.62	0.61	0.60	0.60	0.59
Combustion Data								
Engine Avg Peak Pressure[psi]	533.15	528.93	532.88	543.15	550.73	555.35	560.55	566.55
Engine Avg Peak Pres Std Dev[psi]	27.24	26.59	24.55	24.05	22.86	21.72	21.67	21.58
Engine Avg Peak Pres COV[%]	9.13	9.06	8.34	7.95	7.42	7.00	6.92	6.88
Engine Max Peak Pres COV Ch. #6[%]	28.04	19.09	23.35	23.50	21.53	18.35	15.26	14.51
Engine Min Peak Pres COV Ch. #8[%]	0.27	0.20	0.20	0.18	0.18	0.18	0.18	0.17
Engine Avg Peak Loc[*ATDC]	17.89	17.98	17.75	17.28	16.87	16.61	16.38	16.09
Engine Avg IMEP[psi]	80.63	80.23	79.97	80.22	80.18	80.00	80.07	80.01
Engine Avg IMEP COV[%]	74.22	3357.00	-936.00	-1771.00	-399.70	197.90	76.11	70.87
Engine Max IMEP COV Ch. #9[%]	463.80	29940.00	405.30	433.40	441.70	1678.00	632.90	609.10
Engine Min IMEP COV Ch. #8[%]	-93.88	-94.75	-8657.00	-16200.00	-3863.00	-95.05	-93.88	-94.24
Avg. Peak Ch. #1psi	539.40	534.90	537.00	545.90	551.00	552.80	556.40	560.50
Avg. Peak Ch. #2psi	533.40	528.60	534.10	540.90	545.80	548.90	554.30	559.80
Avg. Peak Ch. #3psi	528.90	526.90	531.90	544.50	557.70	565.40	571.30	577.80
Avg. Peak Ch. #4psi	530.90	525.30	528.50	541.30	548.40	554.30	560.20	568.10
Avg. Peak Ch. #5psi	524.60	519.90	523.10	535.70	542.80	548.10	553.40	561.20
Avg. Peak Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Avg. Peak Ch. #7psi	109.50	110.70	110.60	110.50	110.60	110.60	110.60	110.60
Avg. Peak Ch. #8psi	1.13	1.14	1.14	1.14	1.14	1.14	1.14	1.14
Avg. Peak Ch. #9psi	110.80	112.50	112.50	112.50	112.70	112.50	112.40	112.50
Peak Std. Dev. Ch. #1psi	41.79	40.90	39.63	38.22	38.11	37.17	35.73	37.11
Peak Std. Dev. Ch. #2psi	43.00	44.97	42.59	40.45	38.03	36.39	36.39	37.07
Peak Std. Dev. Ch. #3psi	59.23	58.35	52.34	50.50	45.45	42.05	43.48	43.84
Peak Std. Dev. Ch. #4psi	50.48	47.44	43.09	43.57	41.98	39.88	39.68	38.04
Peak Std. Dev. Ch. #5psi	49.77	46.83	42.57	43.01	41.43	39.33	39.10	37.46
Peak Std. Dev. Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak Std. Dev. Ch. #7psi	0.35	0.29	0.29	0.27	0.27	0.26	0.27	0.26
Peak Std. Dev. Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak Std. Dev. Ch. #9psi	0.59	0.51	0.48	0.45	0.44	0.43	0.42	0.42
Peak COV Ch. #1%	7.75	7.65	7.38	7.00	6.92	6.72	6.42	6.62
Peak COV Ch. #2%	8.06	8.51	7.97	7.48	6.97	6.63	6.57	6.62
Peak COV Ch. #3%	11.20	11.07	9.84	9.28	8.15	7.44	7.61	7.59
Peak COV Ch. #4%	9.51	9.03	8.15	8.05	7.65	7.19	7.08	6.70
Peak COV Ch. #5%	9.49	9.01	8.14	8.03	7.63	7.18	7.07	6.68
Peak COV Ch. #6%	28.04	19.09	23.35	23.50	21.53	18.35	15.26	14.51
Peak COV Ch. #7%	0.32	0.26	0.26	0.24	0.25	0.23	0.24	0.24
Peak COV Ch. #8%	0.27	0.20	0.20	0.18	0.18	0.18	0.18	0.17
Peak COV Ch. #9%	0.53	0.45	0.43	0.40	0.39	0.38	0.37	0.37
Max Peak Ch. #1psi	647.90	644.10	631.10	645.80	655.00	652.90	645.10	647.40
Max Peak Ch. #2psi	645.50	637.90	636.90	632.40	660.50	643.40	641.20	660.90
Max Peak Ch. #3psi	664.00	657.70	642.70	649.40	684.40	663.50	671.80	674.20
Max Peak Ch. #4psi	644.90	649.40	635.40	638.40	651.00	652.20	651.80	662.20
Max Peak Ch. #5psi	636.90	642.10	628.10	631.00	644.40	645.00	643.80	652.10
Max Peak Ch. #6psi	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Max Peak Ch. #7psi	111.00	111.90	111.60	111.40	111.70	111.90	111.60	111.40
Max Peak Ch. #8psi	1.15	1.16	1.15	1.15	1.15	1.15	1.15	1.15

Max Peak Ch. #9psi	112.50	114.50	113.70	113.70	113.70	113.60	113.40	113.70
Min Peak Ch. #1psi	289.70	348.00	303.50	408.20	370.30	342.60	432.00	392.40
Min Peak Ch. #2psi	341.60	285.60	316.70	344.30	366.20	315.20	318.60	294.30
Min Peak Ch. #3psi	289.10	287.80	291.60	297.80	292.00	374.60	314.00	384.70
Min Peak Ch. #4psi	290.00	291.00	343.40	312.70	384.90	376.90	368.10	417.60
Min Peak Ch. #5psi	287.40	288.90	340.20	309.80	381.40	373.30	364.10	413.00
Min Peak Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Min Peak Ch. #7psi	108.60	110.00	109.70	109.60	109.80	109.50	109.90	109.80
Min Peak Ch. #8psi	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13
Min Peak Ch. #9psi	108.10	110.10	109.60	110.30	110.60	109.50	109.60	109.70
Avg. Peak Loc. Ch. #1psi	18.09	18.20	17.97	17.58	17.30	17.12	16.97	16.77
Avg. Peak Loc. Ch. #2psi	17.51	17.58	17.32	17.00	16.74	16.59	16.31	16.07
Avg. Peak Loc. Ch. #3psi	18.52	18.65	18.43	17.78	17.11	16.72	16.46	16.13
Avg. Peak Loc. Ch. #4psi	17.45	17.47	17.29	16.75	16.33	16.02	15.78	15.38
Avg. Peak Loc. Ch. #5psi	17.87	17.87	17.69	17.14	16.74	16.42	16.20	15.79
Avg. Peak Loc. Ch. #6psi	-25.08	-22.34	-24.97	-31.47	-57.71	-74.34	-86.71	-82.65
Avg. Peak Loc. Ch. #7psi	131.40	131.00	131.10	131.10	131.10	131.00	131.30	131.00
Avg. Peak Loc. Ch. #8psi	131.60	131.30	131.30	131.10	131.30	131.70	131.70	131.60
Avg. Peak Loc. Ch. #9psi	134.50	134.70	134.60	134.40	134.30	134.10	134.00	134.00
Peak Loc. Std. Dev Ch. #1psi	2.12	2.06	2.00	1.87	1.90	1.81	1.75	1.77
Peak Loc. Std. Dev Ch. #2psi	2.17	2.36	2.23	2.08	1.98	1.93	1.84	1.88
Peak Loc. Std. Dev Ch. #3psi	3.19	3.11	2.69	2.50	2.27	2.04	2.13	2.11
Peak Loc. Std. Dev Ch. #4psi	2.58	2.42	2.23	2.17	2.07	2.00	1.98	1.87
Peak Loc. Std. Dev Ch. #5psi	2.58	2.41	2.20	2.16	2.06	1.98	1.96	1.85
Peak Loc. Std. Dev Ch. #6psi	107.40	97.02	94.88	100.70	105.60	104.70	98.65	93.30
Peak Loc. Std. Dev Ch. #7psi	2.58	4.42	3.98	3.99	3.99	4.38	3.29	4.61
Peak Loc. Std. Dev Ch. #8psi	3.54	4.66	4.57	5.33	4.74	3.37	3.10	3.63
Peak Loc. Std. Dev Ch. #9psi	1.60	1.13	1.53	1.32	1.35	1.68	1.70	1.41
Peak Loc. COV Ch. #1%	11.71	11.30	11.13	10.66	10.97	10.59	10.31	10.55
Peak Loc. COV Ch. #2%	12.38	13.40	12.90	12.24	11.82	11.62	11.28	11.68
Peak Loc. COV Ch. #3%	17.24	16.68	14.58	14.06	13.28	12.18	12.95	13.05
Peak Loc. COV Ch. #4%	14.81	13.86	12.87	12.93	12.70	12.51	12.57	12.13
Peak Loc. COV Ch. #5%	14.45	13.48	12.46	12.58	12.28	12.08	12.09	11.70
Peak Loc. COV Ch. #6%	-428.40	-434.30	-379.90	-319.90	-183.10	-140.80	-113.80	-112.90
Peak Loc. COV Ch. #7%	1.96	3.38	3.04	3.04	3.04	3.35	2.51	3.52
Peak Loc. COV Ch. #8%	2.69	3.55	3.48	4.06	3.61	2.56	2.35	2.76
Peak Loc. COV Ch. #9%	1.19	0.84	1.14	0.98	1.01	1.25	1.27	1.05
AVG IMEP Ch. #1psi	76.99	76.64	76.33	76.46	76.17	75.90	75.93	75.77
AVG IMEP Ch. #2psi	79.98	79.36	79.13	79.34	79.24	78.92	78.93	78.86
AVG IMEP Ch. #3psi	90.54	90.45	90.29	90.78	91.09	91.17	91.36	91.49
AVG IMEP Ch. #4psi	75.02	74.46	74.11	74.29	74.23	73.99	74.05	73.92
AVG IMEP Ch. #5psi	74.59	74.14	73.80	73.98	73.92	73.63	73.63	73.50
AVG IMEP Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AVG IMEP Ch. #7psi	-0.68	-0.68	-0.68	-0.68	-0.68	-0.68	-0.68	-0.68
AVG IMEP Ch. #8psi	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
AVG IMEP Ch. #9psi	0.14	0.00	-0.01	0.00	-0.02	0.04	0.10	0.10
IMEP STD DEV Ch. #1psi	2.10	2.08	2.00	1.82	2.00	1.99	1.96	1.95
IMEP STD DEV Ch. #2psi	1.18	2.88	1.03	0.95	0.86	0.85	0.80	0.85
IMEP STD DEV Ch. #3psi	4.06	3.76	2.66	2.45	2.22	1.93	1.96	1.99
IMEP STD DEV Ch. #4psi	1.75	1.59	1.45	1.43	1.43	1.47	1.43	1.39
IMEP STD DEV Ch. #5psi	1.76	1.60	1.45	1.44	1.43	1.46	1.43	1.38
IMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IMEP STD DEV Ch. #7psi	0.60	0.61	0.61	0.61	0.61	0.61	0.61	0.61
IMEP STD DEV Ch. #8psi	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
IMEP STD DEV Ch. #9psi	0.63	0.64	0.64	0.64	0.64	0.64	0.63	0.64
IMEP COV Ch. #1%	2.72	2.71	2.61	2.39	2.63	2.62	2.58	2.57
IMEP COV Ch. #2%	1.47	3.62	1.30	1.19	1.09	1.07	1.02	1.08
IMEP COV Ch. #3%	4.48	4.16	2.94	2.70	2.44	2.11	2.15	2.17
IMEP COV Ch. #4%	2.33	2.13	1.96	1.93	1.93	1.98	1.93	1.87
IMEP COV Ch. #5%	2.36	2.15	1.97	1.94	1.94	1.99	1.94	1.87
IMEP COV Ch. #6%	373.30	437.40	405.30	433.40	441.70	278.50	225.00	202.40
IMEP COV Ch. #7%	-88.56	-89.56	-89.18	-90.03	-90.23	-89.82	-88.66	-89.02
IMEP COV Ch. #8%	-93.88	-94.75	-94.35	-95.25	-95.42	-95.05	-93.88	-94.24
IMEP COV Ch. #9%	463.80	29940.00	-8657.00	-16200.00	-3863.00	1678.00	632.90	609.10
AVG NMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #7psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #9psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

AVG PMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #7psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #9psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
MFB 10% Ch. #1*ATDC	5.43	5.58	5.38	5.14	4.90	4.75	4.69	4.52		
MFB 10% Ch. #2*ATDC	4.06	4.12	3.90	3.63	3.42	3.32	3.11	2.86		
MFB 10% Ch. #3*ATDC	5.58	5.62	5.48	4.99	4.60	4.29	4.06	3.78		
MFB 10% Ch. #4*ATDC	3.85	3.86	3.74	3.27	2.94	2.74	2.54	2.27		
MFB 10% Ch. #5*ATDC	4.15	4.16	4.04	3.58	3.25	3.06	2.87	2.60		
MFB 10% Ch. #6*ATDC	35.05	35.23	35.27	35.15	35.09	34.97	35.20	35.15		
MFB 10% Ch. #7*ATDC	35.54	35.54	35.54	35.53	35.52	35.52	35.52	35.51		
MFB 10% Ch. #8*ATDC	35.53	35.55	35.54	35.54	35.53	35.52	35.52	35.51		
MFB 10% Ch. #9*ATDC	35.55	35.65	35.65	35.66	35.66	35.62	35.57	35.57		
MFB 50% Ch. #1*ATDC	13.19	13.30	13.10	12.70	12.42	12.22	12.09	11.86		
MFB 50% Ch. #2*ATDC	12.51	12.62	12.30	11.95	11.64	11.48	11.18	10.92		
MFB 50% Ch. #3*ATDC	14.44	14.51	14.22	13.54	12.89	12.48	12.17	11.82		
MFB 50% Ch. #4*ATDC	12.36	12.44	12.25	11.58	11.15	10.81	10.58	10.13		
MFB 50% Ch. #5*ATDC	12.76	12.83	12.65	11.99	11.56	11.23	11.00	10.56		
MFB 50% Ch. #6*ATDC	87.12	87.05	87.34	86.88	86.90	87.33	87.16	87.25		
MFB 50% Ch. #7*ATDC	84.66	84.76	84.74	84.74	84.74	84.71	84.71	84.69		
MFB 50% Ch. #8*ATDC	84.69	84.78	84.78	84.77	84.76	84.75	84.76	84.74		
MFB 50% Ch. #9*ATDC	85.28	85.31	85.30	85.30	85.29	85.29	85.30	85.29		
MFB 90% Ch. #1*ATDC	23.27	23.51	23.29	22.67	22.26	22.05	21.87	21.59		
MFB 90% Ch. #2*ATDC	23.98	24.21	23.64	23.16	22.69	22.28	21.92	21.52		
MFB 90% Ch. #3*ATDC	31.16	31.22	30.40	29.85	29.11	28.51	28.23	28.08		
MFB 90% Ch. #4*ATDC	23.91	24.12	23.63	22.75	22.28	21.75	21.39	20.78		
MFB 90% Ch. #5*ATDC	24.28	24.47	23.99	23.13	22.68	22.16	21.81	21.23		
MFB 90% Ch. #6*ATDC	144.70	145.20	145.40	144.80	145.30	145.80	145.20	145.60		
MFB 90% Ch. #7*ATDC	131.40	131.60	131.60	131.60	131.60	131.60	131.60	131.60		
MFB 90% Ch. #8*ATDC	131.80	132.10	132.10	132.10	132.10	132.10	132.20	132.20		
MFB 90% Ch. #9*ATDC	131.80	132.00	132.00	131.90	131.80	131.80	131.80	131.80		
Low Cycles [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Low Cycles [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Low Cycles [%] Ch. #3*ATDC	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00		
Low Cycles [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Low Cycles [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Low Cycles [%] Ch. #6*ATDC	6.60	6.30	6.30	5.30	5.00	7.60	9.90	10.40		
Low Cycles [%] Ch. #7*ATDC	0.00	-0.20	0.00	0.00	0.00	0.00	0.00	0.00		
Low Cycles [%] Ch. #8*ATDC	0.00	-0.20	0.00	0.00	0.00	0.00	0.00	0.00		
Low Cycles [%] Ch. #9*ATDC	8.40	0.20	-1.30	-0.80	-2.90	4.40	7.70	7.90		
Misfires [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Misfires [%] Ch. #2*ATDC	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00		
Misfires [%] Ch. #3*ATDC	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Misfires [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Misfires [%] Ch. #5*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Misfires [%] Ch. #6*ATDC	28.40	30.20	30.30	30.00	31.20	25.40	18.20	17.50		
Misfires [%] Ch. #7*ATDC	99.90	99.90	100.00	100.00	100.00	100.00	100.00	100.00		
Misfires [%] Ch. #8*ATDC	99.90	99.90	100.00	100.00	100.00	100.00	100.00	100.00		
Misfires [%] Ch. #9*ATDC	4.30	38.60	44.40	42.30	46.20	22.70	5.70	5.30		
<u>Analysis Corrections for H2 Blending</u>										
Total Fuel Flow (lb/hr)	180.00	179.10	176.80	175.30	173.30	171.10	169.50	167.70		
H2 Fuel Flow (lb/hr)	0.00	0.20	1.01	2.01	2.99	3.94	4.88	5.81		
H2 mass fraction (%)	0.000	0.114318	0.572930	1.147910	1.724069	2.301655	2.881464	3.463333		
H2 mole fraction (%)	0.0	1.0	4.8	9.3	13.4	17.2	20.7	24.0		
Average MW (kg/kmol)	17.71	17.55	16.96	16.26	15.62	15.02	14.48	13.96		
PCC H2 Mole Fraction (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		
<u>Updated Fuel Composition Analysis</u>										
METHANE [%]	89.91	88.98	85.50	81.48	77.82	74.39	71.17	68.24		
ETHANE [%]	7.81	7.82	7.56	7.25	6.90	6.61	6.35	6.08		
PROPANE [%]	0.50	0.41	0.40	0.38	0.36	0.35	0.34	0.32		
BUTANE [%]	0.06	0.05	0.04	0.04	0.04	0.04	0.03	0.03		
PENTANE [%]	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00		
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
HYDROGEN [%]	0.000	0.995	4.819	9.260	13.355	17.152	20.692	23.980		
NITROGEN [%]	0.50	0.48	0.46	0.43	0.41	0.40	0.38	0.36		
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
CARBON DIOXIDE [%]	1.22	1.27	1.22	1.16	1.10	1.06	1.03	0.99		
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Total Composition Check (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00		
LHV (kJ/kg)	47780	47803	48124	48550	48976	49384	49783	50204		
LHV (Btu/g)	45.29	45.31	45.61	46.02	46.42	46.81	47.18	47.58		
<u>Updated A/F Ratio and BS Parameter Analysis</u>										
Carbon #	1.09	1.07	1.03	0.98	0.94	0.90	0.86	0.83		
Hydrogen #	4.11	4.09	4.01	3.91	3.83	3.75	3.67	3.60		
Oxygen #	0.0243	0.0253	0.0244	0.0232	0.0221	0.0213	0.0206	0.0198		
Nitrogen #	0.01005	0.00960	0.00921	0.00868	0.00825	0.00792	0.00756	0.00725		
y, H/C	3.789	3.807	3.881	3.976	4.072	4.169	4.267	4.368		
z, O/C	0.02243	0.02362	0.02362	0.02354	0.02347	0.02365	0.02392	0.02394		
f, N/C	0.009262	0.008943	0.008920	0.008813	0.008781	0.008809	0.008780	0.008787		

Stoichiometric A/F Ratio	16.40	16.41	16.49	16.59	16.70	16.80	16.89	17.00
CO2 (% , dry)	3.26	3.22	3.15	3.12	3.07	3.01	2.96	2.90
O2 (% , dry)	14.72	14.73	14.76	14.80	14.84	14.88	14.89	14.94
THC (ppmd)	1193	1092	1028	1005	939	961	971	977
CO (ppmd)	68.2	68.7	67.0	65.8	64.2	63.4	62.4	64.4
NOx (ppmd)	500.00	459.70	444.40	472.00	480.50	470.80	477.50	482.40
CH4 (ppmd)	919	841	792	773	722	741	748	751
VOC (ppmd)	31.6	28.1	24.8	24.3	21.7	20.7	20.7	24.3
Formaldehyde, CH2O (ppmd)	10.8	10.0	8.9	8.8	8.3	8.2	7.5	8.4
U&S, H2FAC	0.003695	0.003744	0.003720	0.003740	0.003742	0.003781	0.003806	0.004025
U&S, a	6.218	6.302	6.433	6.519	6.641	6.761	6.855	6.997
phi, overall	0.3114	0.3078	0.3044	0.3040	0.3021	0.3003	0.2997	0.2973
A/F, overall	52.69	53.30	54.15	54.57	55.27	55.93	56.36	57.18
phi, trapped	0.6429	0.6377	0.6329	0.6321	0.6300	0.6263	0.6256	0.6226
A/F, trapped	25.52	25.73	26.05	26.25	26.50	26.82	27.00	27.30
Airflow (kg/hr)	9484	9545	9574	9567	9579	9569	9553	9589
BS THC (g/bhp-hr)	6.44	5.94	5.63	5.48	5.12	5.24	5.28	5.34
BS CO (g/bhp-hr)	0.64	0.65	0.64	0.63	0.61	0.60	0.59	0.61
BS NOx (g/bhp-hr)	7.733	7.169	6.977	7.384	7.503	7.360	7.444	7.556
reduction in BS NOx (g/bhp-hr) / H2 mole frac (%)	0.000	-0.567	-0.157	-0.038	-0.017	-0.022	-0.014	-0.007
BS NOx (change from baseline)	0.000	-7.294	-9.771	-4.516	-2.968	-4.817	-3.734	-2.281
BS CH4 (g/bhp-hr)	4.955	4.572	4.334	4.216	3.934	4.038	4.067	4.101
reduction in BS CH4 (g/bhp-hr) / H2 mole frac (%)	0.000	0.384	0.129	0.080	0.076	0.053	0.043	0.036
BS CH4 (g/bhp-hr/C atom)	4.566	4.261	4.198	4.283	4.185	4.492	4.724	4.971
BS VOC (g/bhp-hr)	0.171	0.153	0.136	0.133	0.118	0.113	0.112	0.133
BS CH2O (g/bhp-hr)	0.058	0.054	0.049	0.048	0.045	0.045	0.041	0.046
BS CO2 (g/bhp-hr)	483	480	473	466	458	450	442	434
BS CO2e (g/bhp-hr)	606	594	581	572	556	551	543	537
BSFC (Btu/bhp-hr)	8417	8368	8329	8328	8286	8264	8240	8227
BSFC (% change from baseline)	0.00	-0.59	-1.05	-1.06	-1.56	-1.82	-2.11	-2.26
Ignition Delay (deg)	13.72	13.78	13.61	13.24	12.95	12.76	12.59	12.34
Combustion Duration (deg)	20.8	21.0	20.6	20.3	20.1	19.9	19.8	19.6

MGAV - Load Sweep Blending

Data Point Name	Base	Load 70 H2 0	Load 70 H2 20	Load 80 H2 0	Load 80 H2 20	Load 90 H2 0	Load 90 H2 20	Load 100 H2 0	Load 100 H2 20
Engine Data									
Start Time	44932.40903	44932.65069	44932.67361	44932.69028	44932.68264	44935.45833	44935.475	44935.43403	44935.51181
End Time	44932.4125	44932.65417	44932.67708	44932.69375	44932.68611	44935.46181	44935.47847	44935.4375	44935.51528
Speed [rpm]	299.40	300.00	299.80	299.70	299.50	299.50	299.50	299.60	299.70
Torque [lb-ft]	7703.00	5267.00	5353.00	6167.00	6181.00	6941.00	6928.00	7682.00	7683.00
Power [bhp]	439.20	300.80	305.60	352.00	352.40	395.80	395.20	438.10	438.40
Load [%]	100.00	68.38	69.50	80.06	80.24	90.11	89.94	99.72	99.73
Ambient Press [psia]	12.26	12.27	12.28	12.28	12.28	12.27	12.26	12.28	12.25
Ambient Temp [F]	36.96	47.83	45.86	44.78	45.01	54.35	54.29	50.60	55.20
Ambient Humidity [%]	51.24	34.00	36.86	38.28	38.02	22.27	22.49	26.33	24.68
Inlet Air Pres [in Hg]	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50
Inlet Air Temp [F]	109.40	109.40	109.20	109.50	109.50	107.60	109.40	109.10	109.30
Inlet Air Humidity [%]	5.23	5.56	5.64	5.53	5.55	4.99	4.55	4.68	5.35
Inlet Air Flow [scfm]	1878.00	1883.00	1899.00	1892.00	1903.00	1887.00	1892.00	1868.00	1870.00
IC Water Temp [F]	116.40	113.80	112.70	114.10	115.90	111.50	118.80	113.80	114.10
Exh Back Pres [in Hg]	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Exh Cyl 1 Temp [F]	604.00	584.20	552.80	572.70	546.90	572.00	562.10	605.00	602.20
Exh Cyl 2 Temp [F]	637.90	611.50	586.10	604.50	579.10	616.20	606.60	648.90	647.70
Exh Cyl 3 Temp [F]	554.30	502.70	512.40	536.70	518.10	539.00	525.20	556.50	553.30
Exh Cyl 4 Temp [F]	640.20	587.70	577.50	606.60	587.90	622.30	611.50	654.50	653.00
Avg Exh Temp [F]	609.10	571.50	557.20	580.10	558.00	587.40	576.40	616.20	614.00
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	180.00	157.10	142.80	161.10	147.10	168.50	159.40	181.60	174.80
Sensor NOx [ppm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor Lambda	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orifice Temp [F]	45.15	44.18	43.76	44.22	44.90	42.18	45.65	44.01	44.06
Eng Fuel Pres [psig]	21.45	18.99	18.47	19.55	19.74	20.00	20.69	21.94	23.05
Eng Fuel Temp [F]	82.98	87.30	87.80	87.30	87.38	81.45	81.82	80.99	82.78
JW Out Temp [F]	145.20	143.80	149.80	147.40	149.80	149.00	148.50	149.20	149.30
JW In Temp [F]	140.20	141.10	145.90	143.70	146.20	144.30	143.70	144.20	144.90
JW Flow [gpm]	485.20	487.50	486.60	487.60	487.50	487.10	483.30	487.30	489.30
Lube Press [psig]	33.36	33.89	34.58	32.12	31.84	32.48	35.52	30.82	32.08
Lube In Temp [F]	149.20	150.20	151.90	150.10	152.00	150.40	150.20	150.80	151.30
Lube Out Temp [F]	159.60	157.30	159.90	159.70	160.90	160.30	160.30	161.10	162.20
Thrust 1 Temp [F]	158.80	157.70	160.50	160.40	161.00	160.20	160.10	160.00	160.90
Thrust 2 Temp [F]	158.40	157.90	160.70	160.80	161.20	160.10	160.00	159.60	160.90
Main 2A Temp [F]	159.60	157.80	160.70	160.70	161.30	160.80	160.60	160.80	161.60
Main 2B Temp [F]	159.10	157.20	160.10	160.10	160.70	160.40	160.10	160.40	161.00
Main 3A Temp [F]	160.40	158.40	160.80	161.10	161.50	161.50	161.30	161.60	162.40
Main 3B Temp [F]	160.40	158.20	160.70	161.00	161.40	161.40	161.30	161.60	162.60
Main 4A Temp [F]	156.20	154.40	157.40	157.40	158.10	157.50	157.30	157.40	158.10
Main 4B Temp [F]	156.10	154.60	157.70	157.70	158.30	157.50	157.40	157.30	158.10
THC [ppmd]	-9.20	-9.29	-9.30	-9.30	-9.30	-9.13	-9.15	-9.10	-9.20
NOx [ppmd]	500.00	24.36	6.42	52.65	19.77	167.30	137.50	515.30	527.40
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	14.72	15.88	16.05	15.53	15.81	15.19	15.38	14.70	14.72
CO2 [%d]	3.26	2.58	2.39	2.77	2.52	3.01	2.79	3.29	3.11
CO [ppmd]	442.00	1030.00	668.00	643.90	487.90	515.00	446.20	485.30	424.10
AFR Left	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AFR Right	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Flow [lb/hr]	8438.00	8463.00	8534.00	8502.00	8549.00	8480.00	8500.00	8393.00	8404.00
Piezo 1 [F]	267.40	244.10	242.30	254.10	250.80	259.90	259.60	270.20	273.30
Piezo 2 [F]	275.30	240.40	240.90	254.00	252.80	268.40	268.70	280.60	284.90
Piezo 3 [F]	259.30	218.20	225.50	237.00	239.70	250.40	254.10	265.20	270.00
Piezo 4 [F]	279.80	231.70	234.90	248.00	250.50	270.90	272.60	286.30	292.20
Jacket Water Flow [gpm]	485.20	487.50	486.60	487.60	487.50	487.10	488.30	487.30	489.30
Jacket Water Valve Pos [%]	73.00	75.00	74.00	74.00	70.51	69.10	68.79	68.86	72.00
Supercharger Speed [%]	40.72	41.92	42.11	41.72	42.13	42.29	42.43	41.54	42.16
SC IC Temp Valve Pos [%]	85.20	84.05	83.68	83.67	83.89	85.05	84.79	83.83	83.65
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	40.76	42.19	41.83	41.26	41.38	41.32	41.40	40.64	40.80
Load Valve Pos [%]	21.41	1.76	5.40	21.39	21.37	13.30	12.38	23.66	24.56
Dyno Water Flow [gpm]	269.20	232.30	231.50	230.80	230.40	267.20	268.40	264.10	262.20
Dyno Water In [F]	74.38	78.38	74.60	74.18	74.32	83.55	84.62	82.84	87.24
Dyno Water Out [F]	87.31	89.26	85.50	86.59	86.68	95.59	96.80	96.03	100.50
Dyno Inboard Bearing [F]	108.60	113.10	111.30	109.40	110.30	114.30	115.30	110.50	115.80
Dyno Outboard Bearing [F]	124.20	142.30	138.50	136.10	136.90	117.00	120.10	109.50	125.10
Air Flow Static Pressure [kPa]	118.30	118.40	118.50	118.40	118.50	118.40	118.50	118.20	118.30
Air Flow Diff Pressure [kPa]	7.72	7.74	7.86	7.81	7.91	7.73	7.84	7.62	7.64
Air Flow Temperature [C]	45.15	44.18	43.76	44.22	44.90	42.18	45.65	44.01	44.06
Ethane Flow [lb/hr]	0.10	0.10	0.11	0.07	0.10	0.06	0.10	0.10	0.10
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.11	0.01	0.00	-0.02	-0.01	0.02	0.04	0.01	0.04
Ethane Temperature [C]	16.02	15.52	15.25	14.94	15.03	14.99	15.22	15.16	15.75
PCC H2 Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC H2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spare	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Manifold Pres Stpt [in Hg]	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50
PCC 4 Temp [F]	56.23	58.91	59.02	59.21	59.11	58.96	58.79	59.26	58.72
NOx Correction Step	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Averaging Time [s]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Feedback Time [s]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor NOx @ 15% O2	476.40	28.65	7.80	57.85	22.90	172.90	146.90	490.50	503.30
ePCC Pressure [psig]	2.88	1.70	1.61	1.53	1.57	0.87	0.89	0.84	0.92
Fuel Flow Static P [kPa]	322.50	327.50	358.10	322.30	350.00	318.00	331.60	321.10	318.70
Fuel Flow Temp [C]	29.10	28.53	28.20	28.39	28.30	28.88	28.78	29.82	29.94
Fuel Flow Diff P [kPa]	20.73	15.33	10.96	16.42	11.91	18.28	14.88	21.22	18.82
Low Press Orifice Flow [lb/hr]	179.90	157.10	139.50	161.10	143.60	168.40	155.80	181.60	170.70
Air Flow Diff 0 offset	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ign Spark #	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign Timing [deg]	-9.42	-9.42	-9.42	-10.52	-10.52	-11.18	-10.08	-9.20	-8.11
Ign Offset Cyl 1 [deg]	1.97	1.97	1.97	1.97	1.97	1.53	1.53	1.53	1.53
Ign Offset Cyl 2 [deg]	0.00	0.00	0.00	0.00	0.00	0.66	0.66	0.66	0.66
Ign Offset Cyl 3 [deg]	0.88	0.88	0.88	0.88	0.88	0.44	0.44	0.44	0.66
Ign Offset Cyl 4 [deg]	-1.10	-1.10	-1.10	-1.10	-1.10	0.00	0.00	0.00	0.00

