Laser Ignition System

ABSTRACT

As the demand for higher engine efficiencies and lower emissions drive stationary, spark-ignited reciprocating engine combustion to leaner air/fuel operating conditions and higher in-cylinder pressures, increased spark energy is required for maintain stable combustion and low emissions. Unfortunately, increased spark energy negatively impacts spark plug durability and its effectiveness in transmitting adequate energy as an ignition source. Laser ignition offers the potential to improve ignition system durability, reduce maintenance, as well as to improve engine combustion performance.

This paper discusses recent engine combustion testing with an open beam path laser ignition system in a single-cylinder engine fueled by natural gas. In particular, engine knock and misfire maps are developed for both conventional spark plug and laser spark ignition. The misfire limit is shown to be significantly extended for laser ignition while the knock limit remains virtually unaffected. The results are discussed in detail as are other combustion related phenomena.

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1. INTRODUCTION

Fuel-lean combustion yields lower combustion temperatures which lead to lower NOx, and higher thermal efficiency due to lower heat losses. Lean mixtures of natural gas and air are relatively difficult to ignite. Also, as engine are forced to operate at higher power densities to further improve efficiency, the resulting increase in in-cylinder pressure at the time of ignition further impedes the quality of the electric spark discharge. Providing the necessary ignition energy to ignite low emission ultra-lean burn natural gas engines or highly efficient (high BMEP) engines severely limits spark plug life and creates a significant operating cost to the user. The lack of spark plugs with the required durability is quickly becoming the limiting factor for their development. The investigation of laser ignition's feasibility and performance is warranted by the potential to improve ignition system durability as well as to improve engine combustion and emission performance.

In contrast to conventional spark plug ignition, the point of ignition (spark) from a laser can be positioned at a considerable distance from potential heat sinks thus eliminating problems involving flame kernel heat transfer quenching common in spark plugs. High peak power laser pulses can be focused to a point to create strong sparks with high surface area. Laser-induced sparks can create instantaneous temperatures and pressures approaching 105 K and 103 atm, respectively with a sudden release of large quantities of reactive and excited chemical species. These extreme local conditions relative to the surrounding gas give rise to rapid, supersonic expansion and dissipation of energy in the form of heat thus providing for hydrocarbon bond breaking and radical species production.
In this study, we investigate combustion, knock and misfire limits of a single-cylinder engine operating with a laser ignition system. A comparison is made at the same engine operating conditions using a conventional spark system.

2. BACKGROUND
The history of laser induced ignition has progressed in three distinct directions. The first is the theoretical analysis of the breakdown phenomenon in which the physical ignition processes at the molecular level of the ignition event are investigated. The second is comprised of laboratory experiments conducted to gain insight and understanding of the ignition process and to help test and tune previously developed theories. The third consists of experiments and analysis performed on slider-crank piston engines to gauge the effectiveness of laser energy ignition on the engine operating parameters.

Past theoretical studies have lead to the statistical development and comparison of ignition delay and ignition probability models to experimental observations allowing the direct correlation of gas (usually methane) concentration to ignitability and ignition delay. Theoretical analysis has also led to the development of shock wave heating models, which aid in the explanation of the propagation of hot expanding gas, produced by the laser spark, that perpetuates the combustion process. Further theoretical examinations and the availability of experimental data have allowed researchers to develop more precise estimations of the minimum required laser induced breakdown energy required for ignition of combustible gases as well as focal length effects.

The method by which the laser induces breakdown in a combustible gaseous mixture has been divided into four basic processes: thermal heating, non resonant breakdown and photochemical excitation. Thermal heating takes place where the laser beam is incident on a solid target and induces excitation by heating the target or by exciting a rotational or vibrational modes of oscillation in the surrounding gas. Resonant breakdown occurs when the incident radiation ionizes the gas molecules and frees up electrons to absorb the radiation energy and in turn ionize other gas molecules leading to an avalanche breakdown.

Photochemical ignition occurs when a single photon dissociates a molecule thus allowing the ionized constituents to react with the surrounding gases. Non-resonant breakdown occurs when laser light is focused into a gas and the electrical field component of the light is strong enough to initiate the electrical breakdown of the gas. The non-resonant breakdown mechanism is the predominant factor governing the results presented in this work.