Ign 4-20 mA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EFI Hyd Sup Pres [psig]	5.18	5.31	5.31	5.22	5.23	5.26	5.23	5.17	5.31
EFI Hyd Ret Pres [psig]	16.98	15.36	17.01	16.37	15.71	18.89	18.51	21.13	18.53
LECM RPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOI Cylinder 1 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 2 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 3 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 4 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 1 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Global Duration [usec]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cylinder 1 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
LECM Fuel Temp [deg F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LECM Fuel Pres [psia]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HP Meter Fuel Flow [lb/hr]	1.56	1.57	1.58	1.58	1.58	1.57	1.57	1.57	1.57
SC IC Coolant Out [C]	46.78	45.56	44.97	45.64	46.69	44.00	48.30	45.46	45.71
SC IC Coolant In [C]	46.87	45.45	44.86	45.59	46.61	44.14	48.23	45.45	45.60
SC IC Air 1 [C]	47.25	45.85	45.28	45.95	47.07	43.29	48.16	45.55	45.69
SC IC Air 2 [C]	43.41	50.98	49.90	49.18	49.47	52.66	53.30	50.21	53.86
SC ID Pres Diff	367.30	370.90	376.00	372.60	377.10	373.10	376.30	366.20	369.60
HPFI H2 Meter 1 Flow [g/hr]	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.01	0.01
HPFI H2 Meter 2 Flow [kg/hr]	0.08	0.07	0.08	0.07	0.08	0.08	0.08	0.06	0.08
HPFI H2 Meter 3 Flow [kg/hr]	-0.02	-0.05	-0.03	-0.01	0.00	-0.01	-0.03	-0.02	-0.03
HPFI H2 Meter 1 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 3 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Total Flow [kg/hr]	0.08	0.04	0.07	0.09	0.11	0.10	0.08	0.05	0.06
HPFI H2 Total Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LP Orifice Fuel Flow [lb/hr]	179.90	157.10	139.50	161.10	143.60	168.40	155.80	181.60	170.70
LPFI H2 Meter Setpoint	0.00	0.00	1.49	0.00	1.54	0.00	1.67	0.00	1.83
LPFI H2 Meter Flow [kg/hr]	0.00	0.00	1.49	0.00	1.54	0.00	1.67	0.00	1.83
FTIR Data									
NO (350,3000) 191C	407.40	20.64	11.42	49.73	28.19	161.30	127.60	443.40	511.70
NO2 (150) 191C (1o2)	15.26	13.84	10.57	16.44	14.97	16.53	16.74	15.53	18.05
NO2 (2000) 191C (2o2)	11.66	11.73	10.52	15.10	14.47	14.37	15.10	14.98	17.22
N2O (100,200,300) 191C	0.32	0.19	0.23	0.18	0.23	0.28	0.20	0.27	0.23
NH3 (300) 191C (1o2)	0.02	0.11	-0.03	0.11	0.00	0.09	0.00	0.05	0.00
NH3 (3000) 191C (2o2)	0.39	-0.21	0.52	0.54	0.74	0.44	-0.03	-0.80	0.72
H2O% (25) 191C	6.57	5.44	5.59	5.94	5.91	6.16	6.26	6.61	6.88
CO2% (20) 191C (1o2) R4	3.32	2.71	2.55	2.99	2.84	3.15	3.07	3.42	3.36
CO (500) 191C (1o3)	63.69	84.35	80.44	74.15	74.73	72.55	66.39	64.48	57.84
CO% (1) 191C (2o3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CH4 (3000) 191C (1o2)	858.40	2685.00	1584.00	1059.00	864.20	760.50	737.30	777.70	734.10
CH4 (20000) 191C (2o2)	873.60	2681.00	1583.00	1060.00	876.50	772.50	753.70	788.60	736.20
Ethane (500) 191C	70.42	225.10	134.90	88.61	72.17	66.93	64.95	71.31	68.12
Ethylene (100,3000) 191C	5.53	8.96	7.08	7.90	7.47	7.05	6.28	5.83	5.88
Acetylene (1000) 191C	0.20	0.20	0.01	0.18	0.34	0.50	0.21	0.06	0.31
Propane (200) 191C	4.92	13.37	8.64	5.59	4.44	6.93	6.35	6.81	6.36
Propylene (200,1000) 191C	1.33	1.06	0.94	1.20	0.84	0.82	0.87	0.90	1.28
Oil as octane (200) 191C	2.03	2.18	2.02	2.20	2.09	2.06	2.08	2.33	2.21
Formaldehyde (70,500) 191C	10.06	14.05	10.41	13.34	12.27	11.91	11.04	10.32	10.14
Acetaldehyde (1000) 191C	3.97	5.70	4.31	4.44	4.04	3.64	3.38	4.32	3.23
Formic Acid (100) 191C	0.39	0.39	0.27	0.30	0.26	0.44	0.32	0.50	0.36
MeOH (1000) 191C	0.12	0.72	0.46	0.76	0.48	0.33	0.45	-0.09	0.12
CO% (10) 191C (3o3)	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.01
CO2 low% (4) 191C (2o2)	3.27	2.67	2.52	2.93	2.77	3.09	3.00	3.34	3.29
1,3 butadiene (80) 191C	0.06	0.35	0.05	-0.23	-0.42	-0.34	-0.22	-0.04	0.20
Temp (C)	190.60	190.60	190.60	190.60	190.60	190.60	190.60	190.60	190.60
Pressure (Atm)	0.97	0.97	0.97	0.98	0.98	0.99	0.99	0.99	0.99
NOx autorange	422.70	34.49	21.99	66.18	43.16	177.80	144.40	458.90	529.80
CO autorange	63.69	84.35	80.44	74.15	74.73	72.55	66.39	64.48	57.84
CH4 autorange	858.40	2685.00	1584.00	1059.00	864.20	760.50	737.30	777.70	734.10
NH3 autorange	0.02	0.11	-0.03	0.11	0.00	0.09	0.00	0.05	0.00
NOx autorange dry	452.40	36.47	23.29	70.35	45.87	189.50	154.00	491.40	568.90
CO autorange dry	68.17	89.21	85.20	78.83	79.42	77.31	70.83	69.05	62.12
CO2% autorange dry	3.50	2.82	2.67	3.12	2.94	3.29	3.20	3.58	3.54
N2O dry	0.34	0.20	0.24	0.19	0.25	0.30	0.22	0.29	0.25
NH3 autorange dry	0.02	0.12	-0.03	0.12	0.00	0.10	0.00	0.06	0.00
FIDeq THC ppmC	1115.00	3465.00	2055.00	1378.00	1126.00	1008.00	974.90	1032.00	978.40
FIDeq NMHC ppmC	170.40	510.90	311.90	212.90	175.10	171.60	163.80	176.80	170.90
FIDeq NMNEHC ppmC	29.55	60.62	42.10	35.67	30.74	37.73	33.93	34.22	34.64
CO2% autorange	3.27	2.67	2.52	2.93	2.77	3.09	3.00	3.34	3.29
FTIR NMHC ppmC	181.60	527.00	323.90	228.20	188.80	184.90	176.30	188.30	182.20
FTIR NMNEHC ppmC	40.79	76.75	54.08	50.96	44.48	51.04	46.42	45.65	45.91
Igram DC	3.77	3.69	3.78	3.77	3.80	3.80	3.79	3.75	3.69
Igram PP	6.02	5.93	5.97	5.95	5.98	6.02	6.00	5.92	5.95
phase Angle	89.76	90.54	90.44	90.57	90.37	89.72	90.21	89.65	90.35
laser PP	8.76	8.71	8.86	8.81	8.98	8.88	8.85	8.82	8.98
laser DC	-6.09	-6.30	-6.32	-6.31	-6.31	-6.15	-6.15	-6.08	-6.24
Bad Scan counter	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00
Centerburst Location	1129.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00
Linearizer Check	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNR 2500	693.50	686.30	742.30	697.30	711.50	683.40	690.80	698.40	658.70
sBeam @ 2500	1.36	1.34	1.34	1.34	1.34	1.35	1.35	1.35	1.34
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GC Data									
METHANE [%]	89.91	89.75	89.68	89.65	89.65	88.63	88.56	88.41	88.38
ETHANE [%]	7.81	8.00	8.06	8.09	8.09	8.38	8.44	8.59	8.583
PROPANE [%]	0.50	0.42	0.43	0.43	0.43	0.77	0.77	0.7603	0.7966
BUTANE [%]	0.06	0.04	0.04	0.04	0.04	0.11	0.11	0.1036	0.1087
PENTANE [%]	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01444	0.01455
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0

HYDROGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
NITROGEN [%]	0.50	0.48	0.48	0.48	0.48	0.55	0.55	0.5566	0.5552
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
CARBON DIOXIDE [%]	1.22	1.30	1.30	1.30	1.30	1.55	1.57	1.566	1.563
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
LHV Actual [kJ/kg]	47780.00	47690.00	47690.00	47690.00	47690.00	47310.00	47300.00	47290	47290
LHV Actual [BTU/scf]	960.30	959.60	960.20	960.40	960.40	966.00	966.40	967.2	967.8
HHV Dry [kJ/kg]	52880.00	52790.00	52790.00	52790.00	52790.00	52350.00	52330.00	52330	52330
HHV Dry [BTU/scf]	1063.00	1062.00	1063.00	1063.00	1063.00	1069.00	1069.00	1070	1071
Gas Density [kg/m3]	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.762	0.7625
Stoich A/F	16.34	16.31	16.31	16.31	16.31	16.17	16.17	16.17	16.17
Avg. Mol Weight	17.71	17.72	15.04	17.74	15.04	17.99	15.22	18.02	15.23
Cp [kJ/kg*K]	2.13	2.13	2.13	2.13	2.13	2.11	2.11	2.107	2.106
Cv [kJ/kg*K]	1.66	1.66	1.66	1.66	1.66	1.65	1.65	1.644	1.644
Cp/Cv	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.281	1.281
Calculated Data									
AFR	52.60	59.99	67.07	60.42	66.13	56.61	60.21	52.02	54.24
Phi total	0.31	0.27	0.24	0.27	0.25	0.29	0.27	0.31	0.30
Air Flow [kg/hr]	4294.00	4275.00	4345.00	4416.00	4411.00	4326.00	4355.00	4286.00	4299.00
Exh Flow [kg/hr]	4375.00	4346.00	4410.00	4489.00	4478.00	4402.00	4427.00	4368.00	4379.00
BMEP [kPa]	477.30	326.30	331.70	382.10	382.90	430.10	429.20	475.90	476.00
thermal eff	0.30	0.24	0.27	0.27	0.30	0.29	0.31	0.30	0.31
BSFC [kJ/kW-hr]	11910.00	15150.00	13560.00	13280.00	12100.00	12250.00	11610.00	11930.00	11470.00
Abs Humidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BSTHC [g/bkW-hr]	8.18	37.32	22.42	13.09	10.80	8.30	8.19	7.57	7.32
BS NOx [g/bkW-hr]	10.52	0.75	0.20	1.43	0.54	3.95	3.31	10.84	11.31
BS CO [g/bkW-hr]	0.87	1.68	1.62	1.31	1.33	1.11	1.04	0.88	0.81
THC @15%O2	1063.00	4075.00	2498.00	1515.00	1304.00	1042.00	1042.00	982.80	933.70
NOx @15%O2	477.00	28.65	7.80	57.89	22.91	173.00	147.00	490.50	503.40
CO @15%O2	65.04	104.90	103.60	86.69	92.00	79.92	75.71	65.73	59.28
Wet 2 Dry Scaler	1.07	1.06	1.05	1.06	1.05	1.06	1.06	1.07	1.06
15% O2 Factor	0.95	1.18	1.22	1.10	1.16	1.03	1.07	0.95	0.95
BS Calc Factor	457.10	671.30	680.00	592.00	597.80	513.00	523.40	457.10	466.20
Delivery Ratio	1.68	1.67	1.70	1.73	1.73	1.69	1.70	1.68	1.68
Scavenging Efficiency	0.81	0.81	0.82	0.82	0.82	0.81	0.82	0.81	0.81
Trapping Efficiency	0.48	0.49	0.48	0.48	0.48	0.48	0.48	0.49	0.48
Trapped AF Ratio	25.47	29.17	32.28	28.77	31.50	27.35	28.92	25.23	26.26
Trapped Equivalence Ratio	0.64	0.56	0.51	0.57	0.52	0.59	0.56	0.64	0.62
Combustion Data									
Engine Avg Peak Pressure[psi]	533.15	359.08	361.90	409.60	420.98	486.50	502.03	526.00	532.98
Engine Avg Peak Pres Std Dev[psi]	27.24	36.08	33.35	41.28	35.27	34.19	26.96	26.13	22.35
Engine Avg Peak Pres COV[%]	9.13	18.22	16.76	18.17	15.13	12.92	9.68	9.02	7.50
Engine Max Peak Pres COV Ch. #6[%]	28.04	20.24	18.73	21.70	17.94	28.78	29.50	21.43	17.97
Engine Min Peak Pres COV Ch. #8[%]	0.27	0.92	0.62	0.61	0.44	0.31	0.22	0.20	0.19
Engine Avg Peak Loc[*ATDC]	17.89	16.17	16.74	18.30	18.91	18.42	17.99	18.31	18.14
Engine Avg IMEP[psi]	80.63	59.27	59.98	67.19	66.87	74.89	74.70	80.81	80.73
Engine Avg IMEP COV[%]	74.22	115.70	145.60	75.78	67.31	-59.89	28.59	134.40	-2.49
Engine Max IMEP COV Ch. #9[%]	463.80	862.50	1065.00	535.20	404.50	300.50	770.30	1137.00	478.80
Engine Min IMEP COV Ch. #8[%]	-93.88	-133.40	-113.30	-109.20	-97.35	-679.30	-348.50	-95.75	-325.50
Avg. Peak Ch. #1psi	539.40	393.00	392.60	448.50	448.80	506.80	511.20	531.90	531.70
Avg. Peak Ch. #2psi	533.40	361.10	359.20	414.30	421.40	489.30	497.00	523.50	527.50
Avg. Peak Ch. #3psi	528.90	341.80	355.60	391.40	417.30	469.30	507.20	531.00	545.60
Avg. Peak Ch. #4psi	530.90	340.40	340.20	384.20	396.40	480.60	492.70	517.60	527.10
Avg. Peak Ch. #5psi	524.60	336.40	336.20	378.40	391.00	476.00	488.30	511.80	522.60
Avg. Peak Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Avg. Peak Ch. #7psi	109.50	110.80	110.30	110.70	110.20	109.70	109.70	109.60	110.40
Avg. Peak Ch. #8psi	1.13	1.14	1.14	1.14	1.14	1.13	1.13	1.13	1.14
Avg. Peak Ch. #9psi	110.80	110.70	110.50	110.70	110.70	111.30	111.60	111.00	112.40
Peak Std. Dev. Ch. #1psi	41.79	61.82	57.70	62.85	53.65	50.33	42.19	43.00	38.36
Peak Std. Dev. Ch. #2psi	43.00	66.51	59.75	70.89	61.48	55.92	43.08	40.68	36.25
Peak Std. Dev. Ch. #3psi	59.23	69.17	66.61	84.94	74.85	86.26	61.37	61.04	44.51
Peak Std. Dev. Ch. #4psi	50.48	62.96	57.73	76.29	63.60	57.42	47.85	45.12	40.86
Peak Std. Dev. Ch. #5psi	49.77	62.00	56.80	74.85	62.52	56.76	47.33	44.51	40.41
Peak Std. Dev. Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peak Std. Dev. Ch. #7psi	0.35	1.12	0.77	0.75	0.55	0.39	0.31	0.28	0.28
Peak Std. Dev. Ch. #8psi	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Peak Std. Dev. Ch. #9psi	0.59	1.13	0.83	0.96	0.73	0.61	0.49	0.51	0.45
Peak COV Ch. #1%	7.75	15.73	14.70	14.01	11.95	9.93	8.25	8.08	7.21
Peak COV Ch. #2%	8.06	18.42	16.63	17.11	14.59	11.43	8.67	7.77	6.87
Peak COV Ch. #3%	11.20	20.24	18.73	21.70	17.94	18.38	12.10	11.49	8.16
Peak COV Ch. #4%	9.51	18.49	16.97	19.86	16.04	11.95	9.71	8.72	7.75
Peak COV Ch. #5%	9.49	18.43	16.89	19.78	15.99	11.92	9.69	8.70	7.73
Peak COV Ch. #6%	28.04	19.32	17.06	13.00	12.26	28.78	29.50	21.43	17.97
Peak COV Ch. #7%	0.32	1.01	0.69	0.68	0.50	0.36	0.28	0.26	0.25
Peak COV Ch. #8%	0.27	0.92	0.62	0.61	0.44	0.31	0.22	0.20	0.19
Peak COV Ch. #9%	0.53	1.02	0.75	0.87	0.66	0.55	0.44	0.46	0.40
Max Peak Ch. #1psi	647.90	563.90	562.40	620.50	611.80	638.60	607.80	628.90	640.40
Max Peak Ch. #2psi	645.50	559.20	550.90	579.30	568.90	624.90	599.20	622.60	614.20
Max Peak Ch. #3psi	664.00	582.70	579.40	604.10	609.00	653.70	648.20	654.40	652.10
Max Peak Ch. #4psi	644.90	578.00	540.20	594.10	579.30	609.70	603.50	644.30	656.10
Max Peak Ch. #5psi	636.90	570.20	533.10	584.50	571.20	603.50	597.50	636.10	649.60
Max Peak Ch. #6psi	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Max Peak Ch. #7psi	111.00	114.10	113.00	114.50	113.20	112.40	110.90	110.80	111.20
Max Peak Ch. #8psi	1.15	1.18	1.16	1.17	1.16	1.15	1.14	1.14	1.15
Max Peak Ch. #9psi	112.50	114.00	113.00	113.70	113.10	113.20	112.90	112.10	113.60
Min Peak Ch. #1psi	289.70	281.20	284.10	282.40	287.50	289.30	291.10	315.40	386.00
Min Peak Ch. #2psi	341.60	277.00	278.70	280.80	283.00	284.20	288.10	290.20	374.60
Min Peak Ch. #3psi	289.10	279.50	283.80	283.20	286.10	287.70	289.60	288.90	324.30
Min Peak Ch. #4psi	290.00	276.00	278.80	280.40	284.20	286.70	296.20	346.60	369.70
Min Peak Ch. #5psi	287.40	273.40	276.00	276.60	280.90	284.70	294.20	343.10	366.80
Min Peak Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Min Peak Ch. #7psi	108.60	106.40	106.60	107.80	108.00	107.50	108.10	108.50	109.30
Min Peak Ch. #8psi	1.12	1.10	1.10	1.11	1.12	1.11	1.12	1.12	1.13
Min Peak Ch. #9psi	108.10	106.90	107.00	107.60	108.30	108.90	109.30	108.10	109.70
Avg. Peak Loc. Ch. #1psi	18.09	21.47	20.81	20.13	19.77	18.23	17.87	18.24	18.33
Avg. Peak Loc. Ch. #2psi	17.51	17.13	17.31	18.93	18.98	18.34	17.97	18.20	18.21
Avg. Peak Loc. Ch. #3psi	18.52	12.65	15.07	17.44	18.71	18.52	17.99	18.41	17.92
Avg. Peak Loc. Ch. #4psi	17.45	13.43	13.76	16.69	18.18	18.57	18.13	18.37	18.10
Avg. Peak Loc. Ch. #5psi	17.87	13.80	14.08	17.02	18.57	18.97	18.53	18.78	18.49

Avg. Peak Loc. Ch. #6psi	-25.08	-76.20	-67.51	-79.37	-66.18	-61.16	-54.51	-82.37	-59.39
Avg. Peak Loc. Ch. #7psi	131.40	116.40	121.90	126.50	127.60	130.90	131.40	131.60	131.60
Avg. Peak Loc. Ch. #8psi	131.60	114.10	119.50	125.10	126.10	130.50	131.70	131.80	131.90
Avg. Peak Loc. Ch. #9psi	134.50	120.00	128.00	132.20	133.40	134.30	134.20	134.80	134.90
Peak Loc. Std. Dev Ch. #1psi	2.12	6.85	6.27	4.56	3.51	2.63	2.26	2.19	1.93
Peak Loc. Std. Dev Ch. #2psi	2.17	9.82	8.96	6.50	4.98	3.25	2.35	2.14	1.96
Peak Loc. Std. Dev Ch. #3psi	3.19	11.80	11.00	9.84	7.33	6.04	3.51	3.22	2.21
Peak Loc. Std. Dev Ch. #4psi	2.58	10.93	10.32	8.91	6.44	3.24	2.46	2.30	2.04
Peak Loc. Std. Dev Ch. #5psi	2.58	10.94	10.34	8.92	6.46	3.21	2.44	2.29	2.03
Peak Loc. Std. Dev Ch. #6psi	107.40	93.66	97.58	102.70	104.80	112.60	99.26	91.92	96.22
Peak Loc. Std. Dev Ch. #7psi	2.58	49.03	34.08	21.57	17.72	4.62	2.88	2.03	1.72
Peak Loc. Std. Dev Ch. #8psi	3.54	52.72	39.02	25.86	21.93	11.41	3.12	2.51	2.12
Peak Loc. Std. Dev Ch. #9psi	1.60	49.77	29.17	11.94	7.52	1.92	1.64	1.45	1.35
Peak Loc. COV Ch. #1%	11.71	31.90	30.12	22.63	17.77	14.41	12.63	11.99	10.51
Peak Loc. COV Ch. #2%	12.38	57.35	51.77	34.34	26.22	17.73	13.07	11.78	10.76
Peak Loc. COV Ch. #3%	17.24	93.31	73.01	56.43	39.18	32.62	19.51	17.50	12.30
Peak Loc. COV Ch. #4%	14.81	81.43	75.00	53.38	35.44	17.46	13.58	12.50	11.28
Peak Loc. COV Ch. #5%	14.45	79.29	73.45	52.41	34.80	16.94	13.16	12.17	10.99
Peak Loc. COV Ch. #6%	-428.40	-122.90	-144.60	-129.40	-158.40	-184.10	-182.10	-111.60	-162.00
Peak Loc. COV Ch. #7%	1.96	42.11	27.97	17.05	13.89	3.53	2.19	1.54	1.31
Peak Loc. COV Ch. #8%	2.69	46.20	32.66	20.68	17.38	8.74	2.37	1.90	1.60
Peak Loc. COV Ch. #9%	1.19	41.49	22.79	9.03	5.64	1.43	1.22	1.08	1.00
AVG IMEP Ch. #1psi	76.99	66.08	63.47	69.14	66.70	72.22	71.07	76.37	75.79
AVG IMEP Ch. #2psi	79.98	61.54	60.01	67.33	65.85	74.61	73.85	80.56	80.32
AVG IMEP Ch. #3psi	90.54	57.78	64.55	72.46	74.28	82.18	83.86	90.66	91.08
AVG IMEP Ch. #4psi	75.02	51.67	51.89	59.83	60.65	70.55	70.03	75.66	75.74
AVG IMEP Ch. #5psi	74.59	51.35	51.55	59.26	60.14	70.29	69.79	75.24	75.52
AVG IMEP Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AVG IMEP Ch. #7psi	-0.68	-0.67	-0.67	-0.67	-0.70	-0.68	-0.70	-0.67	-0.67
AVG IMEP Ch. #8psi	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
AVG IMEP Ch. #9psi	0.14	0.10	0.07	0.28	0.16	-0.10	-0.18	0.06	-0.19
IMEP STD DEV Ch. #1psi	2.10	4.63	4.22	4.45	3.25	2.38	1.97	2.05	1.95
IMEP STD DEV Ch. #2psi	1.18	14.24	9.59	10.21	4.77	2.22	1.22	1.13	0.93
IMEP STD DEV Ch. #3psi	4.06	28.76	19.23	18.32	11.62	9.95	4.16	3.30	2.18
IMEP STD DEV Ch. #4psi	1.75	21.52	16.57	15.74	6.78	3.37	1.50	1.48	1.34
IMEP STD DEV Ch. #5psi	1.76	21.37	16.47	15.61	6.78	3.39	1.52	1.49	1.35
IMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IMEP STD DEV Ch. #7psi	0.60	0.87	0.73	0.70	0.64	0.63	0.60	0.60	0.60
IMEP STD DEV Ch. #8psi	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
IMEP STD DEV Ch. #9psi	0.63	0.86	0.74	0.72	0.66	0.65	0.63	0.63	0.63
IMEP COV Ch. #1%	2.72	7.00	6.65	6.44	4.88	3.30	2.78	2.69	2.58
IMEP COV Ch. #2%	1.47	23.15	15.99	15.17	7.24	2.97	1.65	1.40	1.15
IMEP COV Ch. #3%	4.48	49.77	29.79	25.29	15.64	12.11	4.95	3.64	2.39
IMEP COV Ch. #4%	2.33	41.65	31.94	26.30	11.18	4.78	2.14	1.96	1.77
IMEP COV Ch. #5%	2.36	41.62	31.96	26.34	11.28	4.82	2.17	1.98	1.78
IMEP COV Ch. #6%	373.30	277.70	350.50	535.20	340.70	300.50	770.30	247.20	478.80
IMEP COV Ch. #7%	-88.56	-128.90	-108.60	-104.10	-92.36	-91.62	-86.67	-90.41	-90.07
IMEP COV Ch. #8%	-93.88	-133.40	-113.30	-109.20	-97.35	-96.53	-91.47	-95.75	-95.22
IMEP COV Ch. #9%	463.80	862.50	1065.00	260.50	404.50	-679.30	-348.50	1137.00	-325.50
AVG NMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #7psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP STD DEV Ch. #9psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP STD DEV Ch. #1psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #2psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #3psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #4psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #5psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #6psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #7psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #8psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP STD DEV Ch. #9psi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

MFB 10% Ch. #1*ATDC	5.43	9.06	8.60	6.92	6.53	5.05	5.04	5.49	5.81
MFB 10% Ch. #2*ATDC	4.06	8.38	8.09	6.18	5.46	4.40	4.29	4.79	5.01
MFB 10% Ch. #3*ATDC	5.58	10.30	9.78	8.33	7.23	5.74	4.86	5.36	5.38
MFB 10% Ch. #4*ATDC	3.85	9.06	8.85	7.07	6.38	4.67	4.35	4.82	4.82
MFB 10% Ch. #5*ATDC	4.15	9.07	8.88	7.22	6.55	4.93	4.63	5.11	5.11
MFB 10% Ch. #6*ATDC	35.05	35.23	35.27	35.19	35.33	35.11	35.15	35.12	35.24
MFB 10% Ch. #7*ATDC	35.54	35.41	35.42	35.49	35.44	35.52	35.48	35.59	35.56
MFB 10% Ch. #8*ATDC	35.53	35.41	35.42	35.48	35.44	35.52	35.48	35.60	35.57
MFB 10% Ch. #9*ATDC	35.55	35.48	35.49	35.41	35.43	35.66	35.68	35.60	35.75
MFB 50% Ch. #1*ATDC	13.19	19.37	18.69	16.22	15.56	13.43	13.10	13.34	13.48
MFB 50% Ch. #2*ATDC	12.51	20.86	20.34	17.09	16.06	13.71	13.17	13.31	13.30
MFB 50% Ch. #3*ATDC	14.44	24.67	23.17	21.07	18.55	16.28	14.14	14.26	13.68
MFB 50% Ch. #4*ATDC	12.36	22.20	21.77	18.77	17.38	14.02	13.35	13.39	13.11
MFB 50% Ch. #5*ATDC	12.76	22.35	21.93	19.03	17.67	14.38	13.72	13.78	13.50
MFB 50% Ch. #6*ATDC	87.12	87.36	87.27	87.40	87.27	86.89	86.98	87.06	86.89
MFB 50% Ch. #7*ATDC	84.66	84.72	84.65	84.68	84.64	84.76	84.69	84.90	84.83
MFB 50% Ch. #8*ATDC	84.69	84.76	84.70	84.75	84.71	84.79	84.71	84.91	84.83
MFB 50% Ch. #9*ATDC	85.28	85.33	85.30	85.35	85.32	85.32	85.28	85.36	85.31
MFB 90% Ch. #1*ATDC	23.27	33.22	32.29	28.78	27.50	24.45	23.62	23.70	23.46
MFB 90% Ch. #2*ATDC	23.98	40.46	38.90	33.38	30.69	26.48	25.01	24.84	24.28
MFB 90% Ch. #3*ATDC	31.16	51.12	47.07	44.68	38.69	36.11	31.09	31.01	29.35
MFB 90% Ch. #4*ATDC	23.91	41.96	40.95	36.26	33.17	26.79	25.25	24.88	24.14
MFB 90% Ch. #5*ATDC	24.28	41.78	40.81	36.31	33.29	27.06	25.56	25.22	24.49
MFB 90% Ch. #6*ATDC	144.70	144.80	145.00	145.40	145.00	145.30	145.40	146.00	144.70
MFB 90% Ch. #7*ATDC	131.40	131.90	131.90	131.70	131.60	131.60	131.60	131.60	131.50
MFB 90% Ch. #8*ATDC	131.80	133.80	133.90	133.60	133.40	131.90	131.90	132.00	131.90
MFB 90% Ch. #9*ATDC	131.80	134.10	134.00	133.40	133.20	132.20	132.10	132.00	132.00
Low Cycles [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #2*ATDC	0.00	1.30	0.60	0.70	0.10	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #3*ATDC	0.00	2.80	1.20	1.30	0.40	0.10	0.00	0.00	0.00
Low Cycles [%] Ch. #4*ATDC	0.00	2.20	1.20	0.90	0.60	0.10	0.00	0.00	0.00
Low Cycles [%] Ch. #5*ATDC	0.00	2.20	1.20	1.00	0.60	0.10	0.00	0.00	0.00
Low Cycles [%] Ch. #6*ATDC	6.60	6.50	7.20	5.00	5.80	7.00	3.60	7.90	5.30
Low Cycles [%] Ch. #7*ATDC	0.00	-5.10	-3.00	-4.00	-1.10	-0.90	-0.10	0.00	0.00
Low Cycles [%] Ch. #8*ATDC	0.00	-5.00	-2.90	-4.10	-1.10	-1.00	-0.10	0.00	0.00
Low Cycles [%] Ch. #9*ATDC	8.40	4.20	4.50	8.20	8.70	-8.40	-12.20	6.00	-9.80
Misfires [%] Ch. #1*ATDC	0.00	0.10	0.10	0.20	0.10	0.00	0.00	0.00	0.00
Misfires [%] Ch. #2*ATDC	0.00	3.20	1.30	1.40	0.20	0.00	0.00	0.00	0.00
Misfires [%] Ch. #3*ATDC	0.10	16.80	6.40	4.30	1.60	0.90	0.10	0.00	0.00
Misfires [%] Ch. #4*ATDC	0.00	11.00	6.70	4.80	0.40	0.10	0.00	0.00	0.00
Misfires [%] Ch. #5*ATDC	0.00	11.00	6.70	4.80	0.40	0.10	0.00	0.00	0.00
Misfires [%] Ch. #6*ATDC	28.40	26.10	26.80	34.50	28.50	26.30	38.90	22.30	33.60
Misfires [%] Ch. #7*ATDC	99.90	83.20	90.70	92.90	97.80	99.00	99.90	100.00	100.00
Misfires [%] Ch. #8*ATDC	99.90	83.10	90.60	93.00	97.80	99.00	99.90	100.00	100.00
Misfires [%] Ch. #9*ATDC	4.30	40.10	39.50	15.30	13.50	71.60	93.60	20.00	97.00
Analysis Corrections for H2 Blending									
Total Fuel Flow (lb/hr)	180.00	157.10	142.80	161.10	147.10	168.50	159.40	181.60	174.80
H2 Fuel Flow (lb/hr)	0.00	0.00	3.29	0.00	3.38	0.00	3.67	0.00	4.02
H2 mass fraction (%)	0.000	0.00051	2.302272	0.000029	2.300971	0.000	2.303	0.000	2.302
H2 mole fraction (%)	0.0	0.0	17.2	0.0	17.2	0.0	17.4	0.0	17.4
Average MW (kg/kmol)	17.71	17.72	15.04	17.74	15.04	17.99	15.22	18.02	15.24
PCC H2 Mole Fraction (%)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Updated Fuel Composition Analysis									
METHANE [%]	89.91	89.75	74.28	89.65	74.26	88.63	73.16	88.41	73.01
ETHANE [%]	7.81	8.00	6.68	8.09	6.70	8.38	6.97	8.59	7.09
PROPANE [%]	0.50	0.42	0.36	0.43	0.36	0.77	0.63	0.76	0.66
BUTANE [%]	0.06	0.04	0.03	0.04	0.03	0.11	0.09	0.10	0.09
PENTANE [%]	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01
HEXANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.000	0.000	17.173	0.000	17.167	0.000	17.389	0.000	17.396
NITROGEN [%]	0.50	0.48	0.40	0.48	0.39	0.55	0.45	0.56	0.46
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.22	1.30	1.08	1.30	1.08	1.55	1.30	1.57	1.29
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Composition Check (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LHV (kJ/kg)	47780	47690	49355	47690	49354	47310	48974	47290	48964
LHV (Btu/g)	45.29	45.20	46.78	45.20	46.78	44.84	46.42	44.82	46.41
Updated A/F Ratio and BS Parameter Analysis									
Carbon #	1.09	1.09	0.90	1.09	0.90	1.10	0.91	1.10	0.91
Hydrogen #	4.11	4.11	3.75	4.11	3.75	4.12	3.75	4.12	3.76
Oxygen #	0.0243	0.0260	0.0215	0.0260	0.0216	0.0310	0.0259	0.0313	0.0258
Nitrogen #	0.01005	0.00967	0.00796	0.00951	0.00788	0.01103	0.00902	0.01113	0.00917
y, H/C	3.789	3.786	4.167	3.785	4.166	3.756	4.138	3.752	4.134
z, O/C	0.02243	0.02393	0.02394	0.02395	0.02395	0.02828	0.02858	0.02849	0.02842
f, N/C	0.009262	0.008912	0.008850	0.008757	0.008757	0.010055	0.009942	0.010127	0.010094
Stoichiometric A/F Ratio	16.40	16.38	16.79	16.38	16.79	16.24	16.65	16.23	16.65
CO2 (% dry)	3.26	2.58	2.39	2.77	2.52	3.01	2.79	3.29	3.11
O2 (% dry)	14.72	15.88	16.05	15.53	15.81	15.19	15.38	14.70	14.72
THC (ppmd)	1193	3664	2177	1465	1197	1074	1040	1105	1051
CO (ppmd)	68.2	89.2	85.2	78.8	79.4	77.3	70.8	69.0	62.1
NOx (ppmd)	500.00	24.36	6.42	52.65	19.77	167.30	137.50	515.30	527.40
CH4 (ppmd)	919	2839	1678	1126	918	810	787	833	788
VOC (ppmd)	31.6	64.1	44.6	37.9	32.7	40.2	36.2	36.6	37.2
Formaldehyde, CH2O (ppmd)	10.8	14.9	11.0	14.2	13.0	12.7	11.8	11.1	10.9
U&S, H2FAC	0.003695	0.004837	0.005085	0.004271	0.004738	0.004156	0.004194	0.003707	0.003674
U&S, a	6.218	7.066	8.005	7.141	7.912	6.722	7.242	6.177	6.533
phi, overall	0.3114	0.2738	0.2536	0.2708	0.2565	0.2864	0.2789	0.3115	0.3091
A/F, overall	52.69	59.81	66.21	60.46	65.44	56.71	59.69	52.11	53.85
phi, trapped	0.6429	0.5631	0.5270	0.5688	0.5386	0.5926	0.5807	0.6421	0.6384
A/F, trapped	25.52	29.08	31.86	28.79	31.17	27.40	28.67	25.28	26.07
Airflow (kg/hr)	9484	9397	9454	9741	9627	9555	9514	9463	9413
BS THC (g/bhp-hr)	6.44	28.84	16.95	10.20	8.22	6.50	6.26	5.96	5.64
BS CO (g/bhp-hr)	0.64	1.23	1.16	0.96	0.95	0.82	0.74	0.65	0.58
BS NOx (g/bhp-hr)	7.733	0.550	0.143	1.052	0.389	2.902	2.374	7.970	8.125
reduction in BS NOx (g/bhp-hr) / H2 mole frac (%)	0.000								
BS NOx (change from baseline)	0.000								
BS CH4 (g/bhp-hr)	4.955	22.350	13.066	7.841	6.307	4.902	4.735	4.491	4.235
reduction in BS CH4 (g/bhp-hr) / H2 mole frac (%)	0.000								
BS CH4 (g/bhp-hr/C atom)	4.566	20.598	14.527	7.219	7.010	4.467	5.220	4.086	4.661
BS VOC (g/bhp-hr)	0.171	0.505	0.347	0.264	0.224	0.243	0.218	0.198	0.200

BS CH2O (g/bhp-hr)	0.058	0.117	0.086	0.099	0.090	0.077	0.071	0.060	0.058
BS CO2 (g/bhp-hr)	483	557	510	530	474	499	461	487	458
BS CO2e (g/bhp-hr)	606	1116	836	726	632	622	580	600	564
BSFC (Btu/bhp-hr)	8417	10706	9913	9382	8855	8657	8491	8426	8392
BSFC (% change from baseline)	0.00	27.19	17.77	11.46	5.21	2.85	0.88	0.10	-0.30
Ignition Delay (deg)	13.72	18.18	17.82	17.21	16.48	15.49	14.06	13.66	12.65
Combustion Duration (deg)	20.8	32.5	31.0	28.7	26.1	23.5	21.6	21.0	20.1

Data Point Name	Load 100 H2 0	Load 90 H2 0	Load 90 H2 20	Load 100 H2 20	Load 100 H2 0 #2
Engine Data					
Start Time	44935.43403	44935.45833	44935.475	44935.51181	44935.525
End Time	44935.4375	44935.46181	44935.47847	44935.51528	44935.52847
Speed [rpm]	299.6	299.5	299.6	299.7	299.7
Torque [lb-ft]	7682	6941	6928	7683	7717
Power [bhp]	438.1	395.8	395.2	438.4	440.3
Load [%]	99.72	90.11	89.94	99.73	100.2
Ambient Press [psia]	12.28	12.27	12.26	12.25	12.25
Ambient Temp [F]	50.6	54.35	54.29	55.2	53.87
Ambient Humidity [%]	26.33	22.27	22.49	24.68	26.3
Inlet Air Pres [in Hg]	32.5	32.5	32.5	32.5	32.5
Inlet Air Temp [F]	109.1	107.6	109.4	109.3	108.6
Inlet Air Humidity [%]	4.684	4.99	4.554	5.353	5.578
Inlet Air Flow [scfm]	1868	1887	1892	1870	1873
IC Water Temp [F]	113.8	111.5	118.8	114.1	119.5
Exh Back Pres [in Hg]	30	30	30	30	30
Exh Cyl 1 Temp [F]	605	572	562.1	602.2	603.3
Exh Cyl 2 Temp [F]	648.9	616.2	606.6	647.7	648.3
Exh Cyl 3 Temp [F]	556.5	539	525.2	553.3	553.5
Exh Cyl 4 Temp [F]	654.5	622.3	611.5	653	655.2
Avg Exh Temp [F]	616.2	587.4	576.4	614	615.1
Stack Temp [F]	0	0	0	0	0
Fuel Flow [lb/hr]	181.6	168.5	159.4	174.8	181.3
Sensor NOx [ppm]	0	0	0	0	0
Sensor Lambda	0	0	0	0	0
Orifice Temp [F]	44.01	42.18	45.65	44.06	45.01
Eng Fuel Pres [psig]	21.94	20	20.69	23.05	22.05
Eng Fuel Temp [F]	80.99	81.45	81.82	82.78	83.63
JW Out Temp [F]	149.2	149	148.5	149.3	148.9
JW In Temp [F]	144.2	144.3	143.7	144.9	145
JW Flow [gpm]	487.3	487.1	488.3	489.3	489
Lube Press [psig]	30.82	32.48	35.52	32.08	31.46
Lube In Temp [F]	150.8	150.4	150.2	151.3	151.1
Lube Out Temp [F]	161.1	160.3	160.3	162.2	161.9
Thrust 1 Temp [F]	160	160.2	160.1	160.9	161
Thrust 2 Temp [F]	159.6	160.1	160	160.9	161.1
Main 2A Temp [F]	160.8	160.8	160.6	161.6	161.7
Main 2B Temp [F]	160.4	160.4	160.1	161	161.1
Main 3A Temp [F]	161.6	161.5	161.3	162.4	162.6
Main 3B Temp [F]	161.6	161.4	161.3	162.6	162.7
Main 4A Temp [F]	157.4	157.5	157.3	158.1	158.2
Main 4B Temp [F]	157.3	157.5	157.4	158.1	158.2
THC [ppmd]	-9.095	-9.128	-9.151	-9.2	-9.207
NOx [ppmd]	515.3	167.3	137.5	527.4	516.6
NO [ppmd]	0	0	0	0	0
NO2 [ppmd]	0	0	0	0	0
O2 [%d]	14.7	15.19	15.38	14.72	14.61
CO2 [%d]	3.294	3.009	2.794	3.108	3.277
CO [ppmd]	485.3	515	446.2	424.1	477.1
AFR Left	0	0	0	0	0
AFR Right	0	0	0	0	0
Air Flow [lb/hr]	8393	8480	8500	8404	8415
Piezo 1 [F]	270.2	259.9	259.6	273.3	272.4
Piezo 2 [F]	280.6	268.4	268.7	284.9	283.6
Piezo 3 [F]	265.2	250.4	254.1	270	266.8
Piezo 4 [F]	286.3	270.9	272.6	292.2	289.4
Jacket Water Flow [gpm]	487.3	487.1	488.3	489.3	489
Jacket Water Valve Pos [%]	68.86	69.1	68.79	72	71.84
Supercharger Speed [%]	41.54	42.29	42.43	42.16	42.1
SC IC Temp Valve Pos [%]	83.83	85.05	84.79	83.65	85.21
Steam Valve Pos [%]	0	0	0	0	0
Back Pressure Valve Pos [%]	40.64	41.32	41.4	40.8	40.83

Load Valve Pos [%]	23.66	13.3	12.38	24.56	24.32
Dyno Water Flow [gpm]	264.1	267.2	268.4	262.2	261.7
Dyno Water In [F]	82.84	83.55	84.62	87.24	86.97
Dyno Water Out [F]	96.03	95.59	96.8	100.5	100.3
Dyno Inboard Bearing [F]	110.5	114.3	115.3	115.8	116.5
Dyno Outboard Bearing [F]	109.5	117	120.1	125.1	131.8
Air Flow Static Pressure [kPa]	118.2	118.4	118.5	118.3	118.3
Air Flow Diff Pressure [kPa]	7.615	7.727	7.84	7.635	7.679
Air Flow Temperature [C]	44.01	42.18	45.65	44.06	45.01
Ethane Flow [lb/hr]	0.1034	0.05595	0.1034	0.1035	0.07535
Ethane Control Valve Pos [%]	0	0	0	0	0
Ethane Pressure [kPa]	0.01197	0.02267	0.03809	0.04439	0.05034
Ethane Temperature [C]	15.16	14.99	15.22	15.75	15.73
PCC H2 Flow [lb/hr]	0	0	0.00004	-0.000002	0.000027
PCC Nat Gas Flow [lb/hr]	0	0	0.000042	0.000076	-0.000034
PCC H2 Stpt	0	0	0	0	0
PCC Nat Gas Stpt	0	0	0	0	0
Spare	NaN	NaN	NaN	NaN	NaN
Lambda Setpoint	1	1	1	1	1
NOx Setpoint	0	0	0	0	0
Air Manifold Pres Stpnt [in Hg]	32.5	32.5	32.5	32.5	32.5
PCC 4 Temp [F]	59.26	58.96	58.79	58.72	58.63
NOx Correction Step	0	0	0	0	0
NOx Averaging Time [s]	1	1	1	1	1
NOx Feedback Time [s]	0	0	0	0	0
PCC Flow [lb/hr]	0	0	0.000082	0.000074	-0.000006
Sensor NOx @ 15% O2	490.5	172.9	146.9	503.3	484.5
ePCC Pressure [psig]	0.8353	0.8666	0.8851	0.9227	0.9333
Fuel Flow Static P [kPa]	321.1	318	331.6	318.7	321
Fuel Flow Temp [C]	29.82	28.88	28.78	29.94	30.71
Fuel Flow Diff P [kPa]	21.22	18.28	14.88	18.82	21.2
Low Press Orifice Flow [lb/hr]	181.6	168.4	155.8	170.7	181.2
Air Flow Diff 0 offset	0.1	0.1	0.1	0.1	0.1
Ign Spark #	0	0	0	0	0
Ign Timing [deg]	-9.204	-11.18	-10.08	-8.108	-9.423
Ign Offset Cyl 1 [deg]	1.534	1.534	1.534	1.534	1.534
Ign Offset Cyl 2 [deg]	0.6574	0.6574	0.6574	0.6574	0.6574
Ign Offset Cyl 3 [deg]	0.4383	0.4383	0.4383	0.6574	0.4383
Ign Offset Cyl 4 [deg]	0	0	0	0	0
Ign 4-20 mA	0	0	0	0	0
EFI Hyd Sup Pres [psig]	5.166	5.261	5.227	5.307	5.298
EFI Hyd Ret Pres [psig]	21.13	18.89	18.51	18.53	17.91
LECM RPM	0	0	0	0	0
SOI Cylinder 1 [dATDC]	0.8	0.8	0.8	0.8	0.8
SOI Cylinder 2 [dATDC]	0.8	0.8	0.8	0.8	0.8
SOI Cylinder 3 [dATDC]	0.8	0.8	0.8	0.8	0.8
SOI Cylinder 4 [dATDC]	0.8	0.8	0.8	0.8	0.8
Cylinder 1 Bias Factor	0.8	0.8	0.8	0.8	0.8
Cylinder 2 Bias Factor	0.8	0.8	0.8	0.8	0.8
Cylinder 3 Bias Factor	0.8	0.8	0.8	0.8	0.8
Cylinder 4 Bias Factor	0.8	0.8	0.8	0.8	0.8
Global Duration [usec]	0	0	0	0	0
Cylinder 1 Duration [usec]	0.8	0.8	0.8	0.8	0.8
Cylinder 2 Duration [usec]	0.8	0.8	0.8	0.8	0.8
Cylinder 3 Duration [usec]	0.8	0.8	0.8	0.8	0.8
Cylinder 4 Duration [usec]	0.8	0.8	0.8	0.8	0.8
LECM Fuel Temp [deg F]	0	0	0	0	0
LECM Fuel Pres [psia]	0	0	0	0	0
HP Meter Fuel Flow [lb/hr]	1.571	1.573	1.571	1.571	1.571
SC IC Coolant Out [C]	45.46	44	48.3	45.71	48.4
SC IC Coolant In [C]	45.45	44.14	48.23	45.6	48.59
SC IC Air 1 [C]	45.55	43.29	48.16	45.69	47.6
SC IC Air 2 [C]	50.21	52.66	53.3	53.86	53.3
SC ID Pres Diff	366.2	373.1	376.3	369.6	372.6

HPFI H2 Meter 1 Flow [g/hr]	0.006151	0.02157	0.02599	0.009469	0.02727
HPFI H2 Meter 2 Flow [kg/hr]	0.06229	0.08382	0.08163	0.08108	0.06038
HPFI H2 Meter 3 Flow [kg/hr]	-0.02307	-0.005315	-0.02553	-0.03433	-0.02892
HPFI H2 Meter 1 Stpt	0	0	0	0	0
HPFI H2 Meter 2 Stpt	0	0	0	0	0
HPFI H2 Meter 3 Stpt	0	0	0	0	0
HPFI H2 Total Flow [kg/hr]	0.04537	0.1001	0.08209	0.05622	0.05874
HPFI H2 Total Setpoint	0	0	0	0	0
LP Orifice Fuel Flow [lb/hr]	181.6	168.4	155.8	170.7	181.2
LPFI H2 Meter Setpoint	0	0	1.665	1.825	0
LPFI H2 Meter Flow [kg/hr]	0	0	1.665	1.825	-0.000014
FTIR Data					
NO (350,3000) 191C	443.4	161.3	127.6	511.7	477.5
NO2 (150) 191C (1of2)	15.53	16.53	16.74	18.05	17.06
NO2 (2000) 191C (2of2)	14.98	14.37	15.1	17.22	14.85
N2O (100,200,300) 191C	0.2687	0.2792	0.2039	0.2323	0.257
NH3 (300) 191C (1of2)	0.05147	0.09027	0.002035	0.001411	0.03474
NH3 (3000) 191C (2of2)	-0.7991	0.4443	-0.02877	0.7172	-0.09082
H2O% (25) 191C	6.609	6.16	6.26	6.881	6.68
CO2% (20) 191C (1of2) R4	3.423	3.149	3.069	3.355	3.411
CO (500) 191C (1of3)	64.48	72.55	66.39	57.84	62.47
CO% (1) 191C (2of3)	0.006702	0.007285	0.006907	0.005791	0.006324
CH4 (3000) 191C (1of2)	777.7	760.5	737.3	734.1	778.7
CH4 (20000) 191C (2of2)	788.6	772.5	753.7	736.2	795.4
Ethane (500) 191C	71.31	66.93	64.95	68.12	70.69
Ethylene (100,3000) 191C	5.829	7.05	6.281	5.882	5.56
Acetylene (1000) 191C	0.06493	0.5012	0.2069	0.3096	0.2268
Propane (200) 191C	6.806	6.932	6.345	6.355	7.095
Propylene (200,1000) 191C	0.9046	0.8197	0.8655	1.284	0.9537
Oil as octane (200) 191C	2.331	2.063	2.082	2.21	2.263
Formaldehyde (70,500) 191C	10.32	11.91	11.04	10.14	9.967
Acetaldehyde (1000) 191C	4.323	3.635	3.38	3.232	4.216
Formic Acid (100) 191C	0.5016	0.4428	0.3247	0.3577	0.3609
MeOH (1000) 191C	-0.08524	0.3251	0.4543	0.1158	0.2601
CO% (10) 191C (3of3)	0.002327	0.006045	0.00551	0.00603	-0.001869
CO2 low% (4) 191C (2of2)	3.338	3.091	2.999	3.293	3.351
1,3 butadiene (80) 191C	-0.0393	-0.3385	-0.2177	0.203	-0.3528
Temp (C)	190.6	190.6	190.6	190.6	190.6
Pressure (Atm)	0.988	0.9898	0.9876	0.9874	0.9855
NOx autorange	458.9	177.8	144.4	529.8	494.6
CO autorange	64.48	72.55	66.39	57.84	62.47
CH4 autorange	777.7	760.5	737.3	734.1	778.7
NH3 autorange	0.05147	0.09027	0.002035	0.001411	0.03474
NOx autorange dry	491.4	189.5	154	568.9	530
CO autorange dry	69.05	77.31	70.83	62.12	66.95
CO2% autorange dry	3.575	3.293	3.2	3.536	3.591
N2O dry	0.2877	0.2975	0.2175	0.2495	0.2754
NH3 autorange dry	0.05512	0.09617	0.002164	0.00152	0.03721
FIDeq THC ppmC	1032	1008	974.9	978.4	1033
FIDeq NMHC ppmC	176.8	171.6	163.8	170.9	176.5
FIDeq NMNEHC ppmC	34.22	37.73	33.93	34.64	35.11
CO2% autorange	3.338	3.091	2.999	3.293	3.351
FTIR NMHC ppmC	188.3	184.9	176.3	182.2	187.7
FTIR NMNEHC ppmC	45.65	51.04	46.42	45.91	46.31
Igram DC	3.746	3.799	3.794	3.689	3.704
Igram PP	5.918	6.018	6	5.949	5.947
phase Angle	89.65	89.72	90.21	90.35	90.24
laser PP	8.819	8.877	8.847	8.975	8.926
laser DC	-6.081	-6.152	-6.145	-6.244	-6.277
Bad Scan counter	1	1	1	2	2
Centerburst Location	1130	1130	1130	1130	1130
Linearizer Check	0.00121	0.001184	0.001211	0.001305	0.001195