Experimental studies have been vital to extending the value of the theoretical examinations and in gaining a further understanding of the combustion process. Combustion vessel and open flame jet experimentation with methane (CH4) and other combustible gases have proven invaluable in the search for better fuel economy and emissions and provide a better understanding of the general ignition and combustion processes. Results of the laser spark combustion vessel studies has indicated a shortened ignition delay and higher peak pressures than an electrical spark ignited combustion event. Some studies investigated the ignition energy effect on the combustion process and found that for stoichiometric conditions the amount of energy had only a slight pressure dependence, however more energy was required for breakdown as the equivalence ratio approached either lean or rich conditions. Other studies have examined multi-point laser ignition as a means of gaining quicker combustion which allows for higher thermal efficiency due to reduced time for thermal losses during the combustion event and overall shorter travel distances for the flames [8,12]. The most promising result of the combustion vessel examination of laser ignition is the ability of the optical energy to ignite and more readily burn lean mixtures. This offers the potential for extending the lean limit in spark ignited engines which is, in part, the purpose of this study.

Laser ignition studies performed on internal combustion engines have allowed researchers to directly study the effect that laser induced ignition has on the operating and emissions characteristics of an operating engine. Past and recent studies have indicated a higher and quicker combustion pressure rise with laser ign
The experimentation performed by Dale et al., used a gasoline-fueled stoichiometric operating internal combustion engine for testing. The research performed by Ma et al., involved a motored slider crank mechanism that was not self sustaining. To date, prior work at NETL and in Austria represents the only natural gas-fueled lean-burn engine studies.

3. EXPERIMENTAL
Natural gas was used as the test fuel. Its chemistry was determined via gas chromatographic analysis during each test series to account for C/H ratio, heat of combustion as well as hydrocarbon makeup. The ignition system used in baseline testing was a commercial microprocessor based inductive ignition system designed for use on stationary gaseous-fueled industrial engines operating in a variety of applications. Timing was adjustable over a range of 50° CA and spark dwell was adjustable from 500 to 2,000 microseconds. A constant spark dwell of 1500 microseconds was used throughout testing.

4. DESCRIPTION OF TIMING SCHEMES
During the course of the investigation precise timing adjustments must be made in order to accurately compare the spark events. Careful attention must be taken to ensure that the two systems are timed properly with respect to the experimental test plan and identically, to each other, to ensure the quality of the combustion and emissions data collection. It is assumed and has been verified that the signal propagation times through the electrical systems are negligible, as compared to the overall time scale of the combustion event. The optical path length for the laser was also considered to pose a negligible effect on the operation of the laser ignition system.

The electric spark was timed and initiated via an ignition controller. This unit utilized a Hall Effect sensor to discern the cam position and a flywheel encoder to determine the crank position in order to properly time the electrical discharge. The cam sensor produced a logic low pulse, of a fixed width, that indicated the cam position at 180 degrees before top dead center encoder to initiate the spark at the proper time. A side-gap type spark plug was used for the electrical discharge testing. The side-gap plug style was chosen over the standard J-Gap plug due to slight perceived advantages in startup and cyclic variability performance. A picture of the side gap spark plug can be found in Figure 1. For scale, the threads are standard 14 mm spark plug threads. The plugs were torqued for repeatable alignment in the engine but were not indexed for any necessary alignment direction due to the type of combustion chamber (torroidal) used in this study. In the torroidal bowl, the nearly centrally located plug, was located at the center of the swirl axis.

Figure 1: Side Gap Spark Plug

The timing, as well as the spark energy, was also independently measured and verified via compensated voltage and current probes. These probe types have been used and described in previous ignition studies. The voltage and current waveforms were then displayed with respect to time on a digitizing oscilloscope. The current transformer was mounted on the engine near the ignition system and the spark plug wire was allowed to pass through the center of the probe. The current probe converted the current pulses through the spark plug wire into a voltage waveform that was directly proportional to the amount of current flowing in the secondary wire lead. The voltage probe was connected directly to the center conductor of the secondary spark plug wire. The current and voltage measurement setup are illustrated in Figure 2.