SNR 2500	698.4	683.4	690.8	658.7	605.4
sBeam @ 2500	1.345	1.348	1.346	1.343	1.343
GC Data					
METHANE [%]	88.41	88.63	88.56	88.38	88.37
ETHANE [%]	8.59	8.38	8.44	8.58	8.58
PROPANE [%]	0.76	0.77	0.77	0.80	0.80
BUTANE [%]	0.10	0.11	0.11	0.11	0.11
PENTANE [%]	0.01	0.01	0.01	0.01	0.01
HEXANE [%]	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.00	0.00	0.00	0.00	0.00
NITROGEN [%]	0.56	0.55	0.55	0.56	0.54
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.57	1.55	1.57	1.56	1.59
WATER [%]	0.00	0.00	0.00	0.00	0.00
LHV Actual [kJ/kg]	47290.00	47310.00	47300.00	47290.00	47280.00
LHV Actual [BTU/scf]	967.20	966.00	966.40	967.80	967.70
HHV Dry [kJ/kg]	52330.00	52350.00	52330.00	52330.00	52310.00
HHV Dry [BTU/scf]	1070.00	1069.00	1069.00	1071.00	1071.00
Gas Density [kg/m3]	0.76	0.76	0.76	0.76	0.76
Stioch A/F	16.17	16.17	16.17	16.17	16.16
Avg. Mol Weight	18.02	17.99	18.00	18.03	18.03
Cp [kJ/kg*K]	2.11	2.11	2.11	2.11	2.11
Cv [kJ/kg*K]	1.64	1.65	1.65	1.64	1.64
Cp/Cv	1.28	1.28	1.28	1.28	1.28
Calculated Data					
AFR	5.20E+01	5.66E+01	6.02E+01	5.42E+01	5.20E+01
Phi total	3.11E-01	2.86E-01	2.69E-01	2.98E-01	3.11E-01
Air Flow [kg/hr]	4.29E+03	4.33E+03	4.36E+03	4.30E+03	4.27E+03
Exh Flow [kg/hr]	4.37E+03	4.40E+03	4.43E+03	4.38E+03	4.36E+03
BMEP [kPa]	4.76E+02	4.30E+02	4.29E+02	4.76E+02	4.78E+02
thermal eff	3.02E-01	2.94E-01	3.10E-01	3.14E-01	3.04E-01
BSFC [kJ/kW-hr]	1.19E+04	1.23E+04	1.16E+04	1.15E+04	1.18E+04
Abs Humidity	2.40E-03	2.44E-03	2.36E-03	2.76E-03	2.82E-03
BSTHC [g/bkW-hr]	7.57E+00	8.30E+00	8.19E+00	7.32E+00	7.56E+00
BS NOx [g/bkW-hr]	1.08E+01	3.95E+00	3.31E+00	1.13E+01	1.08E+01
BS CO [g/bkW-hr]	8.84E-01	1.11E+00	1.04E+00	8.11E-01	8.56E-01
THC @15%O2	9.83E+02	1.04E+03	1.04E+03	9.34E+02	9.69E+02
NOx @15%O2	4.91E+02	1.73E+02	1.47E+02	5.03E+02	4.85E+02
CO @15%O2	6.57E+01	7.99E+01	7.57E+01	5.93E+01	6.28E+01
Wet 2 Dry Scaler	1.07E+00	1.06E+00	1.06E+00	1.06E+00	1.07E+00
15% O2 Factor	9.52E-01	1.03E+00	1.07E+00	9.54E-01	9.38E-01
BS Calc Factor	4.57E+02	5.13E+02	5.23E+02	4.66E+02	4.56E+02
Delivery Ratio	1.68E+00	1.69E+00	1.70E+00	1.68E+00	1.67E+00
Scavenging Efficiency	8.13E-01	8.15E-01	8.18E-01	8.14E-01	8.11E-01
Trapping Efficiency	4.85E-01	4.83E-01	4.80E-01	4.84E-01	4.87E-01
Trapped AF Ratio	2.52E+01	2.74E+01	2.89E+01	2.63E+01	2.53E+01
Trapped Equivalence Ratio	6.41E-01	5.91E-01	5.59E-01	6.16E-01	6.39E-01
Combustion Data					
Engine Avg Peak Pressure[psi]	3.15E+02	2.94E+02	3.02E+02	3.20E+02	3.18E+02
Engine Avg Peak Pres Std Dev[psi]	2.61E+01	3.42E+01	2.70E+01	2.24E+01	2.68E+01
Engine Avg Peak Pres COV[%]	7.46E+00	1.04E+01	8.76E+00	6.28E+00	8.78E+00
Engine Max Peak Pres COV Ch. #6[%]	2.14E+01	2.88E+01	2.95E+01	1.80E+01	3.26E+01
Engine Min Peak Pres COV Ch. #8[%]	1.96E-01	3.09E-01	2.19E-01	1.88E-01	2.15E-01
Engine Avg Peak Loc[*ATDC]	4.53E+01	4.75E+01	4.82E+01	4.78E+01	5.23E+01
Engine Avg IMEP[psi]	4.42E+01	4.10E+01	4.09E+01	4.42E+01	4.41E+01

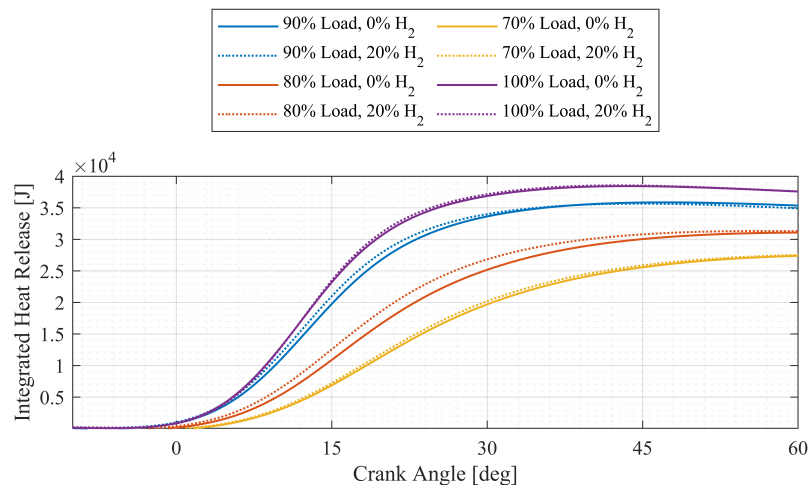
Engine Avg IMEP COV[%]	1.34E+02	-5.99E+01	2.86E+01	-2.49E+00	-3.60E+01
Engine Max IMEP COV Ch. #9[%]	1.14E+03	3.01E+02	7.70E+02	4.79E+02	4.95E+02
Engine Min IMEP COV Ch. #8[%]	-9.58E+01	-6.79E+02	-3.49E+02	-3.26E+02	-6.47E+02
Avg. Peak Ch. #1psi	5.32E+02	5.07E+02	5.11E+02	5.32E+02	5.34E+02
Avg. Peak Ch. #2psi	5.24E+02	4.89E+02	4.97E+02	5.28E+02	5.25E+02
Avg. Peak Ch. #3psi	5.31E+02	4.69E+02	5.07E+02	5.46E+02	5.36E+02
Avg. Peak Ch. #4psi	5.18E+02	4.81E+02	4.93E+02	5.27E+02	5.23E+02
Avg. Peak Ch. #5psi	5.12E+02	4.76E+02	4.88E+02	5.23E+02	5.18E+02
Avg. Peak Ch. #6psi	3.74E-03	3.83E-03	3.89E-03	3.76E-03	4.09E-03
Avg. Peak Ch. #7psi	1.10E+02	1.10E+02	1.10E+02	1.10E+02	1.11E+02
Avg. Peak Ch. #8psi	1.13E+00	1.13E+00	1.13E+00	1.14E+00	1.14E+00
Avg. Peak Ch. #9psi	1.11E+02	1.11E+02	1.12E+02	1.12E+02	1.12E+02
Peak Std. Dev. Ch. #1psi	4.30E+01	5.03E+01	4.22E+01	3.84E+01	4.31E+01
Peak Std. Dev. Ch. #2psi	4.07E+01	5.59E+01	4.31E+01	3.63E+01	4.29E+01
Peak Std. Dev. Ch. #3psi	6.10E+01	8.63E+01	6.14E+01	4.45E+01	5.90E+01
Peak Std. Dev. Ch. #4psi	4.51E+01	5.74E+01	4.79E+01	4.09E+01	4.79E+01
Peak Std. Dev. Ch. #5psi	4.45E+01	5.68E+01	4.73E+01	4.04E+01	4.73E+01
Peak Std. Dev. Ch. #6psi	8.01E-04	1.10E-03	1.15E-03	6.76E-04	1.33E-03
Peak Std. Dev. Ch. #7psi	2.80E-01	3.95E-01	3.09E-01	2.75E-01	2.96E-01
Peak Std. Dev. Ch. #8psi	2.21E-03	3.50E-03	2.48E-03	2.14E-03	2.45E-03
Peak Std. Dev. Ch. #9psi	5.12E-01	6.14E-01	4.91E-01	4.49E-01	4.91E-01
Peak COV Ch. #1%	8.08E+00	9.93E+00	8.25E+00	7.21E+00	8.08E+00
Peak COV Ch. #2%	7.77E+00	1.14E+01	8.67E+00	6.87E+00	8.16E+00
Peak COV Ch. #3%	1.15E+01	1.84E+01	1.21E+01	8.16E+00	1.10E+01
Peak COV Ch. #4%	8.72E+00	1.20E+01	9.71E+00	7.75E+00	9.16E+00
Peak COV Ch. #5%	8.70E+00	1.19E+01	9.69E+00	7.73E+00	9.14E+00
Peak COV Ch. #6%	2.14E+01	2.88E+01	2.95E+01	1.80E+01	3.26E+01
Peak COV Ch. #7%	2.55E-01	3.60E-01	2.82E-01	2.49E-01	2.68E-01
Peak COV Ch. #8%	1.96E-01	3.09E-01	2.19E-01	1.88E-01	2.15E-01
Peak COV Ch. #9%	4.61E-01	5.52E-01	4.40E-01	3.99E-01	4.37E-01
Max Peak Ch. #1psi	6.29E+02	6.39E+02	6.08E+02	6.40E+02	6.29E+02
Max Peak Ch. #2psi	6.23E+02	6.25E+02	5.99E+02	6.14E+02	6.35E+02
Max Peak Ch. #3psi	6.54E+02	6.54E+02	6.48E+02	6.52E+02	6.73E+02
Max Peak Ch. #4psi	6.44E+02	6.10E+02	6.04E+02	6.56E+02	6.40E+02
Max Peak Ch. #5psi	6.36E+02	6.04E+02	5.98E+02	6.50E+02	6.34E+02
Max Peak Ch. #6psi	1.11E-02	1.44E-02	1.31E-02	9.04E-03	1.40E-02
Max Peak Ch. #7psi	1.11E+02	1.12E+02	1.11E+02	1.11E+02	1.12E+02
Max Peak Ch. #8psi	1.14E+00	1.15E+00	1.14E+00	1.15E+00	1.15E+00
Max Peak Ch. #9psi	1.12E+02	1.13E+02	1.13E+02	1.14E+02	1.13E+02
Min Peak Ch. #1psi	3.15E+02	2.89E+02	2.91E+02	3.86E+02	3.42E+02
Min Peak Ch. #2psi	2.90E+02	2.84E+02	2.88E+02	3.75E+02	3.26E+02
Min Peak Ch. #3psi	2.89E+02	2.88E+02	2.90E+02	3.24E+02	2.88E+02
Min Peak Ch. #4psi	3.47E+02	2.87E+02	2.96E+02	3.70E+02	2.90E+02
Min Peak Ch. #5psi	3.43E+02	2.85E+02	2.94E+02	3.67E+02	2.89E+02
Min Peak Ch. #6psi	3.41E-03	3.41E-03	3.41E-03	3.41E-03	3.41E-03
Min Peak Ch. #7psi	1.09E+02	1.08E+02	1.08E+02	1.09E+02	1.09E+02
Min Peak Ch. #8psi	1.12E+00	1.11E+00	1.12E+00	1.13E+00	1.13E+00
Min Peak Ch. #9psi	1.08E+02	1.09E+02	1.09E+02	1.10E+02	1.10E+02
Avg. Peak Loc. Ch. #1psi	1.82E+01	1.82E+01	1.79E+01	1.83E+01	1.81E+01
Avg. Peak Loc. Ch. #2psi	1.82E+01	1.83E+01	1.80E+01	1.82E+01	1.81E+01
Avg. Peak Loc. Ch. #3psi	1.84E+01	1.85E+01	1.80E+01	1.79E+01	1.79E+01
Avg. Peak Loc. Ch. #4psi	1.84E+01	1.86E+01	1.81E+01	1.81E+01	1.82E+01
Avg. Peak Loc. Ch. #5psi	1.88E+01	1.90E+01	1.85E+01	1.85E+01	1.86E+01
Avg. Peak Loc. Ch. #6psi	-8.24E+01	-6.12E+01	-5.45E+01	-5.94E+01	-1.79E+01
Avg. Peak Loc. Ch. #7psi	1.32E+02	1.31E+02	1.31E+02	1.32E+02	1.32E+02
Avg. Peak Loc. Ch. #8psi	1.32E+02	1.31E+02	1.32E+02	1.32E+02	1.32E+02
Avg. Peak Loc. Ch. #9psi	1.35E+02	1.34E+02	1.34E+02	1.35E+02	1.35E+02
Peak Loc. Std. Dev Ch. #1psi	2.19E+00	2.63E+00	2.26E+00	2.19E+00	2.19E+00
Peak Loc. Std. Dev Ch. #2psi	2.14E+00	3.25E+00	2.35E+00	1.96E+00	2.14E+00
Peak Loc. Std. Dev Ch. #3psi	3.22E+00	6.04E+00	3.51E+00	2.21E+00	3.24E+00
Peak Loc. Std. Dev Ch. #4psi	2.30E+00	3.24E+00	2.46E+00	2.04E+00	2.48E+00
Peak Loc. Std. Dev Ch. #5psi	2.29E+00	3.21E+00	2.44E+00	2.03E+00	2.47E+00
Peak Loc. Std. Dev Ch. #6psi	9.19E+01	1.13E+02	9.93E+01	9.62E+01	1.14E+02
Peak Loc. Std. Dev Ch. #7psi	2.03E+00	4.62E+00	2.88E+00	1.72E+00	2.58E+00

Peak Loc. Std. Dev Ch. #8psi	2.51E+00	1.14E+01	3.12E+00	2.12E+00	2.97E+00
Peak Loc. Std. Dev Ch. #9psi	1.45E+00	1.92E+00	1.64E+00	1.35E+00	1.52E+00
Peak Loc. COV Ch. #1%	1.20E+01	1.44E+01	1.26E+01	1.05E+01	1.21E+01
Peak Loc. COV Ch. #2%	1.18E+01	1.77E+01	1.31E+01	1.08E+01	1.18E+01
Peak Loc. COV Ch. #3%	1.75E+01	3.26E+01	1.95E+01	1.23E+01	1.81E+01
Peak Loc. COV Ch. #4%	1.25E+01	1.75E+01	1.36E+01	1.13E+01	1.37E+01
Peak Loc. COV Ch. #5%	1.22E+01	1.69E+01	1.32E+01	1.10E+01	1.33E+01
Peak Loc. COV Ch. #6%	-1.12E+02	-1.84E+02	-1.82E+02	-1.62E+02	-6.39E+02
Peak Loc. COV Ch. #7%	1.54E+00	3.53E+00	2.19E+00	1.31E+00	1.97E+00
Peak Loc. COV Ch. #8%	1.90E+00	8.74E+00	2.37E+00	1.60E+00	2.26E+00
Peak Loc. COV Ch. #9%	1.08E+00	1.43E+00	1.22E+00	1.00E+00	1.13E+00
AVG IMEP Ch. #1psi	7.64E+01	7.22E+01	7.11E+01	7.58E+01	7.61E+01
AVG IMEP Ch. #2psi	8.06E+01	7.46E+01	7.39E+01	8.03E+01	8.03E+01
AVG IMEP Ch. #3psi	9.07E+01	8.22E+01	8.39E+01	9.11E+01	9.05E+01
AVG IMEP Ch. #4psi	7.57E+01	7.06E+01	7.00E+01	7.57E+01	7.58E+01
AVG IMEP Ch. #5psi	7.52E+01	7.03E+01	6.98E+01	7.55E+01	7.55E+01
AVG IMEP Ch. #6psi	7.45E-06	6.09E-06	2.38E-06	4.07E-06	3.96E-06
AVG IMEP Ch. #7psi	-6.66E-01	-6.82E-01	-6.97E-01	-6.69E-01	-6.72E-01
AVG IMEP Ch. #8psi	-6.54E-03	-6.72E-03	-6.87E-03	-6.58E-03	-6.61E-03
AVG IMEP Ch. #9psi	5.55E-02	-9.61E-02	-1.82E-01	-1.95E-01	-9.80E-02
IMEP STD DEV Ch. #1psi	2.05E+00	2.38E+00	1.97E+00	1.95E+00	2.02E+00
IMEP STD DEV Ch. #2psi	1.13E+00	2.22E+00	1.22E+00	9.27E-01	1.14E+00
IMEP STD DEV Ch. #3psi	3.30E+00	9.95E+00	4.16E+00	2.18E+00	4.36E+00
IMEP STD DEV Ch. #4psi	1.48E+00	3.37E+00	1.50E+00	1.34E+00	1.56E+00
IMEP STD DEV Ch. #5psi	1.49E+00	3.39E+00	1.52E+00	1.35E+00	1.57E+00
IMEP STD DEV Ch. #6psi	1.84E-05	1.83E-05	1.83E-05	1.95E-05	1.96E-05
IMEP STD DEV Ch. #7psi	6.02E-01	6.25E-01	6.04E-01	6.03E-01	6.05E-01
IMEP STD DEV Ch. #8psi	6.26E-03	6.48E-03	6.28E-03	6.27E-03	6.29E-03
IMEP STD DEV Ch. #9psi	6.31E-01	6.53E-01	6.34E-01	6.34E-01	6.34E-01
IMEP COV Ch. #1%	2.69E+00	3.30E+00	2.78E+00	2.58E+00	2.65E+00
IMEP COV Ch. #2%	1.40E+00	2.97E+00	1.65E+00	1.15E+00	1.42E+00
IMEP COV Ch. #3%	3.64E+00	1.21E+01	4.95E+00	2.39E+00	4.82E+00
IMEP COV Ch. #4%	1.96E+00	4.78E+00	2.14E+00	1.77E+00	2.06E+00
IMEP COV Ch. #5%	1.98E+00	4.82E+00	2.17E+00	1.78E+00	2.08E+00
IMEP COV Ch. #6%	2.47E+02	3.01E+02	7.70E+02	4.79E+02	4.95E+02
IMEP COV Ch. #7%	-9.04E+01	-9.16E+01	-8.67E+01	-9.01E+01	-9.01E+01
IMEP COV Ch. #8%	-9.58E+01	-9.65E+01	-9.15E+01	-9.52E+01	-9.53E+01
IMEP COV Ch. #9%	1.14E+03	-6.79E+02	-3.49E+02	-3.26E+02	-6.47E+02
AVG NMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN
AVG NMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN
NMEP STD DEV Ch. #1psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #2psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #3psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #4psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #5psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #6psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #7psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #8psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP STD DEV Ch. #9psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN
NMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN

NMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #1psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #2psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #3psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #4psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #5psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #6psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #7psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #8psi	NaN	NaN	NaN	NaN	NaN	NaN
AVG PMEP Ch. #9psi	NaN	NaN	NaN	NaN	NaN	NaN
PMEP STD DEV Ch. #1psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #2psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #3psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #4psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #5psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #6psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #7psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #8psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP STD DEV Ch. #9psi	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMEP COV Ch. #1%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #2%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #3%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #4%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #5%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #6%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #7%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #8%	NaN	NaN	NaN	NaN	NaN	NaN
PMEP COV Ch. #9%	NaN	NaN	NaN	NaN	NaN	NaN
MFB 10% Ch. #1*ATDC	5.49E+00	5.05E+00	5.04E+00	5.81E+00	5.39E+00	
MFB 10% Ch. #2*ATDC	4.79E+00	4.40E+00	4.29E+00	5.01E+00	4.69E+00	
MFB 10% Ch. #3*ATDC	5.36E+00	5.74E+00	4.86E+00	5.38E+00	5.13E+00	
MFB 10% Ch. #4*ATDC	4.82E+00	4.67E+00	4.35E+00	4.82E+00	4.55E+00	
MFB 10% Ch. #5*ATDC	5.11E+00	4.93E+00	4.63E+00	5.11E+00	4.84E+00	
MFB 10% Ch. #6*ATDC	3.51E+01	3.51E+01	3.52E+01	3.52E+01	3.51E+01	
MFB 10% Ch. #7*ATDC	3.56E+01	3.55E+01	3.55E+01	3.56E+01	3.56E+01	
MFB 10% Ch. #8*ATDC	3.56E+01	3.55E+01	3.55E+01	3.56E+01	3.56E+01	
MFB 10% Ch. #9*ATDC	3.56E+01	3.57E+01	3.57E+01	3.58E+01	3.57E+01	
MFB 50% Ch. #1*ATDC	1.33E+01	1.34E+01	1.31E+01	1.35E+01	1.32E+01	
MFB 50% Ch. #2*ATDC	1.33E+01	1.37E+01	1.32E+01	1.33E+01	1.32E+01	
MFB 50% Ch. #3*ATDC	1.43E+01	1.63E+01	1.41E+01	1.37E+01	1.39E+01	
MFB 50% Ch. #4*ATDC	1.34E+01	1.40E+01	1.34E+01	1.31E+01	1.31E+01	
MFB 50% Ch. #5*ATDC	1.38E+01	1.44E+01	1.37E+01	1.35E+01	1.35E+01	
MFB 50% Ch. #6*ATDC	8.71E+01	8.69E+01	8.70E+01	8.69E+01	8.71E+01	
MFB 50% Ch. #7*ATDC	8.49E+01	8.48E+01	8.47E+01	8.48E+01	8.48E+01	
MFB 50% Ch. #8*ATDC	8.49E+01	8.48E+01	8.47E+01	8.48E+01	8.48E+01	
MFB 50% Ch. #9*ATDC	8.54E+01	8.53E+01	8.53E+01	8.53E+01	8.53E+01	
MFB 90% Ch. #1*ATDC	2.37E+01	2.45E+01	2.36E+01	2.35E+01	2.35E+01	
MFB 90% Ch. #2*ATDC	2.48E+01	2.65E+01	2.50E+01	2.43E+01	2.47E+01	
MFB 90% Ch. #3*ATDC	3.10E+01	3.61E+01	3.11E+01	2.94E+01	3.06E+01	
MFB 90% Ch. #4*ATDC	2.49E+01	2.68E+01	2.53E+01	2.41E+01	2.46E+01	
MFB 90% Ch. #5*ATDC	2.52E+01	2.71E+01	2.56E+01	2.45E+01	2.49E+01	
MFB 90% Ch. #6*ATDC	1.46E+02	1.45E+02	1.45E+02	1.45E+02	1.45E+02	
MFB 90% Ch. #7*ATDC	1.32E+02	1.32E+02	1.32E+02	1.32E+02	1.32E+02	
MFB 90% Ch. #8*ATDC	1.32E+02	1.32E+02	1.32E+02	1.32E+02	1.32E+02	
MFB 90% Ch. #9*ATDC	1.32E+02	1.32E+02	1.32E+02	1.32E+02	1.32E+02	
Low Cycles [%] Ch. #1*ATDC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Low Cycles [%] Ch. #2*ATDC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Low Cycles [%] Ch. #3*ATDC	0.00E+00	1.00E-01	0.00E+00	0.00E+00	0.00E+00	
Low Cycles [%] Ch. #4*ATDC	0.00E+00	1.00E-01	0.00E+00	0.00E+00	0.00E+00	
Low Cycles [%] Ch. #5*ATDC	0.00E+00	1.00E-01	0.00E+00	0.00E+00	0.00E+00	
Low Cycles [%] Ch. #6*ATDC	7.90E+00	7.00E+00	3.60E+00	5.30E+00	4.20E+00	
Low Cycles [%] Ch. #7*ATDC	0.00E+00	-9.00E-01	-1.00E-01	0.00E+00	0.00E+00	
Low Cycles [%] Ch. #8*ATDC	0.00E+00	-1.00E+00	-1.00E-01	0.00E+00	0.00E+00	
Low Cycles [%] Ch. #9*ATDC	6.00E+00	-8.40E+00	-1.22E+01	-9.80E+00	-1.08E+01	

Misfires [%] Ch. #1*ATDC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Misfires [%] Ch. #2*ATDC	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Misfires [%] Ch. #3*ATDC	0.00E+00	9.00E-01	1.00E-01	0.00E+00	1.00E-01
Misfires [%] Ch. #4*ATDC	0.00E+00	1.00E-01	0.00E+00	0.00E+00	0.00E+00
Misfires [%] Ch. #5*ATDC	0.00E+00	1.00E-01	0.00E+00	0.00E+00	0.00E+00
Misfires [%] Ch. #6*ATDC	2.23E+01	2.63E+01	3.89E+01	3.36E+01	3.43E+01
Misfires [%] Ch. #7*ATDC	1.00E+02	9.90E+01	9.99E+01	1.00E+02	9.99E+01
Misfires [%] Ch. #8*ATDC	1.00E+02	9.90E+01	9.99E+01	1.00E+02	9.99E+01
Misfires [%] Ch. #9*ATDC	2.00E+01	7.16E+01	9.36E+01	9.70E+01	7.81E+01
<u>Analysis Corrections for H2 Blending</u>					
Total Fuel Flow (lb/hr)	181.60	168.50	159.40	174.80	181.30
H2 Fuel Flow (lb/hr)	0.00	0.00	3.67	4.02	0.00
H2 mass fraction (%)	0.000000	0.000000	2.303240	2.302130	-0.000002
H2 mole fraction (%)	0.000	0.000	20.566	20.590	0.000
Average MW (kg/kmol)	18.02	17.99	14.71	14.73	18.03
PCC H2 Mole Fraction (%)	N/A	N/A	N/A	N/A	N/A
<u>Updated Fuel Composition Analysis</u>					
METHANE [%]	88.41	88.63	70.35	70.18	88.37
ETHANE [%]	8.59	8.38	6.70	6.82	8.58
PROPANE [%]	0.76	0.77	0.61	0.63	0.80
BUTANE [%]	0.10	0.11	0.09	0.09	0.11
PENTANE [%]	0.01	0.01	0.01	0.01	0.01
HEXANE [%]	0.00	0.00	0.00	0.00	0.00
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.000	0.000	20.566	20.590	0.000
NITROGEN [%]	0.56	0.55	0.43	0.44	0.54
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.57	1.55	1.25	1.24	1.59
WATER [%]	0.00	0.00	0.00	0.00	0.00
Total Composition Check (%)	100.00	100.00	100.00	100.00	100.00
LHV (kJ/kg)	47290	47310	48974	48964	47280
LHV (Btu/g)	44.82	44.84	46.42	46.41	44.81
<u>Updated A/F Ratio and BS Parameter Analysis</u>					
Carbon #	1.10	1.10	0.87	0.87	1.10
Hydrogen #	4.12	4.12	3.69	3.69	4.13
Oxygen #	0.0313	0.0310	0.0249	0.0248	0.0317
Nitrogen #	0.01113	0.01103	0.00867	0.00882	0.01087
y, H/C	3.752	3.756	4.226	4.223	3.750
z, O/C	0.02849	0.02828	0.02858	0.02842	0.02883
f, N/C	0.010127	0.010055	0.009942	0.010094	0.009882
Stoichiometric A/F Ratio	16.23	16.24	16.74	16.74	16.22
CO2 (% , dry)	3.29	3.01	2.79	3.11	3.28
O2 (% , dry)	14.70	15.19	15.38	14.72	14.61
THC (ppmd)	1105	1074	1040	1051	1107
CO (ppmd)	69.0	77.3	70.8	62.1	66.9
NOx (ppmd)	515.30	167.30	137.50	527.40	516.60
CH4 (ppmd)	833	810	787	788	834
VOC (ppmd)	36.6	40.2	36.2	37.2	37.6
U&S, H2FAC	0.003707	0.004156	0.004283	0.003752	0.003592
U&S, a	6.177	6.722	7.264	6.554	6.171
phi, overall	0.3115	0.2864	0.2811	0.3115	0.3117
A/F, overall	52.11	56.71	59.55	53.74	52.06
phi, trapped	0.6421	0.5926	0.5854	0.6433	0.6406
A/F, trapped	25.28	27.40	28.60	26.02	25.33
Airflow (kg/hr)	9463	9555	9492	9394	9438
BS THC (g/bhp-hr)	5.96	6.50	6.23	5.61	5.96
BS CO (g/bhp-hr)	0.65	0.82	0.74	0.58	0.63
BS NOx (g/bhp-hr)	7.970	2.902	2.362	8.082	7.977
BS CH4 (g/bhp-hr)	4.49	4.90	4.71	4.21	4.49
BS VOC (g/bhp-hr)	0.198	0.243	0.217	0.199	0.203
BS CO2 (g/bhp-hr)	487	499	459	456	484
BS CO2e (g/bhp-hr)	600	622	577	561	596

BSFC (Btu/bhp-hr)	8426	8657	8491	8392	8368
Ignition Delay (deg)	13.66	15.49	14.06	12.65	13.71
Combustion Duration (deg)	21.0	23.5	21.6	20.1	20.9