Figure 2: Current and Voltage Measurement Setup for Electrical Spark Engine Testing.

The voltage, current, and cam trigger waveforms are simultaneously displayed on
the oscilloscope. For simplifying this description, only the cam trigger and the current waveform are used to determine the amount of time between the cam trigger signal and the flow of current across the spark plug gap indicating the start of the ignition discharge inside the combustion chamber. The simplified waveforms are illustrated in Figure 3. The timing delay is measured under test.

The laser spark ignition system utilized the same Hall Effect sensor as the electrical discharge ignition system. The signal from the cam sensor is tapped and fed into a digital delay/pulse generator which acted as a compatible interface between the hall sensor and the pulse delay generator used to trigger the laser. The trigger pulse delay was calculated from the cam signal event, given the speed and timing advance (oCA btdc) desired. The laser system used for this project had a delay time from triggering of the device to laser light exiting the output aperture of approximately 180 microseconds, a pulse width of 3-5 nanoseconds and a pulse to pulse jitter of +/- 0.5 nanoseconds [26]. The most significant of the above properties is the delay time which is approximately two orders of magnitude smaller than the time scale of the ignition process.

Figure 3: Cam Trigger and Current Probe Waveforms
In order to measure and verify the laser spark system ignition timing a 1064 nm reflectively coated high energy laser mirror was used as the final turning mirror for the open beam laser spark setup. A fiber optic cable with a collimator was fixed above the mirror to capture the light from the spark and combustion and couple it into a photo multiplier tube (PMT) detector assembly for sensing and amplification. The PMT included a UV filter in front of its aperture that only allowed the spectrum between 300 and 400 nanometers. This ultraviolet (UV) pass filter ensured that the light that fell upon the sensor was indeed from the spark and/or the combustion event due to the presence of OH- radicals in the spark or the combustion flame. The timing system for the laser spark ignition setup also doubled as a way to indicate laser spark integrity in the engine. The voltage waveform signal produced by the PMT was then fed into the digitizing oscilloscope along with the cam trigger signal to determine and verify the correct ignition timing which is very similarly depicted in Figure 3.

5. SPARK ENERGY MEASUREMENT
In order to more accurately compare the possible differences between the two ignition systems it was necessary to have an accurate measurement of the amount of energy each system delivers to the cylinder. The energy measurement system devised for the electrical discharge system used the high voltage probe and current transformer discussed previously and found in Figure 1. The waveforms were displayed on the digitizing oscilloscope and analyzed using the method found in SAE J973 surface vehicle recommended practice publication. The energy delivery measured for the spark plug was found to be approximately 68 mJ per spark. Energy loss to the electrodes or energy losses due to radiative mechanisms are unknown. The spark plug did not contain an internal resistor. A sample of the experimental waveforms for both voltage and current can be found in Figure 4.

Figure 4: Electrical Current spark voltages and Waveforms used for measuring spark energy.

The energy measurements for the laser spark system were carried out with two laser energy meters. The first energy meter was placed behind a 2.1% beam splitter to provide online laser pulse energy readings throughout the experimentation. The second was used for the characterization of the optical system from test to test. The complete open-beam system was found to have a total energy loss of approximately 25-30%. The laser plug without the final turning mirror was found to have a loss of approximately 15%. The loss percentage for the final focusing lens in the laser plug was thought to be high, as compared to the rest of the system, due to the fact that it was not anti-reflection coated, on either surface, due to the elevated operating temperatures that it would encounter. The tests were performed with input energies that would produce no less than 50 mJ per pulse onc
Due to engine head geometric constraints the laser plug window lens pressure barrier was not placed within the 14 mm spark plug threads but had to be recessed approximately 24 mm inside the engine adaptor. The focal length of the final lens was 30 mm so that the focus (and spark) would occur approximately 6 mm below the top of the combustion chamber well away from any combustion chamber surfaces. Figure 6 contains a photograph of the laser plug window lens pressure barrier mount that is sealed into the engine adaptor approximately 24 mm above the combustion chamber. The clearance volume is actually 1% greater due to the laser plug. This effectively reduces the compression ratio from 13.3 to 13.2. This slight difference is discussed in terms of its minimal impact in these combustion analyses.

The laser spark ignition system optical bench and laser plug setup is illustrated in Figure 7. The abbreviations are as follows: HR-High Reflector, EM-Energy Meter, BE-Beam Expander, PCX-Plano Convex Lens, PCC-Plano Concave Lens, ADJ. BE-Adjustable Beam Expander. The beam expander on the output of the alignment laser was used to set the alignment beam to approximately the same beam diameter as the high energy Nd:YAG laser beam, which aided in the overall alignment process. The adjustable beam expander was used to vary the beam diameter of the high energy laser beam. The beam diameter for the YAG laser had a direct relationship on the energy density of the laser beam for a given amount of energy per pulse. Therefore the beam diameter for the laser energy just prior to reaching the last mirror, which is mounted directly onto the laser plug, was held constant at approximately 4-4.5 millimeters.

Throughout the engine testing the laser alignment was monitored by the PMT module. The optical collection system and PMT module were connected the same way as previously described. The output signal was also connected to monitoring equipment consisting of a boxcar averager and a PC for data interpretation. The averager was setup to integrate the PMT signal for a particular window of time which only encompassed the ignition pulse. The integrated values were then averaged over three samples and displayed via custom software interface. Along with the average values the standard deviation and raw values were also displayed. By recording the average light output over the course of engine testing, it was very easy to determine any trends in the mean or standard deviation that would indicate a gradual misalignment. When a misalignment was detected, very careful and accurate on the fly adjustments were made between tests to ensure adequate alignment and repeatable energy delivery for subsequent testing at energy levels greater than 50 mJ per pulse. The threshold of 50 mJ per pulse represents an energy threshold above which additional energy has no apparent effect on the ignition event.

6. ENGINE TEST BED

The engine facility is located at the U.S. Department of Energy's National Energy Technology Laboratory (NETL) in Morgantown, WV. The engine, a Ricardo Proteus, is a two-valve, four-cycle engine with a toroidal combustion bowl in the piston
The engine has a bore and stroke of 130 mm (5.1 in) and 150 mm (6 in) respectively and a swept volume of 1.997 liters (122.4 cu in) with a compression ratio of 13.3:1. Startup and engine load are controlled by a 420-volt, 100 hp (75 kW), DC dynamometer. Turbocharger conditions are simulated by using a filtered, dried, preheated and pressurized site air source and by using a backpressure control valve in the exhaust. Air/fuel mass ratio is determined via mass flow measurement of both engine inlet air and natural gas fuel. A UEGO exhaust oxygen sensor is also used as a separate reference. NG mass flow was measured using a coriolis mass flow meter. The flow rates used in this study are always well into the mid to upper range of the instrument thus ensuring low measurement error. Engine airflow is measured by using a viscous flow meter which was flow proven using a secondary NIST traceable flow standard. An uncertainty analysis of A/F mass ratio using the RMS method indicates 95% uncertainty error of approximately 1.5% of the indicated A/F mass ratio. This is less than the reported accuracy of the UEGO sensor. For this reason as well as our experience that the UEGO signal contains much more noise, we chose the mass flow measurement based A/F mass ratio as our standard. Subsequent analysis of the fuel was required for determination of lambda (\(?\)) or equivalence ratio (\(f\)). This was obtained via GC analysis.

7. HIGH-SPEED IN-CYLINDER DATA ACQUISITION
A rapid response piezo-electric pressure transducer is used along with a high-speed digital data acquisition system, triggered by a crankshaft mounted incremental encoder. This study employs the use of a multiple channel indicating system for recording cylinder pressure in relation to crank angle. Data is recorded at an overall throughput of up to 1 MHz. An uncooled gallium orthophosphate (GaPO4) piezoelectric pressure transducer is used for in-cylinder pressure measurement. GaPO4 is chosen for its thermal stability at high temperatures. A piezo amplifier is used to condition the output of the transducer. The piezoelectric transducer is ranged at 200 bar and has a linearity of less than \(\pm0.3\%\) full scale output at operating temperature. Its thermal sensitivity shift in the 200°C to 300°C range is less than \(\pm0.5\%\). Its cyclic temperature drift and indicated mean effective pressure (IMEP) stability over a 10 hour test period is less than \(\pm0.4\) bar and 2% respectively. Engine speed and crank angle (oCA) position are measured using a high-precision optical encoder mounted on the crankshaft end. Crank angle measurement is selectable down to 0.05 oCA. Thermodynamic values based on cylinder pressure and heat release using a simplified first law analysis and employing a constant polytropic coefficient is used as recommended by Randolf.