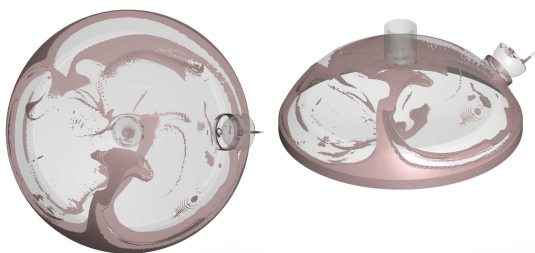


Appendix C

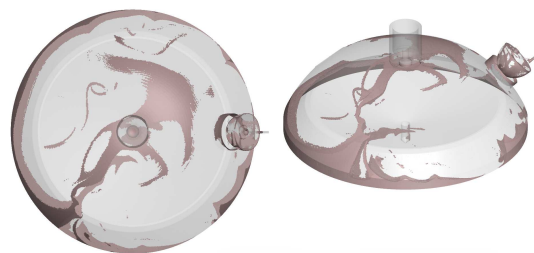
Directional Pre-combustion Chambers

C.1 Extra Plots

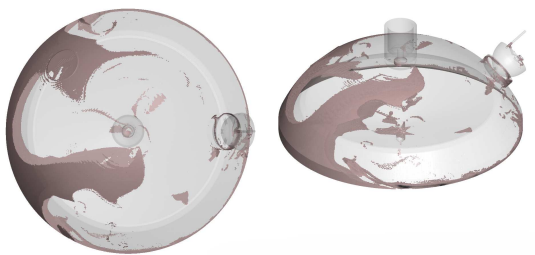
NO₂ Mole Fraction



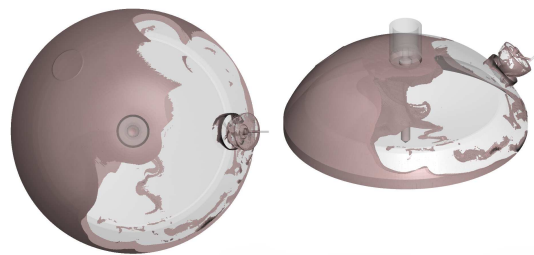
(a) Baseline



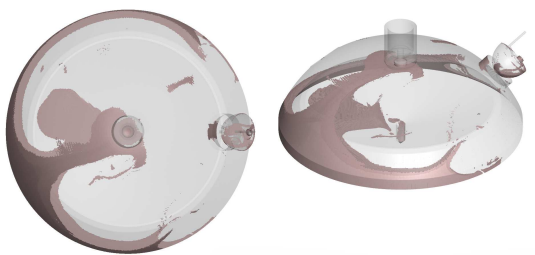
(b) 3orifice_v1



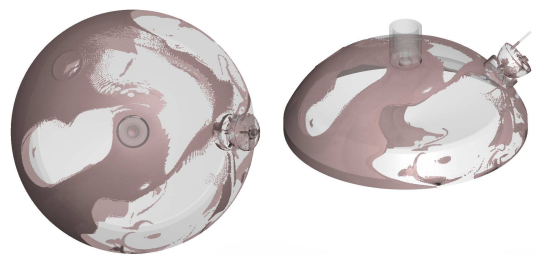
(c) 3orifice_v2



(d) 5orifice

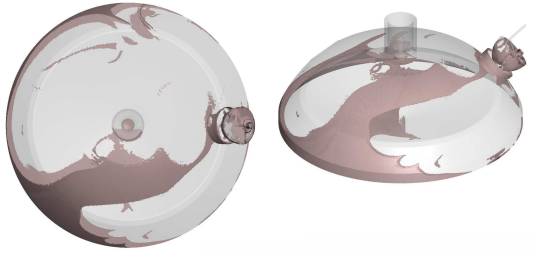


(e) slot

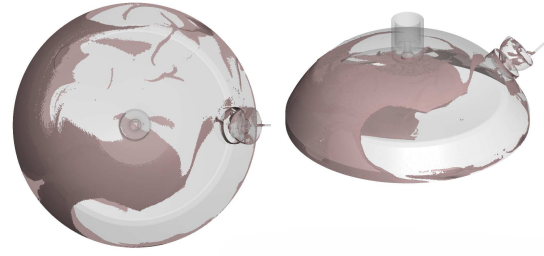


(f) 3v2_angle1

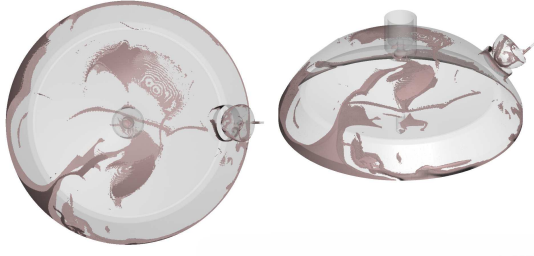
Figure C.1: Locations of residual nitrogen dioxide pockets in each simulated directional PCC design. Images were taken at or near 20 °aTDC when the mass of nitrogen dioxide was highest. Value blanking was utilized and removes all calculation cells that have a nitrogen dioxide mole fraction less than 1e-6. The color of the residuals indicates the mole fraction of the cell, the more nitrogen dioxide in a cell the darker that cell will be - black being high concentrations of residual nitrogen dioxide.



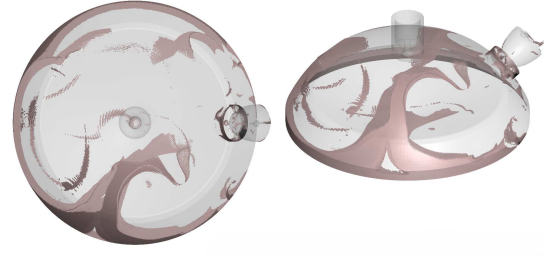
(g) 3v2_angle2



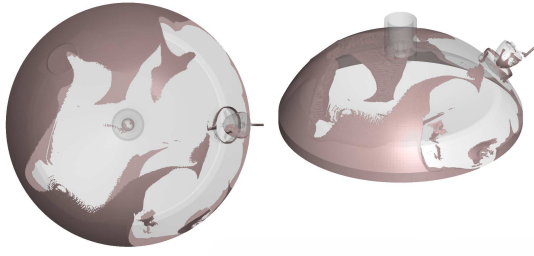
(h) 3v2_area1



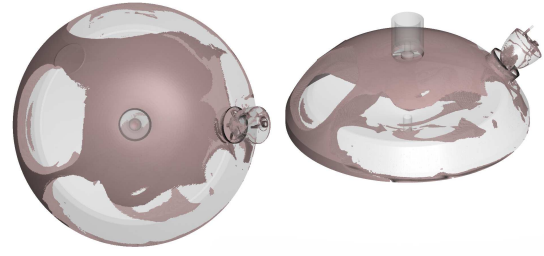
(i) 3v2_area2



(j) 3v2_volume1



(k) 3v2_volume2



(l) 3v2_area2_volume2

Figure C.1: Locations of residual nitrogen dioxide pockets in each simulated directional PCC design. Images were taken at or near 20 °aTDC when the mass of nitrogen dioxide was highest. Value blanking was utilized and removes all calculation cells that have a nitrogen dioxide mole fraction less than $1e-6$. The color of the residuals indicates the mole fraction of the cell, the more nitrogen dioxide in a cell the darker that cell will be - black being high concentrations of residual nitrogen dioxide.

C.2 Experimental Data

ePCI Baseline

Data Point Name	BS_32.7	BS_34.7	BS_36.7	BS_38.7	BS_40.7	BS_41.7
Engine Data						
Start Time	45638.45486	45638.46458	45638.47361	45638.48542	45638.49444	45638.50069
End Time	45638.45833	45638.46806	45638.47708	45638.48889	45638.49792	45638.50417
Speed [rpm]	299.50	299.50	299.40	299.40	299.40	299.40
Torque [lb-ft]	7700.00	7697.00	7707.00	7706.00	7702.00	7713.00
Power [bhp]	439.10	438.90	439.30	439.30	439.10	439.70
Load [%]	99.96	99.92	100.00	100.00	99.99	100.10
Ambient Press [psia]	12.29	12.28	12.28	12.27	12.27	12.27
Ambient Press [in Hg]	25.02	25.00	25.00	24.98	24.98	24.98
Boost [in Hg]	7.68	9.70	11.70	13.72	15.72	16.73
Ambient Temp [F]	46.53	47.78	49.74	50.91	52.75	53.43
Ambient Humidity [%]	23.59	22.76	20.26	19.78	17.71	17.24
Inlet Air Pres [in Hg]	32.70	34.70	36.70	38.70	40.70	41.71
Inlet Air Temp [F]	109.30	109.70	109.10	106.60	108.50	107.50
Inlet Air Humidity [%]	3.42	3.75	3.97	4.80	4.37	4.68
Inlet Air Flow [scfm]	1900.00	1951.00	2004.00	2063.00	2104.00	2161.00
IC Water Temp [F]	118.80	114.50	108.10	114.80	119.40	119.70
Exh Back Pres [in Hg]	30.20	32.20	34.20	36.20	38.21	39.16
Exh Cyl 1 Temp [F]	574.70	570.80	565.00	561.60	560.00	556.70
Exh Cyl 2 Temp [F]	622.70	618.10	615.20	610.10	606.20	600.90
Exh Cyl 3 Temp [F]	544.20	537.70	535.30	523.80	520.90	510.00
Exh Cyl 4 Temp [F]	637.30	634.40	630.50	628.60	627.80	623.20
Avg Exh Temp [F]	594.70	590.30	586.50	581.00	578.70	572.70
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	172.40	171.20	171.70	172.30	173.50	175.10
Sensor NOx [ppm]	312.40	139.70	61.96	41.15	40.44	39.58
Sensor Lambda	10.58	10.74	10.86	10.97	11.03	11.09
Orifice Temp [F]	45.44	44.45	42.96	43.29	45.87	45.66
Eng Fuel Pres [psig]	499.90	500.10	499.90	500.00	500.10	499.90
Eng Fuel Temp [F]	59.45	62.00	63.75	65.48	66.50	67.00
JW Out Temp [F]	143.20	149.60	147.40	147.00	148.30	148.50
JW In Temp [F]	138.10	144.80	142.40	142.30	143.40	143.60
JW Flow [gpm]	479.70	480.40	482.10	483.80	484.20	484.40
Lube Press [psig]	34.00	33.33	31.04	30.83	30.62	30.53
Lube In Temp [F]	150.50	153.00	149.90	149.10	149.80	150.10
Lube Out Temp [F]	154.30	159.60	158.60	158.80	159.00	159.30
Thrust 1 Temp [F]	148.70	156.70	158.20	159.40	159.50	159.80
Thrust 2 Temp [F]	146.50	155.20	157.40	159.10	159.20	159.50
Main 2A Temp [F]	150.40	158.10	159.30	160.50	160.60	161.00
Main 2B Temp [F]	148.90	157.10	158.90	160.40	160.60	161.00
Main 3A Temp [F]	148.70	157.50	159.60	161.10	161.30	161.50
Main 3B Temp [F]	149.50	158.10	160.00	161.40	161.50	161.80
Main 4A Temp [F]	145.00	153.80	155.50	156.80	156.80	157.10
Main 4B Temp [F]	144.90	153.70	155.40	156.70	156.80	157.00
THC [ppmd]	781.30	819.60	878.30	985.10	1146.00	1300.00
NOx [ppmd]	202.10	89.21	41.88	22.14	13.92	11.26
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	14.75	14.98	15.15	15.32	15.44	15.56
CO2 [%d]	3.26	3.11	3.00	2.88	2.80	2.71
CO [ppmd]	71.44	77.00	81.43	98.21	125.70	149.70
AFR Left	0.00	0.00	0.00	0.00	0.00	0.00
AFR Right	0.00	0.00	0.00	0.00	0.00	0.00
Air Flow [lb/hr]	8539.00	8768.00	9006.00	9270.00	9454.00	9712.00
Piezo 1 [F]	286.10	287.70	285.70	284.60	282.50	282.60
Piezo 2 [F]	300.90	302.10	301.50	299.90	298.80	298.10
Piezo 3 [F]	280.30	282.10	281.80	280.70	280.80	279.70
Piezo 4 [F]	313.70	311.80	309.40	308.90	308.80	308.60
Jacket Water Flow [gpm]	479.70	480.40	482.10	483.80	484.20	484.40
Jacket Water Valve Pos [%]	76.00	74.47	75.00	75.00	75.00	75.00
Supercharger Speed [%]	39.59	41.81	44.13	46.38	48.47	50.37
SC IC Temp Valve Pos [%]	77.00	73.53	71.98	77.00	76.97	77.00
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	40.31	43.98	46.51	48.32	49.96	56.79
Load Valve Pos [%]	31.10	31.22	31.25	31.27	31.24	31.26
Dyno Water Flow [gpm]	203.30	204.40	202.80	203.50	204.00	202.60
Dyno Water In [F]	68.37	68.73	69.50	70.23	71.40	72.10
Dyno Water Out [F]	83.87	84.22	85.02	85.76	86.97	87.70
Dyno Inboard Bearing [F]	83.92	92.06	97.92	102.90	105.30	106.50
Dyno Outboard Bearing [F]	79.09	85.38	90.33	95.52	98.63	100.70
Air Flow Static Pressure [kPa]	119.30	126.00	132.80	139.60	146.40	150.10
Air Flow Diff Pressure [kPa]	7.85	7.80	7.76	7.81	7.80	8.02
Air Flow Temperature [C]	45.44	44.45	42.96	43.29	45.87	45.66
Ethane Flow [lb/hr]	0.10	0.06	0.10	0.10	0.07	0.09
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.03	0.04	0.06	0.07	0.07	0.08
Ethane Temperature [C]	16.09	16.38	16.62	16.90	17.05	17.17
PCC H2 Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00
PCC H2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Stpt	0.00	0.00	0.00	0.00	0.00	0.00
NOx Corr Factor	0.85	0.85	0.85	0.85	0.85	0.85
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00
NOx Setpoint	0.00	0.00	0.00	0.00	0.00	0.00

Nominal PCC

Data Point Name	BS_32.7	BS_34.7	BS_36.7	BS_38.7	BS_40.7	BS_41.7	LS_270rpm_70ld	LS_270rpm_100ld	LS_300rpm_70ld	LS_300rpm_100ld
Start Time	45629.46	45629.47	45629.48	45629.49	45629.50	45629.50	45629.61	45629.59	45629.62	45629.53
End Time	45629.46	45629.47	45629.48	45629.49	45629.50	45629.51	45629.61	45629.59	45629.62	45629.53
Speed [rpm]	299.60	299.50	299.50	299.50	299.40	299.40	269.60	269.40	299.60	299.40
Torque [lb-ft]	7704.00	7702.00	7706.00	7711.00	7701.00	7704.00	5412.00	7296.00	5412.00	7707.00
Power [bhp]	439.40	439.30	439.40	439.70	439.00	439.20	277.90	374.30	308.70	439.40
Load [%]	100.00	99.99	100.00	100.10	99.97	100.00	70.26	94.72	70.25	100.10
Ambient Press [psia]	12.36	12.36	12.36	12.35	12.35	12.35	12.33	12.33	12.33	12.34
Ambient Press [in Hg]	25.17	25.17	25.17	25.14	25.14	25.14	25.10	25.10	25.10	25.12
Boost [in Hg]	7.53	9.53	11.53	13.55	15.56	16.56	7.60	7.60	7.60	7.58
Ambient Temp [F]	56.60	57.35	59.21	59.91	59.83	60.86	65.92	64.78	65.63	62.62
Ambient Humidity [%]	21.12	20.08	21.05	18.11	17.65	16.44	12.44	14.43	11.62	15.04
Inlet Air Pres [in Hg]	32.70	34.70	36.70	38.69	40.70	41.70	32.70	32.70	32.70	32.70
Inlet Air Temp [F]	107.90	109.40	110.10	107.30	108.90	109.80	108.00	108.20	109.10	106.70
Inlet Air Humidity [%]	5.13	4.89	5.76	6.28	5.78	5.55	4.28	4.63	3.57	4.84
Inlet Air Flow [scfm]	1883.00	1937.00	1990.00	2048.00	2109.00	2128.00	1962.00	1927.00	1960.00	1895.00
IC Water Temp [F]	117.70	121.70	110.90	101.70	122.60	106.30	103.90	120.10	121.30	113.80
Exh Back Pres [in Hg]	30.20	32.20	34.20	36.20	38.19	39.20	30.20	30.20	30.20	30.20
Exh Cyl1 Temp [F]	522.20	519.20	518.40	516.70	499.90	499.50	409.50	495.30	446.60	550.60
Exh Cyl2 Temp [F]	652.50	641.80	627.70	613.30	602.30	601.60	488.10	556.30	522.20	638.70
Exh Cyl3 Temp [F]	576.70	558.00	542.40	530.70	516.10	517.60	402.30	478.60	436.90	552.40
Exh Cyl4 Temp [F]	650.00	639.90	628.50	617.60	605.40	606.20	462.20	548.30	499.90	635.60
Avg Exh Temp [F]	600.40	589.70	579.30	569.60	555.90	556.20	440.50	519.60	476.40	594.30
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	172.50	171.40	170.50	170.40	169.60	170.50	121.90	149.30	132.90	171.50
Sensor NOx [ppm]	595.90	321.60	218.40	205.70	155.40	151.10	25.89	83.46	27.51	480.90
Sensor Lambda	11.49	11.63	12.11	12.57	12.30	12.25	11.91	10.94	11.54	11.57
Orifice Temp [F]	44.42	46.55	45.27	40.84	47.11	44.53	41.40	45.46	46.34	42.39
Eng Fuel Pres [psig]	1.01	0.99	0.96	0.95	0.93	0.91	500.00	500.00	500.00	0.89
Eng Fuel Temp [F]	70.98	72.59	73.32	73.90	74.92	75.22	78.16	77.36	77.97	76.44
JW Out Temp [F]	149.60	149.60	149.30	148.70	148.00	148.10	133.70	136.80	133.50	148.70
JW In Temp [F]	143.90	144.10	143.90	143.50	142.90	143.00	130.00	132.60	129.90	143.50
JW Flow [gpm]	488.30	489.10	489.30	488.40	488.60	488.70	489.90	490.10	489.90	487.90
Lube Press [psig]	31.40	31.46	31.53	31.75	31.77	31.90	30.88	30.82	33.70	31.94
Lube In Temp [F]	150.60	150.80	150.80	150.40	149.90	149.90	147.00	148.20	147.70	150.80
Lube Out Temp [F]	161.20	161.70	161.70	161.30	160.80	160.70	155.70	158.90	156.10	162.50
Thrust 1 Temp [F]	159.00	160.00	160.50	160.70	160.60	160.50	156.80	157.60	157.20	160.90
Thrust 2 Temp [F]	158.10	159.40	160.00	160.30	160.30	160.30	156.90	157.50	157.30	160.70
Main 2A Temp [F]	159.80	160.80	161.30	161.50	161.40	161.40	156.80	158.00	157.20	161.30
Main 2B Temp [F]	159.60	160.70	161.20	161.40	161.40	161.30	156.80	157.90	157.10	161.10
Main 3A Temp [F]	161.00	162.10	162.50	162.60	162.60	162.50	157.50	158.90	157.70	162.50
Main 3B Temp [F]	161.40	162.40	162.80	162.90	162.80	162.80	157.40	159.00	157.60	162.80
Main 4A Temp [F]	157.00	157.90	158.20	158.30	158.10	158.00	153.60	154.80	154.00	158.20
Main 4B Temp [F]	156.60	157.50	157.90	158.00	157.80	157.70	153.70	154.70	154.20	157.90
THC [ppmd]	648.50	676.60	713.70	764.30	864.20	928.60	1246.00	667.80	1214.00	647.30
NOx [ppmd]	352.40	152.60	62.79	28.74	17.77	14.37	6.01	76.03	6.67	267.80
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	14.62	14.86	15.07	15.27	15.48	15.53	16.85	15.64	16.38	14.68
CO2 [%d]	3.33	3.19	3.06	2.94	2.80	2.77	1.96	2.68	2.23	3.26
CO [ppmd]	51.13	63.11	66.77	74.42	93.86	106.90	193.30	53.97	169.90	52.21
Air Flow [lb/hr]	8461.00	8706.00	8940.00	9202.00	9476.00	9562.00	8814.00	8656.00	8806.00	8514.00
Piezo 1 [F]	268.30	267.40	271.20	271.10	268.90	268.60	249.40	281.30	254.40	290.80
Piezo 2 [F]	308.30	304.60	304.40	300.80	299.60	301.20	266.10	295.80	274.40	318.80
Piezo 3 [F]	287.30	282.80	282.10	279.80	280.10	280.70	238.00	273.90	247.20	295.90
Piezo 4 [F]	310.20	305.20	303.80	300.20	298.00	297.90	257.50	293.30	267.30	314.80
Jacket Water Flow [gpm]	488.30	489.10	489.30	488.40	488.60	488.70	489.90	490.10	489.90	487.90
Jacket Water Valve Pos [%]	71.07	73.00	73.00	73.00	73.00	73.00	73.00	73.00	73.00	73.00
Supercharger Speed [%]	39.78	42.12	44.40	46.62	48.94	50.06	42.91	41.96	42.82	40.95
SC IC Temp Valve Pos [%]	82.00	81.07	73.11	73.40	79.74	69.57	69.70	77.99	76.84	80.59
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	40.49	44.61	47.36	48.51	56.90	50.19	43.93	41.66	42.35	39.13
Load Valve Pos [%]	22.96	23.06	23.08	23.18	23.16	23.25	19.18	38.00	17.63	23.31
Dyno Water Flow [gpm]	247.70	245.80	247.30	246.80	245.70	246.80	202.00	188.30	202.40	246.40
Dyno Water In [F]	75.27	76.28	77.22	77.74	78.20	78.78	78.37	78.24	78.74	80.00
Dyno Water Out [F]	88.29	89.31	90.25	90.79	91.23	91.81	89.03	93.05	90.53	93.11
Dyno Inboard Bearing [F]	102.70	105.80	107.60	108.90	109.90	110.60	108.80	107.50	109.70	112.70
Dyno Outboard Bearing [F]	97.94	101.90	104.90	107.40	110.00	112.00	129.40	127.30	130.30	123.40
Air Flow Static Pressure [kPa]	119.10	125.90	132.70	139.40	146.40	149.70	119.70	119.50	119.80	119.10
Air Flow Diff Pressure [kPa]	7.69	7.74	7.70	7.65	7.86	7.76	8.25	8.07	8.36	7.75
Air Flow Temperature [C]	44.42	46.55	45.27	40.84	47.11	44.53	41.40	45.46	46.34	42.39
Ethane Flow [lb/hr]	0.10	0.08	0.10	0.10	0.08	0.10	0.11	0.10	0.11	0.09
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.14	0.16	0.17	0.18	0.19	0.19	0.17	0.18	0.16	0.20
Ethane Temperature [C]	19.47	19.87	20.18	20.45	20.73	20.95	22.36	22.14	22.51	21.53
PCC H2 Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC H2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Corr Factor	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Manifold Pres Stpt [in Hg]	32.70	34.70	36.70	38.70	40.70	41.70	32.70	32.70	32.70	32.70
PCC 4 Temp [F]	78.51	79.81	80.93	81.87	82.81	83.52	89.86	89.67	89.98	85.62
NOx Correction Step	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Averaging Time [s]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Feedback Time [s]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor NOx @ 15% O2	331.10	149.10	63.53	30.10	19.35	15.81	8.74	85.25	8.72	253.80

Expanded PCC

Data Point Name	BS_300_100_32.7	BS_300_100_34.7	BS_300_100_36.7	BS_300_100_38.7	BS_300_100_40.7	BS_300_100_41.7	LS_270_70	LS_270_100	LS_300_70	LS_300_100
Start Time	45632.48	45632.47	45632.46	45632.46	45632.44	45632.45	45632.54	45632.51	45632.55	45632.48
End Time	45632.48	45632.47	45632.47	45632.46	45632.45	45632.45	45632.54	45632.51	45632.55	45632.49
Speed [rpm]	299.50	299.50	299.50	299.50	299.50	299.40	269.60	269.50	299.50	299.50
Torque [lb-ft]	7699.00	7714.00	7699.00	7700.00	7706.00	7689.00	5397.00	7368.00	5399.00	7704.00
Power [bhp]	439.10	439.90	439.00	439.10	439.30	438.40	277.00	378.20	307.90	439.30
Load [%]	99.96	100.10	99.94	99.96	100.00	99.81	70.06	95.66	70.09	100.00
Ambient Press [psia]	12.38	12.39	12.39	12.39	12.40	12.39	12.36	12.37	12.36	12.38
Ambient Press [in Hg]	25.21	25.23	25.23	25.23	25.25	25.23	25.17	25.19	25.17	25.21
Boost [in Hg]	7.49	9.47	11.47	13.47	15.45	16.47	7.53	7.51	7.53	7.49
Ambient Temp [F]	53.71	53.01	52.96	52.52	50.72	50.94	57.57	56.75	58.64	54.71
Ambient Humidity [%]	21.92	23.54	23.61	24.62	27.54	26.59	18.62	20.04	17.86	21.00
Inlet Air Pres [in Hg]	32.70	34.70	36.70	38.70	40.70	41.70	32.70	32.70	32.70	32.70
Inlet Air Temp [F]	109.20	109.40	109.80	108.40	108.50	110.00	110.00	109.40	109.60	109.30
Inlet Air Humidity [%]	4.47	4.99	5.22	5.88	6.68	6.08	4.29	4.57	4.35	4.41
Inlet Air Flow [scfm]	1894.00	1953.00	2005.00	2064.00	2113.00	2141.00	1964.00	1923.00	1960.00	1893.00
IC Water Temp [F]	116.00	116.40	114.00	115.80	114.70	115.60	116.40	116.20	113.30	116.10
Exh Back Pres [in Hg]	30.20	32.20	34.20	36.20	38.20	39.20	30.20	30.20	30.20	30.20
Exh Cyl 1 Temp [F]	571.60	556.40	551.30	533.90	525.40	523.40	417.80	509.10	450.10	572.50
Exh Cyl 2 Temp [F]	623.30	614.40	607.00	596.60	593.10	589.10	481.40	553.30	509.30	622.40
Exh Cyl 3 Temp [F]	549.50	539.40	532.90	521.60	516.20	515.60	392.90	487.20	434.40	550.50
Exh Cyl 4 Temp [F]	639.90	626.00	619.50	605.70	598.10	593.70	462.70	570.90	513.00	640.30
Avg Exh Temp [F]	596.10	584.10	577.70	564.40	558.20	555.40	438.70	530.10	476.70	596.40
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	171.40	170.60	170.40	169.90	171.30	171.40	122.60	149.90	133.60	171.50
Sensor NOx [ppm]	415.90	212.60	125.90	108.40	105.40	105.50	117.20	201.30	131.60	425.40
Sensor Lambda	11.24	11.42	11.58	11.75	11.82	11.87	13.00	12.07	12.73	11.27
Orifice Temp [F]	44.59	44.96	44.56	44.74	42.09	46.05	44.94	44.74	43.94	44.62
Eng Fuel Pres [psig]	500.00	499.90	500.00	500.10	499.90	500.00	500.00	500.00	500.00	499.90
Eng Fuel Temp [F]	68.47	66.93	65.83	64.88	62.94	63.80	69.47	69.12	69.96	68.77
JW Out Temp [F]	149.80	149.90	149.20	146.00	138.60	142.30	128.00	144.80	129.60	149.80
JW In Temp [F]	144.20	144.40	144.00	140.90	133.40	137.20	124.30	140.30	125.50	143.30
JW Flow [gpm]	485.30	484.80	485.30	484.30	483.10	483.60	483.60	484.60	484.80	485.30
Lube Press [psig]	33.42	33.51	33.65	33.79	31.45	31.19	31.02	29.93	34.13	33.32
Lube In Temp [F]	150.90	150.80	150.50	150.10	150.50	150.40	146.80	147.10	147.80	150.90
Lube Out Temp [F]	161.90	161.20	160.30	159.60	158.20	158.90	155.00	158.60	155.80	162.00
Thrust 1 Temp [F]	160.30	160.10	159.50	159.20	156.90	158.40	156.40	157.70	157.10	160.60
Thrust 2 Temp [F]	159.90	159.60	158.90	158.40	155.50	157.30	156.30	157.60	157.00	160.20
Main 2A Temp [F]	161.00	160.90	160.40	160.20	158.00	159.50	156.20	158.10	156.90	161.20
Main 2B Temp [F]	161.00	160.90	160.40	160.10	157.50	159.20	156.30	158.30	156.90	161.30
Main 3A Temp [F]	161.80	161.50	161.00	160.60	157.80	159.60	156.80	159.20	157.30	162.10
Main 3B Temp [F]	162.00	161.80	161.30	160.90	158.40	160.00	156.70	159.40	157.30	162.40
Main 4A Temp [F]	157.70	157.50	156.90	156.50	154.10	155.70	153.10	154.90	153.90	158.00
Main 4B Temp [F]	157.40	157.20	156.70	156.30	153.80	155.40	153.20	154.70	154.00	157.70
THC [ppmd]	656.60	684.50	711.80	773.90	898.10	967.10	1486.00	671.80	1414.00	655.10
NOx [ppmd]	238.00	98.27	41.90	21.43	12.96	11.14	5.59	86.93	6.05	242.10
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	14.70	14.94	15.13	15.34	15.47	15.55	16.87	15.62	16.40	14.69
CO2 [%d]	3.33	3.18	3.07	2.95	2.88	2.82	1.98	2.75	2.26	3.32
CO [ppmd]	51.25	54.85	57.97	70.36	97.08	110.40	190.80	52.48	175.50	50.44
AFR Left	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AFR Right	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Flow [lb/hr]	8511.00	8776.00	9009.00	9272.00	9496.00	9619.00	8827.00	8641.00	8806.00	8507.00
Piezo 1 [F]	298.00	293.20	287.20	280.20	264.30	268.10	251.00	285.10	253.70	298.40
Piezo 2 [F]	314.50	308.80	302.10	296.20	285.60	289.20	261.70	296.30	264.90	314.30
Piezo 3 [F]	294.70	289.70	281.70	276.30	263.40	267.90	234.50	278.70	244.40	295.60
Piezo 4 [F]	313.30	307.00	300.90	296.90	287.30	288.80	250.50	295.80	265.40	313.40
Jacket Water Flow [gpm]	485.30	484.80	485.30	484.30	483.10	483.60	483.60	484.60	484.80	485.30
Jacket Water Valve Pos [%]	73.86	70.17	74.00	74.00	74.50	74.50	74.00	74.00	74.00	69.67
Supercharger Speed [%]	40.00	42.01	44.05	46.07	47.92	48.98	42.09	40.98	42.10	40.09
SC IC Temp Valve Pos [%]	73.00	73.00	71.58	73.00	70.41	72.12	72.90	73.00	71.25	73.00
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	38.77	43.17	46.16	48.65	49.36	51.73	42.64	40.40	41.10	38.81
Load Valve Pos [%]	31.76	31.82	31.68	31.71	31.73	31.79	22.15	38.00	21.19	31.83
Dyno Water Flow [gpm]	199.60	199.00	199.70	199.90	198.50	198.60	192.40	182.10	192.70	199.80
Dyno Water In [F]	73.47	72.35	71.62	70.98	69.58	70.32	71.12	73.44	72.19	73.80
Dyno Water Out [F]	89.34	88.25	87.53	86.89	85.47	86.20	82.34	88.88	84.36	89.68
Dyno Inboard Bearing [F]	109.20	107.10	105.40	103.60	96.88	100.60	108.70	109.30	108.70	109.80
Dyno Outboard Bearing [F]	106.90	103.40	101.00	98.55	91.52	95.13	114.80	112.90	115.50	108.00
Air Flow Static Pressure [kPa]	119.20	126.00	132.80	139.60	146.40	149.90	119.80	119.40	119.70	119.20
Air Flow Diff Pressure [kPa]	7.79	7.82	7.80	7.85	7.78	7.88	8.36	8.02	8.29	7.78
Air Flow Temperature [C]	44.59	44.96	44.56	44.74	42.09	46.05	44.94	44.74	43.94	44.62
Ethane Flow [lb/hr]	0.08	0.10	0.10	0.10	0.10	0.05	0.10	0.10	0.06	0.06
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.06	0.04	0.03	0.03	0.03	0.03	0.09	0.06	0.10	0.06
Ethane Temperature [C]	18.41	18.03	17.81	17.65	17.38	17.51	19.46	18.92	19.84	18.53
PCC H2 Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC H2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Corr Factor	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Manifold Pres Stpt [in Hg]	32.70	34.70	36.70	38.70	40.70	41.70	32.70	32.70	32.70	32.70
PCC 4 Temp [F]	79.08	78.23	77.67	77.12	75.59	76.34	83.04	81.38	83.66	79.41
NOx Correction Step	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Averaging Time [s]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx Feedback Time [s]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sensor NOx @ 15% O2	226.50	97.30	42.86	22.73	14.08	12.29	8.18	97.10	7.93	230.10
ePCC Pressure [psig]	22.86	23.85	24.84	25.83	26.84	27.35	23.07	22.98	22.89	22.86
Fuel Flow Static P [kPa]	367.40	367.30	367.50	367.00	367.30	367.50	375.00	368.90	371.10	367.50
Fuel Flow Temp [C]	34.47	33.89	33.53	33.34	32.90	33.17	33.82	33.13	33.97	34.43
Fuel Flow Diff P [kPa]	17.73	17.48	17.38	17.20	17.48	17.55	12.74	13.64	13.15	17.70
Low Press Orifice Flow [lb/hr]	177.10	176.00	175.90	174.90	176.30	176.70	152.50	156.50	154.10	177.00
Air Flow Diff 0 offset	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ign Spark #	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign Timing [deg]	-1.32	-1.75	-2.41	-3.51	-4.16	-4.60	-3.95	-1.32	-4.38	-1.32
Ign Offset Cyl 1 [deg]	0.66	0.22	0.22	-0.22	-0.22	-0.22	-1.32	0.66	-1.32	0.66
Ign Offset Cyl 2 [deg]	0.22	0.22	0.22	0.66	0.66	0.66	0.00	0.22	-0.44	0.22
Ign Offset Cyl 3 [deg]	0.44	0.00	0.00	0.00	0.00	0.00	-1.97	0.44	-1.97	0.44
Ign Offset Cyl 4 [deg]	-0.66	-0.66	-0.22	-0.22	-0.22	-0.22	-1.97	-0.66	-1.09	-0.66