8. TEST PROCEDURE
The engine and associated equipment were allowed to reach equilibrium conditions with inlet air temperature, oil temperature and coolant temperature held constant at 40°C, 80°C and 80°C respectively and engine speed at 30 rev/sec (1800 rpm).

8.1 KNOCK AND MISFIRE TESTING
Timing was held constant at 320 btdc. A constant fueling/variable boost approach was taken for the knock and misfire investigation. Fuel rate was held constant at 1.33, 1.58 and 1.82g/s for BMEP levels of 8, 10 and 12 bar respectively. Boost was adjusted over a range of 26 to 117 kpag to control air/fuel ratio. To approach knock or misfire the boost was adjusted in an ascending manner toward misfire limit or a descending manner toward the knock limit. Each approach to misfire (or conversely knock) was followed by an approach to the opposite limit in blocks of two approaches. Three groups of two approaches were randomized and these were further blocked into three groups of load level (8 bar, 10 bar and 12 bar BMEP). By randomizing the approach order and load order, the effect of sequential engine conditioning was minimized.
8.2 VARIABLE TIMING COMBUSTION TESTING
Both spark plug and laser testing were blocked into three groups of 20 tests (4 levels of ?, 5 levels of spark timing). In each group, ? was randomized into four blocks. Within each block of ?, five timing points of 20, 24, 28, 32 and 360 btdc were also randomized giving 60 separate engine operating conditions. At each change in engine test condition, the engine was allowed to stabilize and combustion data were recorded. The time required for stabilization was maintained constant for each set point change, thus aiding measurement repeatability. Inlet air, oil and coolant temperatures were kept constant at each key state condition. By varying timing and equivalence ratio, the response of emissions and combustion provide an understanding of the combustion and ignition phenomena.

9. RESULTS AND DISCUSSION

9.1 GENERAL
Engine startup was readily obtained using the laser spark system. Aligning the laser beam perpendicularly to the window-lens-mirror assembly (tangential to the radial engine axis) minimized the effect of the radial and axial engine vibration components. The optical pressure boundary in the laser lens/plug/window assembly remained clean during engine operation periods of up to 10 hours. We have accumulated approximately 100 hours of laser spark engine operation to date, but we have not attempted single period operation of more than 10 hours after which time we examine the window assembly. It appears that the laser beam energy delivered to particles near the window assembly is sufficient to prevent deposition. However, abnormal operating conditions or significantly longer operational periods required for commercial operation have not been purposely investigated. Optical damage due to the high power density of the laser over a longer period of time should also be investigated to provide the knowledge base for development of durable components necessary for this application.