Appendix D

Premixed Fuel and Air Injection

D.1 Extra Plots

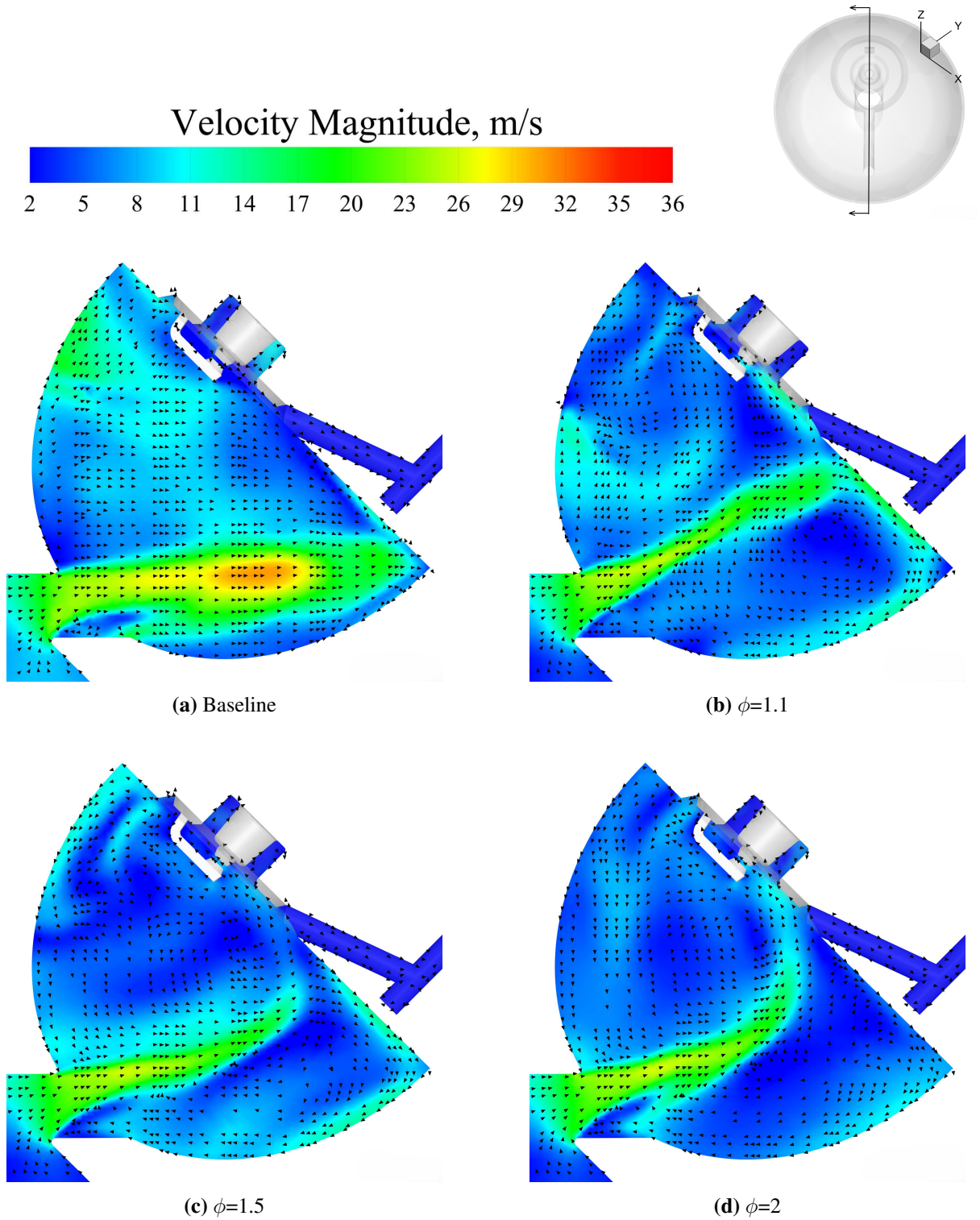
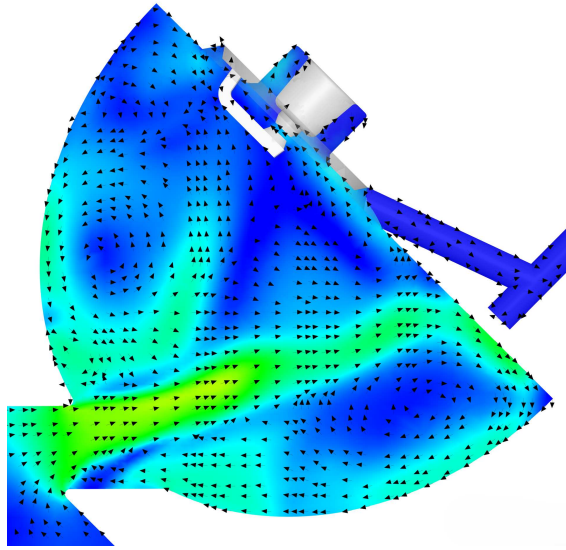
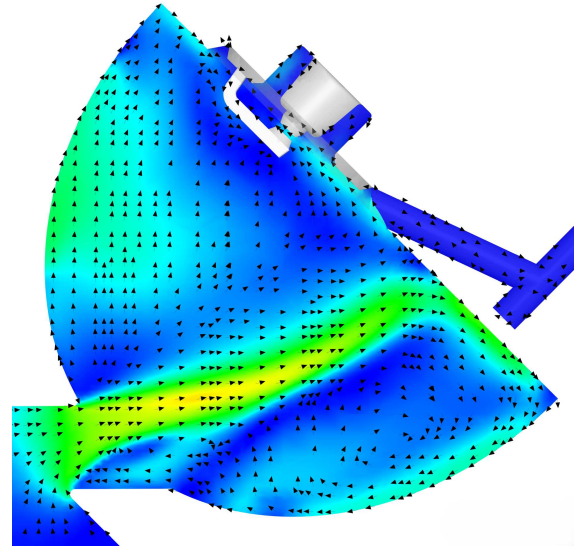


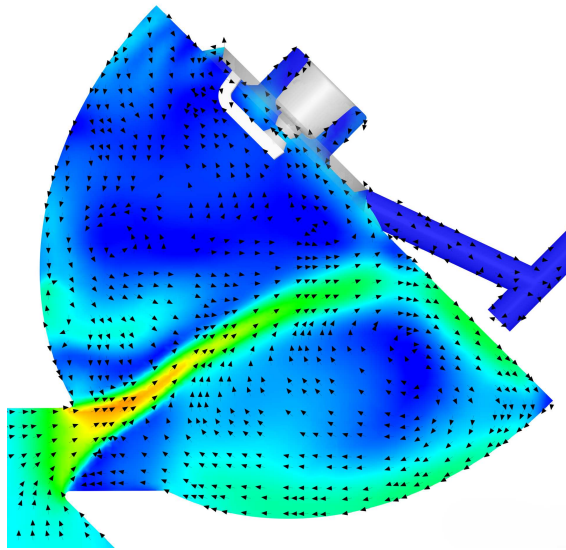
Figure D.1: A view of a slice inside the PCC showcasing the velocity vectors going through the center of the electrode gap at time of spark, -5°aTDC .



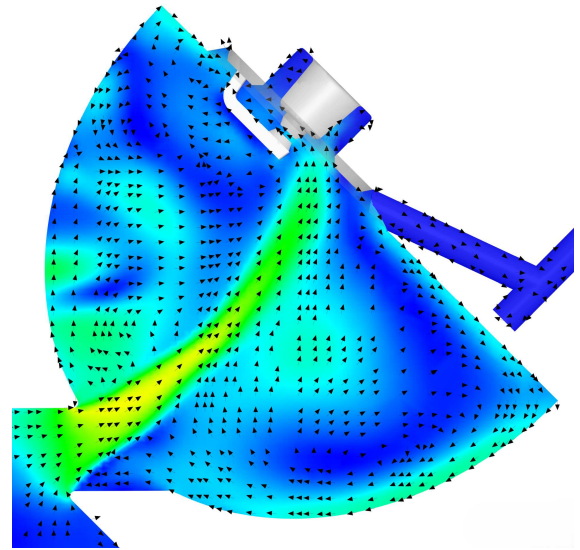
(e) $\phi=2.5$



(f) $\phi=3$



(g) $\phi=5$



(h) $\phi=7$

Figure D.1: A view of a slice inside the PCC showcasing the velocity vectors going through the center of the electrode gap at time of spark, -5°aTDC .

D.2 Experimental Data

Data Point Name	0-7.5-BAD	1.25-7.5-BAD	1.25-7.5-50	1.5-7.5-50	1.75-7.5-50	1.25-7.5-39	0.0-12.5-12	0.5-12.5-33	0.75-12.5-41	1.0-12.5-45	1.25-12.5-50	1.5-12.5-60	1.75-12.5-50	2.0-12.5-60
Start Time	45618.41	45618.42	45618.44	45618.44	45618.45	45618.43	45618.52	45618.50	45618.49	45618.48	45618.48	45618.47	45618.46	45618.46
End Time	45618.42	45618.42	45618.44	45618.45	45618.45	45618.43	45618.52	45618.50	45618.49	45618.49	45618.48	45618.47	45618.46	45618.47
Speed [rpm]	299.50	299.50	299.40	299.40	299.40	299.40	299.40	299.40	299.40	299.50	299.40	299.40	299.40	299.40
Torque [lb-ft]	7708.00	7712.00	7703.00	7706.00	7695.00	7700.00	7703.00	7699.00	7696.00	7705.00	7704.00	7708.00	7694.00	7700.00
Power [bhp]	439.50	439.80	439.20	439.30	438.70	439.10	439.20	438.90	438.70	439.30	439.20	439.40	438.70	439.00
Load [%]	100.10	100.10	100.00	100.00	99.90	99.96	100.00	99.95	99.91	100.00	100.00	100.10	99.88	99.96
Ambient Press [psia]	12.34	12.34	12.34	12.34	12.34	12.34	12.31	12.31	12.32	12.32	12.32	12.33	12.33	12.33
Ambient Temp [F]	45.44	46.82	50.60	51.75	53.82	48.23	61.37	61.15	60.30	57.44	57.45	57.12	55.36	56.01
Ambient Humidity [%]	37.94	35.83	28.19	25.43	22.00	30.56	14.48	16.50	17.68	19.32	21.20	22.40	22.76	21.90
Inlet Air Pres [in Hg]	32.70	32.70	32.70	32.70	32.70	32.70	37.70	37.70	37.70	37.70	37.70	37.70	37.70	37.70
Inlet Air Temp [F]	107.80	106.90	109.90	106.70	108.50	110.00	108.00	109.60	108.40	107.80	109.00	109.80	109.70	108.70
Inlet Air Humidity [%]	5.93	6.49	5.00	5.39	4.75	4.87	4.97	5.14	5.69	5.76	5.96	6.05	5.72	6.02
Inlet Air Flow [scfm]	1924.00	1918.00	1919.00	1922.00	1919.00	1917.00	2047.00	2048.00	2048.00	2049.00	2049.00	2048.00	2047.00	2046.00
IC Water Temp [F]	119.90	102.50	111.30	115.80	104.00	119.90	105.20	118.10	116.40	109.60	117.30	116.50	116.00	109.20
Exh Back Pres [in Hg]	30.20	30.21	30.20	30.20	30.20	30.20	35.20	35.20	35.20	35.20	35.20	35.20	35.20	35.20
Exh Cyl 1 Temp [F]	542.90	551.00	541.80	541.90	543.40	555.60	543.60	550.20	548.50	545.80	547.20	546.00	543.30	548.50
Exh Cyl 2 Temp [F]	609.90	624.80	614.30	614.40	618.60	625.00	618.70	618.30	618.30	617.30	615.30	613.10	619.40	621.60
Exh Cyl 3 Temp [F]	534.30	549.70	539.90	539.10	538.60	553.00	549.50	540.90	541.10	541.30	542.40	542.30	540.00	543.20
Exh Cyl 4 Temp [F]	599.30	606.50	603.60	599.90	602.00	609.90	614.50	611.30	613.00	609.20	612.00	612.60	603.70	611.80
Avg Exh Temp [F]	571.60	583.00	574.90	573.80	575.20	585.90	582.00	580.30	580.20	578.40	579.20	578.50	576.60	581.30
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	166.30	167.90	167.70	167.90	167.80	168.00	169.00	169.20	169.40	169.80	170.10	170.10	169.90	170.80
Sensor NOx [ppm]	456.90	358.10	453.40	435.20	424.70	368.90	126.50	127.90	126.80	124.80	124.30	122.50	120.70	122.00
Sensor Lambda	11.46	11.43	11.43	11.46	11.47	11.45	11.70	11.74	11.74	11.74	11.73	11.72	11.72	11.70
Orifice Temp [F]	45.38	40.35	44.49	43.56	41.79	46.36	41.76	45.92	44.63	42.63	45.31	45.39	45.23	42.99
Eng Fuel Pres [psig]	499.90	500.00	500.20	499.90	500.00	500.00	499.90	500.00	500.00	500.00	500.10	500.00	499.90	500.00
Eng Water Temp [F]	66.34	67.20	70.08	70.89	71.85	68.43	76.88	75.71	74.88	73.99	73.34	72.52	72.28	72.25
JW Out Temp [F]	147.20	147.80	147.00	145.30	149.60	148.20	147.20	149.90	148.80	147.70	146.80	145.90	147.00	145.90
JW In Temp [F]	141.70	143.10	141.50	139.70	144.60	142.20	141.90	145.10	144.00	142.80	141.90	140.90	141.50	140.90
JW Flow [gpm]	481.90	482.80	485.90	486.40	486.40	484.40	489.90	488.80	488.80	487.60	488.00	488.20	487.30	487.30
Lube Press [psig]	33.24	35.31	30.93	31.13	30.62	35.19	32.60	30.52	30.76	31.04	31.16	31.30	32.57	31.24
Lube In Temp [F]	149.40	149.60	149.20	148.00	150.80	149.80	149.20	150.90	149.90	149.00	148.30	147.80	148.60	147.90
Lube Out Temp [F]	159.50	159.30	160.10	159.70	160.80	159.90	160.10	160.50	159.60	158.90	158.40	158.20	159.30	158.50
Thrust 1 Temp [F]	158.80	158.90	159.50	159.50	159.80	159.20	160.50	160.20	159.50	159.00	158.80	158.90	159.90	159.40
Thrust 2 Temp [F]	158.20	158.60	159.30	159.30	159.50	158.90	160.50	160.10	159.50	158.90	158.80	159.00	159.80	159.40
Main 2A Temp [F]	159.40	159.50	159.90	159.90	160.10	159.70	161.10	160.90	160.20	159.60	159.40	159.50	160.40	159.90
Main 2B Temp [F]	159.10	159.20	159.70	159.60	159.80	159.40	160.70	160.40	159.80	159.20	159.00	159.20	160.10	159.60
Main 3A Temp [F]	160.20	160.40	161.00	161.00	161.10	160.70	162.00	161.70	161.10	160.50	160.40	160.60	161.50	161.00
Main 3B Temp [F]	160.40	160.60	161.10	161.10	161.30	160.80	162.20	161.90	161.20	160.70	160.50	160.70	161.60	161.10
Main 4A Temp [F]	156.30	156.40	156.80	156.80	157.00	156.60	157.60	157.30	156.60	156.10	155.90	156.10	157.10	156.60
Main 4B Temp [F]	156.10	156.20	156.70	156.60	156.80	156.40	157.60	157.30	156.60	156.00	155.80	156.10	157.00	156.50
THC [ppm]	841.60	779.70	927.70	910.20	898.70	781.40	949.90	988.00	999.80	1006.00	1006.00	1012.00	997.50	993.60
NOx [ppm]	257.40	189.80	258.60	242.50	237.50	194.90	28.84	27.51	25.53	24.87	24.70	24.65	24.19	22.92
NO [ppm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	14.90	14.84	14.91	14.92	14.92	14.86	15.23	15.25	15.25	15.26	15.25	15.26	15.28	15.24
CO2 [%d]	3.24	3.26	3.20	3.20	3.19	3.24	2.96	2.95	2.95	2.96	2.97	2.97	2.97	2.99
CO [ppm]	85.58	74.48	80.65	80.56	78.50	72.58	89.03	87.82	88.53	88.07	87.12	88.58	89.79	87.62
AFR Left	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AFR Right	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Flow [lb/hr]	8644.00	8617.00	8621.00	8634.00	8621.00	8615.00	9199.00	9201.00	9201.00	9205.00	9206.00	9202.00	9197.00	9193.00
Piezo 1 [F]	308.40	305.80	312.00	312.10	312.10	304.90	300.90	297.50	296.90	295.70	295.50	294.90	296.80	294.60
Piezo 2 [F]	318.80	311.80	320.20	320.10	320.70	313.10	311.90	313.00	312.70	311.70	310.80	310.00	307.50	307.80
Piezo 3 [F]	295.90	293.60	300.30	302.10	302.50	294.40	291.20	293.10	294.30	291.50	289.90	291.20	291.00	290.70
Piezo 4 [F]	325.70	321.10	328.90	329.50	329.70	319.00	318.40	316.80	313.00	310.90	310.40	310.80	314.10	311.30
Jacket Water Flow [gpm]	481.90	482.80	485.90	486.40	486.40	484.40	489.90	488.80	488.80	487.60	488.00	488.20	487.30	487.30
Jacket Water Valve Pos [%]	72.80	73.91	72.60	74.32	75.16	71.94	71.07	73.94	74.00	74.00	74.00	74.00	74.00	74.00
Supercharger Speed [%]	39.98	39.99	40.34	40.41	40.59	40.10	46.46	46.43	46.29	46.07	46.05	46.03	45.86	45.89
SC IC Temp Valve Pos [%]	80.00	76.06	72.85	79.00	72.26	76.79	71.66	73.81	75.00	74.77	75.00	74.57	74.98	74.33
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	40.65	40.21	40.83	40.77	40.81	40.17	47.92	47.67	47.80	47.86	47.71	47.86	48.09	47.79
Load Valve Pos [%]	22.40	22.33	22.53	22.53	22.58	22.35	23.31	23.08	22.96	22.76	22.84	22.86	22.82	22.84
Dyno Water Flow [gpm]	247.60	247.50	247.50	247.20	246.60	246.60	247.70	246.60	247.50	246.80	246.40	247.10	246.50	247.40
Dyno Water In [F]	67.77	68.35	71.24	72.01	72.89	69.63	79.89	78.19	77.16	75.99	75.64	74.93	74.12	74.45
Dyno Water Out [F]	80.59	81.22	84.06	84.84	85.72	82.48	92.76	91.04	89.98	88.84	88.49	87.81	86.98	87.32
Dyno Inboard Bearing [F]	104.90	106.40	109.40	109.60	109.90	107.90	112.50	111.10	111.10	110.80	110.60	110.40	110.10	110.30
Dyno Outboard Bearing [F]	102.40	105.90	118.70	120.80	123.30	111.70	134.70	132.80	131.70	130.30	129.50	128.30	126.30	127.40
Air Flow Static Pressure [kPa]	119.40	119.20	119.30	119.30	119.20	119.30	136.10	136.10	136.20	136.20	136.20	136.20	136.20	136.20
Air Flow Diff Pressure [kPa]	7.96	7.80	7.90	7.90	7.84	7.94	7.78	7.88	7.85	7.81	7.87	7.87	7.85	7.80
Air Flow Temperature [C]	45.38	40.35	44.49	43.56	41.79	46.36	41.76	45.92	44.63	42.63	45.31	45.39	45.23	42.99
Ethane Flow [lb/hr]	0.06	0.10	0.10	0.09	0.08	0.10	0.10	0.11	0.11	0.07	0.09	0.11	0.10	0.11
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.05	0.05	0.06	0.06	0.06	0.05	0.09	0.07	0.06	0.06	0.05	0.06	0.06	0.06
Ethane Temperature [C]	20.07	20.16	20.36	20.42	20.47	20.28	21.68	21.33	21.13	20.89	20.76	20.63	20.56	20.57
PCC H2 Flow [lb/hr]	0.00	1.25	1.25	1.50	1.75	1.25	0.00	0.50	0.75	1.00	1.25	1.50	1	

SOI Cylinder 2 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 3 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SOI Cylinder 4 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 1 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Global Duration [usec]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cylinder 1 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 2 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 3 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Cylinder 4 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
LECM Fuel Temp [deg F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LECM Fuel Pres [psia]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HP Meter Fuel Flow [lb/hr]	164.00	165.40	163.50	163.60	163.40	165.40	166.30	165.90	165.90	166.00	166.10	165.90	165.50	166.20	166.20	166.20	166.20
SC IC Coolant Out [C]	48.31	40.89	45.92	46.40	42.79	48.91	45.36	50.57	49.01	46.14	49.50	49.30	48.69	45.99	45.99	45.99	45.99
SC IC Coolant In [C]	48.85	39.17	44.07	46.53	39.99	48.85	40.66	47.82	46.88	43.13	47.37	46.96	46.66	42.89	42.89	42.89	42.89
SC IC Air 1 [C]	48.20	40.02	45.47	45.76	41.64	48.87	41.94	48.17	46.65	43.62	47.39	47.19	46.85	43.81	43.81	43.81	43.81
SC IC Air 2 [C]	47.21	47.84	50.27	50.89	52.12	48.82	75.64	75.02	73.86	72.22	71.89	70.93	67.64	69.56	69.56	69.56	69.56
SC ID Pres Diff	354.00	347.20	352.20	353.90	350.30	355.10	359.90	365.60	363.20	358.80	361.20	359.40	359.10	354.80	354.80	354.80	354.80
HPFI H2 Meter 1 Flow [g/hr]	15.94	15.93	15.92	15.95	15.96	15.96	16.22	16.24	16.26	16.26	16.26	16.25	16.23	16.22	16.22	16.22	16.22
HPFI H2 Meter 2 Flow [kg/hr]	10.02	10.06	10.08	10.12	10.12	10.06	10.37	10.42	10.39	10.30	10.30	10.19	10.18	10.18	10.18	10.18	10.18
HPFI H2 Meter 3 Flow [kg/hr]	9.78	9.87	9.88	9.88	9.91	9.84	10.13	10.18	10.17	10.06	10.07	9.99	9.90	9.95	9.95	9.95	9.95
HPFI H2 Meter 1 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 3 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Total Flow [kg/hr]	35.75	35.86	35.88	35.95	35.99	35.86	36.72	36.85	36.82	36.63	36.63	36.43	36.31	36.36	36.36	36.36	36.36
HPFI H2 Total Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LP Offline Fuel Flow [lb/hr]	173.60	174.20	174.40	173.90	174.00	174.20	177.10	176.90	177.10	176.60	177.00	176.80	176.00	177.10	177.10	177.10	177.10
LPFI H2 Meter Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LPFI H2 Meter Flow [kg/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO (350,300) 191C	350.70	276.70	353.40	327.50	366.40	265.00	21.83	21.93	20.04	16.10	17.55	18.07	16.70	13.87	13.87	13.87	13.87
NO2 (150) 191C (1of2)	16.51	16.06	15.44	16.06	15.93	15.64	17.51	17.54	17.26	16.59	16.82	17.43	18.04	17.52	17.52	17.52	17.52
NO2 (2000) 191C (2of2)	14.07	14.85	14.30	13.87	11.15	14.23	14.87	15.07	16.97	13.69	13.64	13.18	16.28	13.06	13.06	13.06	13.06
N2O (100,200,300) 191C	0.24	0.16	0.32	0.26	0.27	0.18	0.28	0.27	0.12	0.28	0.20	0.22	0.14	0.26	0.26	0.26	0.26
NH3 (300) 191C (1of2)	-0.02	0.08	0.05	0.01	0.03	0.08	0.03	0.03	-0.03	-0.01	0.06	0.07	0.01	0.03	0.03	0.03	0.03
NH3 (3000) 191C (2of2)	0.67	-0.03	1.17	0.03	0.31	0.43	0.54	0.87	0.32	0.87	0.60	0.92	0.96	1.07	1.07	1.07	1.07
H2O% (25) 191C	6.31	6.34	6.30	6.25	6.25	6.29	5.87	5.90	5.91	5.91	5.91	5.96	5.91	5.94	5.94	5.94	5.94
CO2% (20) 191C (1of2) R4	3.27	3.26	3.22	3.25	3.24	3.26	3.06	3.06	3.06	3.06	3.02	3.03	3.01	3.02	3.02	3.02	3.02
CO (500) 191C (1of3)	101.80	90.14	97.73	97.18	94.56	87.71	110.00	106.70	110.20	107.20	109.70	110.40	110.20	107.10	107.10	107.10	107.10
CO% (1) 191C (2of3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CH4 (3000) 191C (1of2)	664.90	603.50	721.70	723.20	705.60	612.80	749.50	780.00	796.70	791.40	808.10	800.60	795.80	781.20	781.20	781.20	781.20
CH4 (20000) 191C (2of2)	672.00	622.60	742.30	735.50	721.10	633.30	759.40	797.20	804.30	806.50	821.90	818.00	806.30	790.00	790.00	790.00	790.00
Ethane (500) 191C	70.86	63.70	76.71	75.66	74.20	64.44	76.06	80.10	81.46	80.86	82.71	82.29	80.40	80.61	80.61	80.61	80.61
Ethylene (100,3000) 191C	6.87	7.16	6.51	6.70	6.38	7.12	10.76	10.51	10.77	10.57	10.79	10.75	11.03	11.02	11.02	11.02	11.02
Acetylene (1000) 191C	0.16	0.29	0.69	0.69	0.87	0.84	0.50	0.89	0.45	1.08	0.58	0.65	0.45	0.81	0.81	0.81	0.81
Propane (200) 191C	9.93	9.25	10.80	10.98	10.87	9.60	10.37	10.93	11.31	11.42	11.72	11.88	11.30	11.52	11.52	11.52	11.52
Propylene (200,1000) 191C	0.34	1.33	0.57	0.41	0.75	1.28	0.65	1.39	0.96	0.80	1.20	0.50	0.95	0.64	0.64	0.64	0.64
Oil as octane (200) 191C	2.21	2.28	2.36	2.26	2.24	2.33	2.34	2.38	2.51	2.29	2.26	2.35	2.48	2.41	2.41	2.41	2.41
Formaldehyde (70,500) 191C	9.88	10.41	9.47	9.66	9.34	10.75	16.21	15.99	16.10	16.07	15.85	16.25	15.98	16.19	16.19	16.19	16.19
Acetaldehyde (1000) 191C	3.73	3.74	3.89	4.16	3.60	4.55	4.26	4.57	4.04	4.71	4.25	3.97	4.65	3.32	3.32	3.32	3.32
Formic Acid (100) 191C	0.48	0.46	0.53	0.42	0.52	0.48	0.62	0.55	0.59	0.63	0.60	0.69	0.53	0.61	0.61	0.61	0.61
MeOH (1000) 191C	0.36	0.32	0.11	0.38	0.25	0.32	0.36	0.27	0.78	0.47	0.66	0.46	0.58	0.54	0.54	0.54	0.54
CO% (10) 191C (3of3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CO2 low% (4) 191C (2of2)	3.22	3.23	3.19	3.18	3.19	3.21	3.00	3.01	3.01	3.00	2.98	3.00	2.98	3.00	3.00	3.00	3.00
1,3 butadiene (80) 191C	0.57	0.62	-0.13	0.36	1.06	0.62	-0.01	0.39	0.01	0.52	0.68	-0.19	0.35	0.95	0.95	0.95	0.95
Temp (C)	190.30	190.40	190.30	190.30	190.20	190.20	190.30	190.20	190.30	190.20	190.20	190.30	190.20	190.30	190.30	190.30	190.30
Pressure (Atm)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NOx autorange	367.20	292.80	368.90	343.60	382.30	280.60	39.33	39.46	37.29	32.69	34.37	35.50	34.75	31.40	31.40	31.40	31.40
CO autorange	101.80	90.14	97.73	97.18	94.56	87.71	110.00	106.70	110.20	107.20	109.70	110.40	110.20	107.10	107.10	107.10	107.10
CH4 autorange	664.90	603.50	721.70	723.20	705.60	612.80	749.50	780.00	796.70	791.40	808.10	800.60	795.80	781.20	781.20	781.20	781.20
NH3 autorange	-0.02	0.08	0.05	0.01	0.03	0.08	0.03	0.03	-0.03	-0.01	0.06	0.07	0.01	0.03	0.03	0.03	0.03
NOx autorange dry	392.00	312.60	393.70	366.50	407.80	299.50	41.79	41.94	39.63	34.75	36.53	37.75	36.93	33.38	33.38	33.38	33.38
CO autorange dry	108.70	96.25	104.30	103.70	100.90	93.60	116.80	113.40	117.10	113.90	116.60	117.40	117.10	113.90	113.90	113.90	113.90
CO2% autorange dry	3.44	3.45	3.41	3.39	3.40	3.43	3.19	3.20	3.20	3.19	3.19	3.19	3.16	3.19	3.19	3.19	3.19
N2O dry	0.26	0.17	0.34	0.28	0.28	0.19	0.30	0.28	0.13	0.30	0.21	0.23	0.15	0.28	0.28	0.28	0.28
NH3 autorange dry	-0.02	0.08	0.05	0.01	0.03	0.08	0.04	0.03	-0.03	-0.01	0.06	0.08	0.01	0.03	0.03	0.03	0.03
FIDeq THC ppmC	917.30	837.10	995.30	995.30	973.50	851.00	1031.00	1077.00	1097.00	1091.00	1115.00	1104.00	1095.00				

Air Flow [kg/hr]	3970.00	4010.00	4080.00	4090.00	4090.00	4050.00	4300.00	4310.00	4320.00	4350.00	4370.00	4360.00	4390.00	4390.00
Exh Flow [kg/hr]	4040.00	4090.00	4160.00	4170.00	4170.00	4120.00	4380.00	4380.00	4400.00	4420.00	4450.00	4440.00	4470.00	4470.00
BMEP [kPa]	478.00	478.00	477.00	477.00	477.00	477.00	477.00	477.00	477.00	477.00	477.00	478.00	477.00	477.00
thermal eff	0.32	0.32	0.31	0.31	0.31	0.31	0.32	0.31	0.31	0.31	0.31	0.31	0.31	0.31
BSFC [kJ/kW-hr]	11340.22	11459.10	11481.73	11469.37	11467.94	11513.08	11522.92	11550.97	11573.97	11580.48	11601.24	11590.02	11601.76	11651.72
BSEC [BTU/bhp-hr]	6617.00	6657.70	6647.26	6684.39	6701.84	6642.91	6782.62	6767.75	6767.81	6777.28	6794.95	6805.00	6798.16	6835.75
Abs Humidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BSTHC [g/bkW-hr]	6.07	5.60	6.79	6.81	6.66	5.75	7.47	7.79	7.96	7.97	8.20	8.09	8.10	7.98
BSTHC [g/bhp-hr]	4.53	4.18	5.06	5.08	4.97	4.29	5.57	5.81	5.94	5.94	6.11	6.03	6.04	5.95
BS CH4 [g/bhp-hr]	3.43	3.14	3.76	3.78	3.71	3.16	4.22	4.37	4.46	4.45	4.61	4.56	4.55	4.48
BS NOx [g/bkW-hr]	7.43	6.00	7.70	7.19	8.00	5.81	0.87	0.87	0.82	0.73	0.77	0.79	0.78	0.71
BS NOx [g/bhp-hr]	5.54	4.47	5.74	5.36	5.97	4.33	0.65	0.65	0.61	0.54	0.57	0.59	0.58	0.53
BS CO [g/bhp-hr]	0.93	0.84	0.88	0.89	0.88	0.81	1.09	1.04	1.09	1.05	1.10	1.08	1.11	1.07
BS CO2 [g/bhp-hr]	462.11	464.51	460.18	464.87	467.26	460.92	472.58	470.52	469.83	470.93	471.87	473.27	472.25	475.45
BS CO2e [g/bhp-hr]	547.75	542.99	554.19	559.28	560.04	539.94	577.99	579.74	581.25	582.09	587.07	587.37	585.90	587.48
THC @15%O2	901.00	814.00	980.00	982.00	961.00	831.00	1070.00	1130.00	1150.00	1140.00	1160.00	1150.00	1150.00	1130.00
NOx @15%O2	385.00	304.00	388.00	362.00	402.00	293.00	43.50	43.80	41.40	36.40	38.20	39.50	38.80	34.80
CO @15%O2	107.00	93.60	103.00	102.00	99.50	91.40	122.00	118.00	122.00	119.00	122.00	123.00	123.00	119.00
Wet Dry Scaler	1.07	1.07	1.07	1.07	1.07	1.07	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
15% O2 Factor	0.98	0.97	0.99	0.99	0.99	0.98	1.04	1.04	1.04	1.05	1.04	1.05	1.05	1.04
BS Calc Factor	412.00	417.00	425.00	426.00	427.00	421.00	451.00	451.00	452.00	455.00	458.00	456.00	461.00	461.00
Delivery Ratio	1.54	1.55	1.59	1.58	1.59	1.57	1.45	1.45	1.45	1.46	1.47	1.47	1.48	1.48
Scavenging Efficiency	0.79	0.79	0.80	0.80	0.80	0.79	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Trapping Efficiency	0.51	0.51	0.50	0.50	0.50	0.50	0.53	0.53	0.53	0.53	0.52	0.52	0.52	0.52
Trapped AF Ratio	26.50	26.30	26.20	26.30	26.20	26.30	29.20	29.00	29.00	29.00	29.00	28.90	29.00	28.80
Trapped Equivalence Ratio	0.62	0.63	0.63	0.63	0.63	0.63	0.56	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Engine Avg Peak Pressure[psi]	587.00	541.00	584.00	581.00	575.00	539.00	524.00	527.00	525.00	527.00	527.00	531.00	534.00	522.00
Engine Avg Peak Pres Std Dev[psi]	20.90	30.50	21.30	21.50	23.00	30.70	30.30	30.10	30.60	33.60	33.60	34.80	36.20	37.30
Engine Avg Peak Pres COV[%]	3.55	5.65	3.64	3.71	4.00	5.70	5.82	5.73	5.82	6.39	6.39	6.55	6.79	7.14
Engine Max Peak Pres COV Ch. #1[%]	3.89	6.99	4.10	4.26	4.76	6.57	7.92	6.39	6.39	7.24	7.24	7.46	7.97	8.15
Engine Min Peak Pres COV Ch. #4[%]	3.19	4.11	2.94	3.14	3.19	4.44	4.42	4.35	4.80	5.11	5.11	5.50	5.41	5.96
Engine Avg Peak Loc[*ATDC]	13.30	15.90	13.50	13.70	13.90	16.00	17.90	17.70	17.80	17.60	17.60	17.30	17.10	17.80
Engine Avg IMEP[psi]	73.30	73.50	73.30	73.40	73.20	73.40	73.70	73.80	73.80	73.90	73.90	74.00	73.90	74.00
Engine Avg IMEP COV[%]	1.55	1.63	1.64	1.56	1.57	1.58	2.02	1.78	1.76	1.93	1.93	1.83	1.96	1.98
Engine Max IMEP COV Ch. #1[%]	2.77	2.52	3.24	2.91	2.84	2.53	2.85	2.59	2.43	2.65	2.65	2.53	2.60	2.65
Engine Min IMEP COV Ch. #2[%]	0.88	1.15	0.82	0.76	0.88	0.92	1.30	1.15	1.18	1.31	1.31	1.25	1.47	1.57
Avg. Peak Ch. #1psi	592.00	555.00	593.00	591.00	587.00	546.00	547.00	520.00	520.00	526.00	526.00	525.00	536.00	517.00
Avg. Peak Ch. #2psi	594.00	524.00	579.00	569.00	561.00	536.00	522.00	528.00	528.00	539.00	539.00	544.00	521.00	520.00
Avg. Peak Ch. #3psi	587.00	534.00	581.00	587.00	576.00	529.00	497.00	527.00	527.00	516.00	516.00	529.00	531.00	527.00
Avg. Peak Ch. #4psi	577.00	553.00	581.00	576.00	577.00	544.00	533.00	532.00	525.00	526.00	526.00	527.00	549.00	523.00
Peak Std. Dev. Ch. #1psi	23.00	28.40	21.30	21.30	22.40	31.20	26.40	33.30	33.20	35.10	35.10	34.50	35.20	37.40
Peak Std. Dev. Ch. #2psi	20.40	36.60	23.70	24.30	26.70	32.60	31.80	31.00	30.70	35.10	35.10	36.20	41.50	42.40
Peak Std. Dev. Ch. #3psi	21.70	34.10	23.00	22.50	24.30	34.80	39.30	33.20	33.10	37.40	37.40	39.50	38.20	38.20
Peak Std. Dev. Ch. #4psi	18.40	22.70	17.10	18.10	18.40	24.20	23.60	23.10	25.20	26.90	26.90	29.00	29.70	31.20
Peak COV Ch. #1%	3.89	5.11	3.59	3.61	3.83	5.73	4.82	6.39	6.39	6.67	6.67	6.57	6.58	7.23
Peak COV Ch. #2%	3.43	6.99	4.10	4.26	4.76	6.07	6.10	5.86	5.82	6.52	6.52	6.66	7.97	8.15
Peak COV Ch. #3%	3.69	6.38	3.95	3.83	4.22	6.57	7.92	6.30	6.28	7.24	7.24	7.46	7.19	7.24
Peak COV Ch. #4%	3.19	4.11	2.94	3.14	3.19	4.44	4.42	4.35	4.80	5.11	5.11	5.50	5.41	5.96
Max Peak Ch. #1psi	657.00	632.00	648.00	661.00	647.00	633.00	615.00	598.00	616.00	624.00	624.00	627.00	625.00	619.00
Max Peak Ch. #2psi	651.00	606.00	645.00	637.00	629.00	625.00	609.00	607.00	598.00	620.00	620.00	623.00	620.00	616.00
Max Peak Ch. #3psi	640.00	623.00	650.00	649.00	644.00	627.00	618.00	624.00	623.00	617.00	617.00	628.00	626.00	640.00
Max Peak Ch. #4psi	625.00	620.00	621.00	633.00	635.00	608.00	600.00	595.00	607.00	593.00	593.00	599.00	625.00	599.00
Min Peak Ch. #1psi	513.00	466.00	512.00	505.00	511.00	291.00	338.00	376.00	398.00	404.00	404.00	394.00	391.00	352.00
Min Peak Ch. #2psi	527.00	294.00	477.00	474.00	464.00	381.00	401.00	429.00	423.00	395.00	395.00	429.00	328.00	328.00
Min Peak Ch. #3psi	510.00	418.00	488.00	521.00	501.00	295.00	353.00	399.00	384.00	371.00	371.00	387.00	366.00	382.00
Min Peak Ch. #4psi	514.00	474.00	521.00	507.00	488.00	456.00	436.00	448.00	438.00	430.00	430.00	420.00	433.00	389.00
Avg. Peak Loc. Ch. #1psi	13.40	15.40	13.10	13.30	13.50	15.80	16.90	17.90	18.00	17.60	17.60	17.50	17.10	17.90
Avg. Peak Loc. Ch. #2psi	13.10	16.90	13.90	14.30	14.70	16.20	18.10	17.70	17.70	17.10	17.10	16.70	17.80	17.90
Avg. Peak Loc. Ch. #3psi	13.60	16.80	14.00	13.90	14.20	17.00	19.40	17.80	17.80	18.30	18.30	17.70	17.60	18.00
Avg. Peak Loc. Ch. #4psi	13.20	14.70	13.00	13.20	13.20	15.20	17.30	17.20	17.50	17.40	17.40	17.20	16.00	17.50
Peak Loc. Std. Dev Ch. #1psi	1.08	1.39	1.01	1.03	1.07	1.62	1.26	1.48	1.51	1.57	1.57	1.63	1.60	1.70
Peak Loc. Std. Dev Ch. #2psi	0.98	1.96	1.13	1.19	1.35	1.69	1.45	1.34	1.43	1.61	1.61	1.63	1.97	2.03
Peak Loc. Std. Dev Ch. #3psi	1.07	1.79	1.11	1.10	1.15	1.77	1.92	1.43	1.54	1.74	1.74	1.85	1.73	1.79
Peak Loc. Std. Dev Ch. #4psi	0.94	1.18	0.90	0.97	0.98	1.28	1.14	1.10	1.18	1.24	1.24	1.36	1.40	1.47
Peak Loc. COV Ch. #1%	8.10	9.08	7.73	7.69	7.92	10.30	7.44	8.24	8.41	8.93	8.93	9.29	9.38	9.46
Peak Loc. COV Ch. #2%	7.47	11.60	8.13	8.32	9.19	10.40	7.99	7.57	8.04	9.40	9.40	9.75	11.00	11.30
Peak Loc. COV Ch. #3%	7.87	10.70	7.93	7.91	8.12	10.40	9.89	8.04	8.63	9.51	9.51	10.50	9.80	9.95
Peak Loc. COV Ch. #4%	7.10	8.01	6.95	7.32	7.40	8.43	6.59	6.42	6.75	7.14	7.14	7.88	8.76	8.43
AVG IMEP Ch. #1psi	73.00	73.30	72.20	72.70	72.60	73.00	74.10	74.00	74.00	74.30	74.30	74.10	74.10	73.90
AVG IMEP Ch. #2psi	72.50	72.30	72.50	72.30	72.30	72.50	73.10	73.00	73.10	73.60	73.60	73.40	72.70	73.10
AVG IMEP Ch. #3psi	80.00	80.10	80.50	81.10	80.30	79.90	78.60	79.60	79.60	79.10	79.10	79.90	79.90	80.30
AVG IMEP Ch. #4psi	67.60	68.40	67.80	67.40	67.70	68.20	68.70	68.40	68.50	68.70	68.70	68.70	68.80	68.70
IMEP STD DEV Ch. #1psi	2.02	1.85	2.34	2.11	2.06	1.85	2.11	1.92	1.80	1.97	1.97	1.88	1.93	1.96
IMEP STD DEV Ch. #2psi	0.64	0.83	0.59	0.55	0.64	0.67	0.95	0.84	0.86	0.96	0.96	0.91	1.23	1.30
IMEP STD DEV Ch. #3psi	0.79	1.17	0.86	0.86	0.82	1.20	1.90	1.51	1.53	1.74	1.74	1.64	1.65	1.56
IMEP STD DEV Ch. #4psi	1.05	0.94	0.98	1.02	1.03	0.94	1.03	1.02	1.04	1.07	1.07	1.02	1.01	1.08
IMEP COV Ch. #1%	2.77	2.52	3.24	2.91	2.84	2.53	2.85	2.59	2.43	2.65	2.65	2.53	2.60	2.65
IMEP COV Ch. #2%	0.88	1.15	0.82	0.76	0.88	0.92	1.30	1.15	1.18	1.31	1.31	1.25	1.69	1.77
IMEP COV Ch. #3%	0.99	1.46	1.07	1.06	1.02	1.51	2.42	1.89	1.92	2.20	2.20	2.05	2.07	1.95
IMEP COV Ch. #4%	1.5													

Appendix E

GMV

E.1 Repeatability Experimental Data

Data Point Name	Baseline 1	Baseline 2	Baseline 3	Baseline 4	Baseline 5	Baseline 6	Baseline 7	Average	std_dev	cov [%]
Start Time	45618.58333	45618.59931	45618.61736	45618.63472	45618.65139	45618.66944	45618.6875	0.00	0.00	0.00
End Time	45618.58681	45618.60278	45618.62083	45618.63819	45618.65486	45618.67292	45618.69097	0.00	0.00	0.00
Speed [rpm]	299.40	299.40	299.40	299.50	299.40	299.40	299.40	299.41	0.03	0.01
Torque [lb-ft]	7705.00	7705.00	7711.00	7703.00	7703.00	7708.00	7700.00	7705.00	3.34	0.04
Power [bhp]	439.30	439.20	439.60	439.30	439.10	439.40	438.90	439.26	0.21	0.05
Load [%]	100.00	100.00	100.10	100.00	100.00	100.10	99.96	100.02	0.05	0.05
Ambient Press [psia]	12.29	12.29	12.29	12.29	12.29	12.29	12.29	12.29	0.00	0.00
Ambient Temp [F]	64.39	64.61	65.83	63.66	64.23	61.48	59.19	63.34	2.09	3.30
Ambient Humidity [%]	14.57	14.22	13.09	14.46	15.73	19.18	21.24	16.07	2.77	17.23
Inlet Air Pres [in Hg]	37.70	37.70	37.70	37.70	37.70	37.70	37.70	37.70	0.00	0.00
Inlet Air Temp [F]	109.30	108.20	109.90	108.30	108.60	107.50	110.00	108.83	0.86	0.79
Inlet Air Humidity [%]	5.33	5.43	4.81	5.26	5.95	6.79	6.29	5.69	0.63	11.12
Inlet Air Flow [scfm]	2047.00	2049.00	2046.00	2051.00	2047.00	2049.00	2048.00	2048.14	1.55	0.08
IC Water Temp [F]	106.60	115.50	109.90	117.20	102.60	115.50	110.30	111.09	4.94	4.44
Exh Back Pres [in Hg]	35.20	35.20	35.20	35.20	35.20	35.20	35.20	35.20	0.00	0.00
Exh Cyl 1 Temp [F]	553.40	553.60	554.40	552.00	553.50	554.10	554.70	553.67	0.82	0.15
Exh Cyl 2 Temp [F]	620.80	619.50	620.40	619.90	618.80	619.90	618.90	619.74	0.68	0.11
Exh Cyl 3 Temp [F]	547.20	546.30	547.50	546.80	547.60	547.50	548.20	547.30	0.57	0.10
Exh Cyl 4 Temp [F]	614.90	616.60	616.20	615.00	614.80	615.70	614.20	615.34	0.79	0.13
Avg Exh Temp [F]	584.10	584.00	584.60	583.40	583.70	584.30	584.00	584.01	0.36	0.06
Stack Temp [F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel Flow [lb/hr]	166.50	166.60	166.60	166.60	166.40	169.70	169.60	167.43	1.41	0.84
Sensor NOx [ppm]	119.00	119.30	125.40	132.70	138.00	139.90	144.70	131.29	9.49	7.23
Sensor Lambda	11.59	11.60	11.65	11.74	11.77	11.78	11.82	11.71	0.09	0.73
Orifice Temp [F]	42.98	44.39	44.34	45.02	41.72	44.25	44.32	43.86	1.04	2.37
Eng Fuel Pres [psig]	500.00	500.10	500.00	500.10	500.10	500.00	500.00	500.04	0.05	0.01
Eng Fuel Temp [F]	78.34	79.58	78.64	79.47	79.74	78.84	78.54	79.02	0.52	0.66
JW Out Temp [F]	147.90	147.20	147.70	147.50	147.50	148.60	149.30	147.96	0.68	0.46
JW In Temp [F]	142.80	141.80	142.50	142.50	142.30	144.30	144.80	143.00	1.03	0.72
JW Flow [gpm]	491.90	493.50	492.70	492.00	491.30	490.50	488.90	491.54	1.40	0.28
Lube Press [psig]	30.81	30.93	30.82	31.88	32.66	32.69	32.70	31.78	0.85	2.67
Lube In Temp [F]	149.60	149.00	149.50	149.30	149.30	150.10	150.50	149.61	0.48	0.32
Lube Out Temp [F]	160.30	160.00	160.20	160.00	160.10	160.20	160.50	160.19	0.16	0.10
Thrust 1 Temp [F]	160.40	160.20	160.30	160.20	160.20	160.30	160.40	160.29	0.08	0.05
Thrust 2 Temp [F]	160.60	160.40	160.40	160.40	160.50	160.60	160.60	160.50	0.09	0.06
Main 2A Temp [F]	160.90	160.70	160.80	160.70	160.70	160.90	160.90	160.80	0.09	0.06
Main 2B Temp [F]	160.40	160.20	160.30	160.20	160.20	160.30	160.30	160.27	0.07	0.04
Main 3A Temp [F]	161.90	161.70	161.70	161.70	161.70	161.80	161.80	161.76	0.07	0.05
Main 3B Temp [F]	162.10	161.90	161.90	161.90	161.90	162.00	162.00	161.96	0.07	0.04
Main 4A Temp [F]	157.40	157.20	157.20	157.20	157.20	157.30	157.30	157.26	0.07	0.05
Main 4B Temp [F]	157.40	157.20	157.20	157.20	157.20	157.30	157.30	157.26	0.07	0.05
THC [ppmd]	905.60	907.80	900.00	907.80	910.80	912.00	911.30	907.90	3.86	0.43
NOx [ppmd]	27.69	27.50	27.89	27.21	26.63	26.67	26.46	27.15	0.53	1.94
NO [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO2 [ppmd]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2 [%d]	15.21	15.22	15.21	15.23	15.21	15.21	15.22	15.22	0.01	0.05
CO2 [%d]	2.94	2.94	2.95	2.93	2.93	2.94	2.93	2.94	0.01	0.20
CO [ppmd]	86.29	85.75	84.18	85.89	86.43	85.44	86.42	85.77	0.73	0.86
AFR Left	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AFR Right	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Flow [lb/hr]	9196.00	9207.00	9194.00	9214.00	9197.00	9206.00	9204.00	9202.57	6.67	0.07
Piezo 1 [F]	291.40	291.60	292.00	288.80	289.60	289.00	290.26	290.26	1.25	0.43
Piezo 2 [F]	311.10	311.20	335.00	369.90	372.70	373.70	310.20	340.54	28.47	8.36
Piezo 3 [F]	292.70	291.70	292.50	293.50	293.70	291.60	291.90	292.51	0.78	0.27
Piezo 4 [F]	311.30	311.70	312.90	312.10	311.80	311.80	309.60	311.60	0.94	0.30
Jacket Water Flow [gpm]	491.90	493.50	492.70	492.00	491.30	490.50	488.90	491.54	1.40	0.28
Jacket Water Valve Pos [%]	70.81	71.32	70.70	72.52	71.73	73.00	73.42	71.93	0.99	1.38
Supercharger Speed [%]	46.93	46.95	47.03	46.92	46.98	46.85	46.62	46.90	0.12	0.26
SC IC Temp Valve Pos [%]	70.19	75.00	69.73	75.00	68.83	75.00	70.68	72.06	2.60	3.60
Steam Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Back Pressure Valve Pos [%]	47.17	47.02	47.05	47.12	47.20	47.12	47.19	47.12	0.06	0.14
Load Valve Pos [%]	23.29	23.38	23.27	23.18	23.08	23.08	22.77	23.15	0.19	0.80
Dyno Water Flow [gpm]	246.30	247.40	247.00	246.40	247.00	246.70	246.50	246.76	0.37	0.15
Dyno Water In [F]	81.64	81.48	82.10	81.89	81.12	79.89	77.97	80.87	1.36	1.68
Dyno Water Out [F]	94.51	94.32	94.98	94.74	93.94	92.71	90.75	93.71	1.39	1.48
Dyno Inboard Bearing [F]	114.20	114.50	114.80	115.20	115.50	115.60	115.40	115.03	0.50	0.43
Dyno Outboard Bearing [F]	139.00	140.00	140.80	141.40	142.10	142.70	142.90	141.27	1.33	0.94
Air Flow Static Pressure [kPa]	136.20	136.20	136.20	136.30	136.10	136.20	136.20	136.20	0.05	0.04
Air Flow Diff Pressure [kPa]	7.80	7.85	7.83	7.88	7.77	7.85	7.84	7.83	0.03	0.42
Air Flow Temperature [C]	42.98	44.39	44.34	45.02	41.72	44.25	44.32	43.86	1.04	2.37
Ethane Flow [lb/hr]	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.00	0.77
Ethane Control Valve Pos [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane Pressure [kPa]	0.10	0.10	0.09	0.09	0.09	0.08	0.07	0.09	0.01	9.83
Ethane Temperature [C]	22.66	22.87	22.91	23.09	23.25	23.32	23.32	23.06	0.24	1.05
PCC H2 Flow [lb/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-891.00
PCC Nat Gas Flow [lb/hr]	-0.04	0.01	-0.07	-0.08	-0.06	0.00	0.00	-0.03	0.04	-101.83
PCC H2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Nat Gas Stpt	250.00	250.00	250.00	250.00	250.00	0.00	0.00	178.57	112.94	63.25