9.2 KNOCK AND MISFIRE LIMITS
The regularity of combustion in spark ignition engines is often characterized by examining the cyclic variation of the indicated mean effective pressure (IMEP). IMEP is derived from dynamic engine pressure measurement. It may be thought of as the cyclic work divided by the displaced volume. Variations in IMEP are closely associated with hydrocarbon emissions as well as thermal efficiency. Generally, misfire starts to occur at IMEP coefficient of variation (COV) levels of approximately 5%-10%. An IMEP COV of 10% was chosen as the definition of the misfire margin for these studies.
Engine knock is a debilitating phenomenon characterized by rapid combustion (detonation) usually in the end gas region. The resulting shock waves breakdown the thermal boundary layers within the cylinder and the resulting high heat transfer to the piston, cylinder liner and valves result in damaging surface temperatures in these components. Engine knock must be avoided in any engine system and understanding and identifying the engine operating characteristics that produce knock is paramount. High frequency pressure oscillations are measured in the engine to define the knock limit. The pressure voltage signal from rapid response piezoelectric pressure transducer is high pass filtered at 4000 Hz. Each engine cycle of this filtered signal was examined to determine its maximum peak amplitude. These peaks are then averaged over 200 engine cycles to determine the measurement denoted in this work as P_HighMaxAve. The P_HighMaxAve threshold value of 1 bar is used as the knock margin criteria.
The data, for either knock (P_HighMaxAve) or misfire (IMEP COV), is generally spread around the misfire or knock limit. The six blocked data points are fitted in a first order linear regression model with the 95% confidence interval plotted to predict the threshold crossing point. An example of this type of plot is given below in Figure 8.
Figure 8: Scatterplot showing equivalence ratio as a function of IMEP COV for laser operation at 12 bar BMEP and 320btdec timing. The 0.95 confidence intervals are plotted about a linear curve fit with $r^2=0.9233$.

The graph shows the six data points, the linear regression line crossing the 10% IMEP COV line at an equivalence ratio of approximately 0.5122 and 95% confidence boundaries at approximately 0.5110 and 0.5135. This method was followed for all of the misfire data and similarly for the knock data except that a value of one bar for the $P_{HighMaxAve}$ was used as the threshold criteria.

There are two levels of engine operation (knock or misfire) with six replications each, three load conditions (8, 10, and 12 bar BMEP) and two ignition systems (laser and spark plug) for a total of 72 data points. These six replications are averaged and plotted with their associated 95% confidence error bars on an equivalence ratio/BMEP plot in Figure 9. A visual inspection of Figure 9 indicates an extended misfire limit; however the knock limit is generally unchanged as will be explained.

Figure 9: Knock and Misfire Boundaries for Laser and Spark Plug Engine Operation at 320btdec Spark Timing

Upon first inspection of the knock limit, with the exception being 8 bar BMEP knock, there is a statistically significant difference between laser and spark plug ignition ($p<0.05$). However, the actual start of combustion (SOC) is also significantly ($p<0.05$) different. Considering all of the knock data, the average laser ignition SOC begins 2 CA prior to the spark plug ($-14.5$ oCA vs. $-12.5$ oCA). This represents an approximate 7% reduction in ignition delay time. In fact, a difference of 2oCA is fairly typical of each BMEP as indicated by the histogram plot in Figure 10 below.

Figure 10: Histogram, with mean frequency distribution, of Start of Combustion (SOC) for each load and ignition source.

A normal distribution fit to the ignition delay data is also plotted along with the histograms. Note that the spread in the ignition delay data, which may be represented as its variance or standard deviation, is visually less (i.e. the spread in the normal distribution curve is narrower) for the laser spark system. In fact, when considering the data obtained at the misfire limit, the coefficient of variation (COV) of the ignition delay is 4.0% for the spark plug and 1.9% for the laser system. The decrease in ignition delay and its lower COV for the laser ignition system is further indication of the robustness of the ignition event and subsequent flame kernel formation. Further study of the laser ignition event is warranted to understand the spark/flame kernel interaction mechanism and for insight into potential additional benefits that may be gained.

Since it is well known that engine knock is dependent on spark timing, hence SOC , the spark timing was adjusted or spark plug operation to account for the 2oCA retard in SOC experienced with the spark plug over that of the laser at 320btdec spark timing. Operation was repeated at 10 and 12 bar BMEP. The results are given in Figure 11.

Even with the 2oCA timing advance, the average spark plug SOC was still 0.8oCA retarded over that of the laser at 320btdec timing. From Figure 11, the spark plug knock limit converged toward the laser knock limit, however, there was still a significant difference at both load conditions ($p<0.05$).
Minor differences in 10-90% burn duration and the remaining differences in SOC may account for this difference. Temperature, pressure, fuel rate, speed (hence turbulence) and equivalence ratio were constant throughout testing. Combustion phasing is the suspected mechanism that would account for the differences in knock limit.