NOx Corr Factor	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.00	0.00
Lambda Setpoint	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
NOx Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Air Manifold Pres Stpnt [in Hg]	37.70	37.70	37.70	37.70	37.70	37.70	37.70	37.70	0.00	0.00
PCC 4 Temp [F]	90.63	91.20	91.78	92.20	92.65	93.09	93.42	92.14	0.93	1.01
NOx Correction Step	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NOx Averaging Time [s]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
NOx Feedback Time [s]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PCC Flow [lb/hr]	-0.04	0.01	-0.07	-0.08	-0.06	0.00	0.00	-0.03	0.03	-100.49
Sensor NOx @ 15% O2	28.71	28.53	28.91	28.29	27.63	27.67	27.46	28.17	0.54	1.91
ePCC Pressure [psig]	25.65	25.67	25.71	25.70	25.69	25.68	25.67	25.68	0.02	0.07
Fuel Flow Static P [kPa]	367.20	367.30	367.40	367.30	367.30	367.30	367.30	367.30	0.05	0.01
Fuel Flow Temp [C]	37.39	37.54	37.42	37.82	37.87	37.76	37.65	37.64	0.18	0.47
Fuel Flow Diff P [kPa]	17.46	17.50	17.53	17.89	17.48	17.48	17.43	17.54	0.15	0.83
Low Press Orifice Flow [lb/hr]	174.60	174.80	175.00	176.60	174.60	174.60	174.40	174.94	0.70	0.40
Air Flow Diff 0 offset	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.00
Ign Spark #	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign Timing [deg]	-2.63	-2.63	-2.63	0.00	0.00	0.00	0.00	-1.13	1.30	-115.47
Ign Offset Cyl 1 [deg]	-0.44	-0.44	-0.44	0.00	0.00	0.00	0.00	-0.19	0.22	-115.47
Ign Offset Cyl 2 [deg]	0.22	0.22	0.22	0.00	0.00	0.00	0.00	0.09	0.11	115.47
Ign Offset Cyl 3 [deg]	-0.22	-0.22	-0.22	0.00	0.00	0.00	0.00	-0.09	0.11	-115.47
Ign Offset Cyl 4 [deg]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ign 4-20 mA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EFI Hyd Sup Pres [psig]	500.00	500.10	500.00	500.10	500.10	500.00	500.00	500.04	0.05	0.01
EFI Hyd Ret Pres [psig]	28.74	31.31	31.54	31.06	30.84	31.32	31.26	30.87	0.89	2.89
LECM RPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOI Cylinder 1 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
SOI Cylinder 2 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
SOI Cylinder 3 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
SOI Cylinder 4 [dATDC]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Cylinder 1 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Cylinder 2 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Cylinder 3 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Cylinder 4 Bias Factor	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Global Duration [usec]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cylinder 1 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Cylinder 2 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Cylinder 3 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
Cylinder 4 Duration [usec]	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
LECM Fuel Temp [deg F]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LECM Fuel Pres [psia]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HP Meter Fuel Flow [lb/hr]	166.50	166.60	166.70	166.70	166.50	166.60	166.40	166.57	0.10	0.06
SC IC Coolant Out [C]	46.71	48.97	48.53	49.58	45.97	48.70	47.88	48.05	1.19	2.49
SC IC Coolant In [C]	41.47	46.41	43.28	47.32	39.22	46.38	43.48	43.94	2.74	6.23
SC IC Air 1 [C]	43.32	46.44	45.24	47.33	41.31	46.41	45.21	45.04	1.93	4.28
SC IC Air 2 [C]	76.66	77.83	78.25	77.83	77.95	76.75	75.66	77.28	0.87	1.12
SC ID Pres Diff	357.40	361.60	361.80	366.60	363.50	366.10	362.20	362.74	2.87	0.79
HPFI H2 Meter 1 Flow [g/hr]	16.03	16.04	16.11	16.20	16.22	16.23	16.28	16.16	0.09	0.56
HPFI H2 Meter 2 Flow [kg/hr]	10.06	10.09	10.34	10.66	10.90	10.98	11.21	10.61	0.42	3.95
HPFI H2 Meter 3 Flow [kg/hr]	9.83	9.82	10.12	10.43	10.64	10.78	10.96	10.37	0.42	4.06
HPFI H2 Meter 1 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 2 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Meter 3 Stpt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPFI H2 Total Flow [kg/hr]	35.93	35.95	36.57	37.29	37.76	37.99	38.45	37.13	0.93	2.50
HPFI H2 Total Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LP Orifice Fuel Flow [lb/hr]	174.60	174.80	175.00	176.60	174.60	174.60	174.40	174.94	0.70	0.40
LPFI H2 Meter Setpoint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LPFI H2 Meter Flow [kg/hr]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO (350,3000) 191C	19.92	19.25	19.84	19.28	19.82	18.12	18.72	19.28	0.62	3.21
NO2 (150) 191C (1of2)	18.34	17.86	18.44	18.12	18.13	17.84	16.65	17.91	0.55	3.10
NO2 (2000) 191C (2of2)	16.03	14.92	15.53	15.23	15.20	16.52	13.69	15.30	0.83	5.43
N2O (100,200,300) 191C	0.19	0.25	0.23	0.20	0.13	0.22	0.21	0.20	0.04	17.25
NH3 (300) 191C (1of2)	0.05	-0.01	0.12	0.04	-0.04	0.08	-0.02	0.03	0.05	168.22
NH3 (3000) 191C (2of2)	1.69	1.31	1.39	0.97	2.10	0.68	1.77	1.42	0.45	31.72
H2O% (25) 191C	5.89	5.90	5.89	5.89	5.92	5.96	5.98	5.92	0.03	0.58
CO2% (20) 191C (1of2) R4	3.05	3.05	3.06	3.06	3.07	3.03	3.06	3.06	0.01	0.44
CO (500) 191C (1of3)	107.60	107.00	103.80	110.00	106.70	104.90	106.80	106.69	1.83	1.72
CO% (1) 191C (2of3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	1.78
CH4 (3000) 191C (1of2)	704.80	714.60	694.10	716.00	712.10	708.20	709.20	708.43	6.85	0.97
CH4 (20000) 191C (2of2)	713.80	722.50	711.70	726.40	720.10	717.50	720.20	718.89	4.66	0.65
Ethane (500) 191C	71.09	71.75	70.51	72.40	72.44	69.94	68.64	70.97	1.28	1.81
Ethylene (100,3000) 191C	10.67	10.77	10.59	10.81	10.52	10.34	10.25	10.56	0.19	1.84
Acetylene (1000) 191C	1.09	0.59	0.74	0.48	0.69	0.48	0.51	0.65	0.20	30.69
Propane (200) 191C	10.08	10.20	9.75	10.18	9.93	9.99	9.85	10.00	0.16	1.57
Propylene (200,1000) 191C	0.78	1.08	0.47	0.75	0.90	1.19	1.09	0.89	0.23	25.86
Oil as octane (200) 191C	2.23	2.25	2.19	2.21	2.15	2.34	2.19	2.22	0.06	2.57
Formaldehyde (70,500) 191C	16.35	16.09	16.03	16.25	16.19	15.71	16.18	16.11	0.19	1.18
Acetaldehyde (1000) 191C	3.84	4.26	4.37	5.10	3.99	4.44	4.95	4.42	0.43	9.75
Formic Acid (100) 191C	0.62	0.56	0.52	0.65	0.64	0.57	0.66	0.60	0.05	8.28
MeOH (1000) 191C	0.38	0.28	0.59	0.23	0.40	0.33	0.44	0.38	0.11	28.44
CO% (10) 191C (3of3)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	9.64
CO2 low% (4) 191C (2of2)	3.01	3.01	3.01	3.01	3.02	3.02	3.01	3.01	0.00	0.13
1,3 butadiene (80) 191C	0.36	1.04	0.74	0.58	0.55	1.24	0.54	0.72	0.29	40.06
Temp (C)	190.20	190.20	190.20	190.30	190.30	190.20	190.30	190.24	0.05	0.03

Pressure (Atm)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.13
NOx autorange	38.26	37.11	38.28	37.40	37.95	35.96	35.37	37.19	1.05	2.84
CO autorange	107.60	107.00	103.80	110.00	106.70	104.90	106.80	106.69	1.83	1.72
CH4 autorange	704.80	714.60	694.10	716.00	712.10	708.20	709.20	708.43	6.85	0.97
NH3 autorange	0.05	-0.01	0.12	0.04	-0.04	0.08	-0.02	0.03	0.05	168.22
NOx autorange dry	40.65	39.43	40.67	39.74	40.33	38.24	37.62	39.53	1.11	2.80
CO autorange dry	114.30	113.70	110.20	116.90	113.50	111.50	113.60	113.39	1.97	1.73
CO2% autorange dry	3.20	3.20	3.20	3.20	3.21	3.21	3.20	3.20	0.00	0.15
N2O dry	0.20	0.26	0.24	0.22	0.14	0.23	0.23	0.22	0.04	17.24
NH3 autorange dry	0.06	-0.01	0.12	0.04	-0.04	0.08	-0.02	0.03	0.06	168.26
FIDeq THC ppmC	972.80	985.10	957.00	986.70	982.20	973.10	970.70	975.37	9.57	0.98
FIDeq NMHC ppmC	197.50	199.10	193.50	199.20	198.90	194.00	190.60	196.11	3.16	1.61
FIDeq NMNEHC ppmC	55.35	55.55	52.48	54.38	53.98	54.16	53.33	54.18	1.00	1.84
CO2% autorange	3.01	3.01	3.01	3.01	3.02	3.02	3.01	3.01	0.00	0.13
FTIR NMHC ppmC	215.60	217.00	211.50	217.30	217.00	211.70	208.90	214.14	3.14	1.46
FTIR NMNEHC ppmC	73.44	73.49	70.44	72.52	72.12	71.79	71.60	72.20	1.00	1.38
Igram DC	3.12	3.11	3.11	3.11	3.09	3.09	3.09	3.10	0.01	0.33
Igram PP	5.36	5.35	5.34	5.32	5.29	5.27	5.24	5.31	0.04	0.79
phase Angle	91.25	91.36	91.34	91.38	91.69	91.37	91.58	91.42	0.14	0.16
laser PP	8.64	8.67	8.48	8.65	8.41	8.58	8.63	8.58	0.09	1.08
laser DC	-5.89	-5.91	-5.92	-5.93	-5.94	-5.92	-5.93	-5.92	0.01	-0.23
Bad Scan counter	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
Centerburst Location	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	1130.00	0.00	0.00
Linearizer Check	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.75
SNR 2500	677.00	538.00	739.00	627.90	655.30	568.90	697.40	643.36	65.71	10.21
sBeam @ 2500	1.14	1.14	1.13	1.13	1.12	1.12	1.11	1.13	0.01	0.86
METHANE [%]	88.85	89.26	89.26	89.26	89.26	89.26	89.26	89.20	0.14	0.16
ETHANE [%]	8.86	8.70	8.70	8.70	8.70	8.70	8.70	8.72	0.06	0.67
PROPANE [%]	0.90	0.68	0.68	0.68	0.68	0.68	0.68	0.71	0.08	10.77
BUTANE [%]	0.20	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.01	3.13
PENTANE [%]	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.00	0.49
HEXANE [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.75
HEPTANE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89
CARBON MONOXIDE [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HYDROGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NITROGEN [%]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.25
OXYGEN [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARBON DIOXIDE [%]	1.12	1.11	1.11	1.11	1.11	1.11	1.11	1.11	0.00	0.19
WATER [%]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LHV Actual [kJ/kg]	49216.01	49232.72	49232.72	49232.72	49232.72	49232.72	49232.72	49230.33	5.85	0.01
LHV Actual [BTU/scf]	983.50	978.90	978.90	978.90	978.90	978.90	978.90	979.56	1.61	0.16
HHV Dry [kJ/kg]	53340.00	53370.00	53370.00	53370.00	53370.00	53370.00	53370.00	53365.71	10.50	0.02
HHV Dry [BTU/scf]	1088.00	1083.00	1083.00	1083.00	1083.00	1083.00	1083.00	1083.71	1.75	0.16
Gas Density [kg/m3]	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.00	0.18
Stioch A/F	16.48	16.49	16.49	16.49	16.49	16.49	16.49	16.49	0.00	0.02
Avg. Mol Weight	17.97	17.88	17.88	17.88	17.88	17.88	17.88	17.89	0.03	0.18
Cp [kJ/kg*K]	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13	0.00	0.07
Cv [kJ/kg*K]	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	0.00	0.04
Cp/Cv	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	0.00	0.03
C_avg#	1.13	1.12	1.12	1.12	1.12	1.12	1.12	1.12	0.00	0.20
AFR	55.30	55.20	55.30	55.30	55.20	55.10	55.30	55.24	0.07	0.13
Phi total	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.00	0.17
Air Flow [kg/hr]	4180.00	4170.00	4180.00	4170.00	4160.00	4250.00	4250.00	4194.29	35.80	0.85
Exh Flow [kg/hr]	4250.00	4250.00	4250.00	4250.00	4240.00	4320.00	4330.00	4270.00	35.05	0.82
BMEP [kPa]	477.00	477.00	478.00	477.00	477.00	478.00	477.00	477.29	0.45	0.09
thermal eff	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.00	0.82
BSFC [kJ/kW-hr]	11370.32	11383.60	11373.24	11381.01	11372.52	11590.14	11596.51	11438.19	98.23	0.86
BSEC[BTU/bhp-hr]	6656.40	6630.75	6624.72	6629.25	6624.30	6751.06	6754.77	6667.32	55.07	0.83
Abs Humidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.36
BSTHC [g/bkW-hr]	6.83	6.90	6.72	6.92	6.87	6.94	6.94	6.87	0.07	1.06
BSTHC [g/bhp-hr]	5.09	5.15	5.01	5.16	5.12	5.18	5.18	5.13	0.05	1.06
BS CH4 [g/bhp-hr]	3.89	3.93	3.81	3.92	3.88	4.00	3.96	3.91	0.05	1.40
BS NOx [g/bkW-hr]	0.82	0.79	0.82	0.80	0.81	0.78	0.77	0.80	0.02	2.12
BS NOx [g/bhp-hr]	0.61	0.59	0.61	0.60	0.60	0.58	0.57	0.60	0.01	2.12
BS CO [g/bkW-hr]	1.40	1.39	1.35	1.43	1.39	1.39	1.42	1.40	0.02	1.71
BS CO [g/bhp-hr]	1.03	1.04	0.99	1.05	1.01	1.05	1.03	1.03	0.02	1.98
BS CO2 [g/bhp-hr]	462.77	460.30	460.27	460.18	460.00	468.67	469.07	463.04	3.79	0.82
BS CO2c [g/bhp-hr]	560.11	558.53	555.49	558.20	557.10	568.55	568.00	560.85	4.87	0.87
THC @15%O2	1010.00	1020.00	993.00	1030.00	1020.00	1010.00	1010.00	1013.29	10.78	1.06
NOx @15%O2	42.20	40.90	42.20	41.30	41.90	39.70	39.00	41.03	1.16	2.84
CO @15%O2	119.00	118.00	114.00	122.00	118.00	116.00	118.00	117.86	2.29	1.95
Wet 2 Dry Scalar	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	0.00	0.00
15% O2 Factor	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	0.00	0.00
BS Calc Factor	438.00	437.00	438.00	437.00	436.00	444.00	446.00	439.43	3.62	0.82
Delivery Ratio	1.41	1.40	1.41	1.40	1.40	1.43	1.44	1.41	0.01	1.05
Scavenging Efficiency	0.76	0.75	0.76	0.76	0.75	0.76	0.76	0.76	0.00	0.39
Trapping Efficiency	0.54	0.54	0.54	0.54	0.54	0.53	0.53	0.54	0.00	0.44
Trapped AF Ratio	29.70	29.70	29.70	29.70	29.70	29.40	29.30	29.60	0.16	0.54
Trapped Equivalence Ratio	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.00	0.49
Engine Avg Peak Pressure[psi]	516.75	516.75	516.00	517.00	513.25	514.00	513.75	515.36	1.51	0.29
Engine Avg Peak Pres Std Dev[psi]	27.83	27.68	28.58	27.95	28.25	28.40	28.55	28.18	0.33	1.18
Engine Avg Peak Pres COV[%]	5.39	5.36	5.55	5.41	5.51	5.53	5.56	5.47	0.08	1.40
Engine Max Peak Pres COV Ch. #1[%]	5.99	5.79	6.19	5.85	6.12	6.14	6.37	6.06	0.19	3.08
Engine Min Peak Pres COV Ch. #4[%]	4.82	4.94	4.99	5.06	5.05	4.99	5.01	4.98	0.08	1.51

Engine Avg Peak Loc[*ATDC]	18.30	18.30	18.38	18.23	18.40	18.35	18.35	18.33	0.05	0.30
Engine Avg IMEP[psi]	73.70	73.60	73.75	73.80	73.73	73.68	73.43	73.67	0.11	0.16
Engine Avg IMEP COV[%]	1.75	1.76	1.73	1.70	1.78	1.75	1.75	1.75	0.02	1.21
Engine Max IMEP COV Ch. #1[%]	2.50	2.60	2.53	2.44	2.63	2.61	2.56	2.55	0.06	2.46
Engine Min IMEP COV Ch. #2[%]	1.07	1.03	1.07	1.16	1.17	1.07	1.10	1.10	0.05	4.36
Engine Avg MFB 10% *ATDC	6.84	6.84	6.90	6.81	6.91	6.89	6.88	6.87	0.03	0.50
Engine Avg MFB 50% *ATDC	14.88	14.90	14.98	14.88	15.08	15.03	14.98	14.96	0.07	0.48
Engine Avg MFB 90% *ATDC	29.88	29.83	29.93	29.98	30.30	30.18	30.05	30.02	0.16	0.52
Avg. Peak Ch. #1psi	510.00	512.00	511.00	510.00	503.00	507.00	506.00	508.43	2.97	0.58
Avg. Peak Ch. #2psi	519.00	522.00	521.00	523.00	518.00	524.00	520.00	521.00	2.00	0.38
Avg. Peak Ch. #3psi	523.00	516.00	518.00	523.00	522.00	514.00	520.00	519.43	3.29	0.63
Avg. Peak Ch. #4psi	515.00	517.00	514.00	512.00	510.00	511.00	509.00	512.57	2.66	0.52
Peak Std. Dev. Ch. #1psi	30.50	29.50	31.60	29.80	30.80	31.10	32.20	30.79	0.88	2.87
Peak Std. Dev. Ch. #2psi	25.90	25.80	26.60	27.10	27.30	26.20	26.10	26.43	0.54	2.06
Peak Std. Dev. Ch. #3psi	30.10	29.80	30.50	29.00	29.10	29.90	30.00	29.77	0.50	1.68
Peak Std. Dev. Ch. #4psi	24.80	25.60	25.60	25.90	25.80	26.40	25.90	25.71	0.45	1.74
Peak COV Ch. #1%	5.99	5.76	6.19	5.85	6.12	6.14	6.37	6.06	0.19	3.19
Peak COV Ch. #2%	4.98	4.94	5.12	5.19	5.28	4.99	5.01	5.07	0.12	2.31
Peak COV Ch. #3%	5.76	5.79	5.89	5.55	5.57	5.81	5.77	5.73	0.12	2.04
Peak COV Ch. #4%	4.82	4.95	4.99	5.06	5.05	5.17	5.09	5.02	0.10	2.07
Max Peak Ch. #1psi	587.00	592.00	597.00	596.00	597.00	602.00	596.00	595.29	4.33	0.73
Max Peak Ch. #2psi	598.00	595.00	587.00	592.00	597.00	587.00	605.00	594.43	5.95	1.00
Max Peak Ch. #3psi	599.00	625.00	593.00	601.00	598.00	600.00	607.00	603.29	9.66	1.60
Max Peak Ch. #4psi	594.00	593.00	604.00	576.00	585.00	583.00	581.00	588.00	8.82	1.50
Min Peak Ch. #1psi	391.00	356.00	387.00	402.00	369.00	418.00	376.00	385.57	19.25	4.99
Min Peak Ch. #2psi	426.00	425.00	436.00	428.00	422.00	407.00	420.00	423.43	8.21	1.94
Min Peak Ch. #3psi	411.00	388.00	413.00	412.00	428.00	426.00	400.00	411.14	12.92	3.14
Min Peak Ch. #4psi	406.00	412.00	421.00	424.00	427.00	424.00	414.00	418.29	7.15	1.71
Avg. Peak Loc. Ch. #1psi	18.60	18.50	18.60	18.50	18.80	18.60	18.60	18.60	0.09	0.50
Avg. Peak Loc. Ch. #2psi	18.20	18.10	18.20	18.10	18.20	18.10	18.20	18.16	0.05	0.27
Avg. Peak Loc. Ch. #3psi	18.40	18.60	18.60	18.30	18.50	18.60	18.50	18.50	0.11	0.58
Avg. Peak Loc. Ch. #4psi	18.00	18.00	18.10	18.00	18.10	18.10	18.10	18.06	0.05	0.27
Peak Loc. Std. Dev Ch. #1psi	1.41	1.37	1.45	1.40	1.41	1.47	1.45	1.42	0.03	2.28
Peak Loc. Std. Dev Ch. #2psi	1.16	1.19	1.22	1.24	1.23	1.21	1.17	1.20	0.03	2.34
Peak Loc. Std. Dev Ch. #3psi	1.29	1.33	1.38	1.37	1.35	1.36	1.40	1.35	0.03	2.46
Peak Loc. Std. Dev Ch. #4psi	1.18	1.23	1.20	1.28	1.21	1.25	1.24	1.23	0.03	2.53
Peak Loc. COV Ch. #1%	7.58	7.40	7.81	7.56	7.50	7.91	7.78	7.65	0.17	2.25
Peak Loc. COV Ch. #2%	6.40	6.57	6.72	6.81	6.77	6.69	6.42	6.63	0.15	2.31
Peak Loc. COV Ch. #3%	7.04	7.14	7.41	7.47	7.28	7.30	7.59	7.32	0.18	2.40
Peak Loc. COV Ch. #4%	6.55	6.88	6.65	7.09	6.69	6.90	6.83	6.80	0.17	2.48
AVG IMEP Ch. #1psi	74.00	74.20	74.20	74.10	73.90	74.00	74.00	74.06	0.10	0.14
AVG IMEP Ch. #2psi	72.80	72.80	73.10	73.70	73.30	73.90	72.80	73.20	0.42	0.57
AVG IMEP Ch. #3psi	80.00	79.20	79.60	79.70	80.00	79.00	79.50	79.57	0.35	0.44
AVG IMEP Ch. #4psi	68.00	68.20	68.10	67.70	67.70	67.80	67.40	67.84	0.26	0.38
IMEP STD DEV Ch. #1psi	1.85	1.93	1.88	1.81	1.94	1.93	1.89	1.89	0.04	2.35
IMEP STD DEV Ch. #2psi	0.78	0.75	0.78	0.85	0.86	0.79	0.80	0.80	0.04	4.56
IMEP STD DEV Ch. #3psi	1.43	1.46	1.42	1.33	1.36	1.39	1.37	1.39	0.04	2.99
IMEP STD DEV Ch. #4psi	1.11	1.07	1.06	1.05	1.08	1.06	1.08	1.07	0.02	1.71
IMEP COV Ch. #1%	2.50	2.60	2.53	2.44	2.63	2.61	2.56	2.55	0.06	2.46
IMEP COV Ch. #2%	1.07	1.03	1.07	1.16	1.17	1.07	1.10	1.10	0.05	4.36
IMEP COV Ch. #3%	1.79	1.84	1.78	1.67	1.70	1.76	1.72	1.75	0.05	3.09
IMEP COV Ch. #4%	1.63	1.57	1.55	1.54	1.60	1.56	1.61	1.58	0.03	1.97
MFB 10% Ch. #1*ATDC	7.16	7.15	7.20	7.12	7.32	7.24	7.27	7.21	0.07	0.92
MFB 10% Ch. #2*ATDC	6.56	6.51	6.58	6.52	6.54	6.50	6.49	6.53	0.03	0.47
MFB 10% Ch. #3*ATDC	6.85	6.96	7.01	6.85	6.92	6.99	6.90	6.93	0.06	0.86
MFB 10% Ch. #4*ATDC	6.78	6.74	6.82	6.76	6.85	6.84	6.84	6.80	0.04	0.60
MFB 50% Ch. #1*ATDC	15.20	15.20	15.20	15.20	15.60	15.40	15.40	15.31	0.15	0.95
MFB 50% Ch. #2*ATDC	14.60	14.50	14.60	14.50	14.70	14.50	14.50	14.56	0.07	0.50
MFB 50% Ch. #3*ATDC	15.10	15.40	15.40	15.10	15.20	15.50	15.20	15.27	0.15	0.97
MFB 50% Ch. #4*ATDC	14.60	14.50	14.70	14.70	14.80	14.70	14.80	14.69	0.10	0.67
MFB 90% Ch. #1*ATDC	29.20	29.10	29.10	29.20	29.70	29.50	29.60	29.34	0.23	0.79
MFB 90% Ch. #2*ATDC	29.20	29.00	29.30	29.40	29.90	29.30	29.20	29.33	0.26	0.89
MFB 90% Ch. #3*ATDC	31.40	31.70	31.50	31.40	31.50	31.80	31.40	31.53	0.15	0.47
MFB 90% Ch. #4*ATDC	29.70	29.50	29.80	29.90	30.10	30.10	30.00	29.87	0.21	0.69
Low Cycles [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #3*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low Cycles [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #1*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #2*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #3*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Misfires [%] Ch. #4*ATDC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Engine Avg MFB 10% Durations CAD	6.04	6.04	6.10	6.01	6.11	6.09	6.08	6.07	0.03	0.56
Engine Avg MFB 50% Durations CAD	14.08	14.10	14.18	14.08	14.28	14.23	14.18	14.16	0.07	0.51
Engine Avg MFB 90% Durations CAD	29.08	29.03	29.13	29.18	29.50	29.38	29.25	29.22	0.16	0.54

LIST OF ABBREVIATIONS

λ excess air ratio	BTE brake thermal efficiency
CH₄ methane	C celsius
CO₂e carbon dioxide equivalent	CA crank angle
CO₂ carbon dioxide	CAD crank angle degree
NO₂ nitrogen dioxide	CCV cycle-to-cycle variability
NO_x nitrogen oxides	CFD computational fluid dynamics
ϕ equivalence ratio	CFR cooperative fuel research
AFR air-fuel ratio	CO carbon monoxide
AHRR apparent heat release rate	COV coefficient of variation
AMR adaptive mesh refinement	CSU Colorado State University
aTDC after top dead center	DOE Department of Energy
BDC bottom dead center	EFI electronic fuel injection
BESA best efficiency spark advance	EPA Environmental Protection Agency
bhp brake horsepower	EPC exhaust port close
BS brake specific	ePCI electronic pre-chamber injector
BSEC brake-specific energy consumption	EPO exhaust port open
BSFC brake-specific fuel consumption	F fahrenheit
bTDC before top dead center	FE fixed embedding

FTIR Fourier-transform infrared spectroscopy	LS low speed
GHG greenhouse gas	MBT mean brake torque
GHGRP Greenhouse Gas Reduction Program	MCC main combustion chamber
GISS Goddard's Institute for Space Studies	MERP Methane Emission Reduction Program
HL high load	MFB mass fraction burned
HPFI high-pressure fuel injection	MGAV mechanical gas actuated valve
HRR heat release rate	MPa MegaPascal
HS high speed	NASA National Aeronautics and Space Administration
ICE internal combustion engine	NG natural gas
IMEP indicated mean effective pressure	NO nitrogen monoxide
IPC intake port close	OEM original equipment manufacturer
IPCC Intergovernmental Panel on Climate Change	P-V pressure-volume
IPO intake port open	Pa Pascal
K Kelvin	PCC pre-combustion chamber
kPa kilaPascal	PCP peak cylinder pressure
L liter	PP peak pressure
LB lean-burn	ppm parts-per-million
LL low load	psi pounds per square inch
LoPP location of peak pressure	RANS Reynold's-averaged Navier-Stokes
	RNG Re-Normalization Group

ROHR rate of heat release

TER trapped equivalence ratio

rpm revolutions per minute

THC total hydrocarbons

SAGE simulation and analysis of gas-phase
emulsions

TKE turbulent kinetic energy

SI spark ignited

U.S. United States

SOA start of admission

UHC unburned hydrocarbons

TDC top dead center

WEC Waste Emission Charge