There were similar differences (p<0.05) in SOC at the misfire boundary. Since it is well known that engine misfire is also dependent on spark timing, hence SOC, the spark timing was adjusted for spark plug operation to account for the 20°CA retard in SOC experienced with the spark plug over that of the laser at 32°btoc spark timing. Operation was repeated at 10 and 12 bar BMEP. The results are plotted in Figure 12.

The average SOC for the spark plug at 32°btoc spark timing was 1° after top dead center (atdc) while for laser operation at 32°btoc spark timing it was 0.5°btoc. This is a difference of 1.5°CA. Again using a 20°CA advancement in timing at 10 and 12 bar BMEP for the spark plug revealed a significant change in the misfire limit (p<0.05), however, the change moved the limit to higher equivalence ratio. This phenomenon occurred in spite of the fact that the average SOC moved from 1°atdc to 1.5°btoc in moving spark timing from 32°btoc to 34°btoc. Irregardless, the difference in misfire limit is very strong. These results clearly indicate lean misfire limit extension via laser ignition in an operating lean-burn natural gas engine.

10. VARIABLE TIMING/EQUIVALENCE RATIO

Once ignition has occurred in a self-sustaining combustible mixture, the flame propagation rate for a given engine condition (pressure, temperature and air/fuel ratio) is dependent on the fuel chemistry and turbulence level. As engine speed, hence turbulence, is held constant and fuel chemistry changes are negligible (for example, the average molecular weight of NG varied by no more than 0.24% over the test period), any differences with burn rates must be due to combustion phasing. In the experiment, the duration between the point of 10% mass fuel burned and 90% mass fuel burned (10-90% burn duration) is a good representation of the flame propagation rate. The average 10-90% burn duration is given in Figure 13 for the full data set as a function of SOC. The burn duration averaged 1.4°CA longer for the laser (35.6°CA vs 37.0 for the laser) while the SOC for minimum 10-90% burn duration is 4.5°btoc for the laser and 3.8°btoc for the spark plug. Note that the test conditions for the figures in this section are given in the test procedures section under Variable Timing Combustion Testing.

Although the burn duration is slightly longer for the laser, the location of the point at which 90% of the mass fraction of fuel is burned is slightly earlier f
or the laser. Burn rate and its affect on combustion phasing, can account for differences in many engine parameters. For example, engine thermal efficiency is well correlated with SOC and the 10-50% burn duration (Correlation coefficients of -0.91 and -0.72 respectively).

Figure 13: 10-90% Burn Duration as function of SOC. The minima for 10-90% burn duration are located at -4.5oCA and -3.8oCA for the laser and spark plug respectively.

Shorter burn duration also allows for less time for heat transfer during the combustion period and initial expansion stroke. Engine thermal efficiency for the laser and spark plug are given in Figure 14 as a function of SOC and in Figure 15 as a function of 10-50% burn duration. Engine thermal efficiency (ENTHEF) reaches its maxima for laser ignition at an SOC of 8.7obtdc (38.7%) and for spark plug ignition at 7.1obtdc (39.4%). The 10-50% burn duration data in Figure 15 indicates a crossover as the spark plug burn duration apparently decreases beyond that for laser ignition at approximately 12.8oCA duration.

Figure 14: Engine Thermal Efficiency (ENTHEF) for Laser and spark plug operation as a function of start of combustion (SOC).

Figure 15: Engine Thermal Efficiency (ENTHEF) for laser and spark plug operation as a function of 10-50% burn duration.

11. CONCLUSIONS
Engine combustion testing was performed with an open beam path laser ignition system in a single-cylinder engine fueled by natural gas. In particular, engine knock and misfire maps were developed for both conventional spark plug and laser spark ignition. To further understand combustion related phenomena associated with laser spark ignition, a series of engine tests with varying timing and air/fuel ratio were also conducted. The following conclusions may be SOC, at equal spark timing, over the conventional spark plug system. The engine knock limit exhibits a slight decrease due to laser ignition. This is probably due to small differences in combustion phasing and remaining differences in SOC as ignition delay was significantly shorter in the laser spark system. Burn duration was slightly longer for laser spark combustion. The resultant phasing differences are likely manifested in the slight decrease indicated in the brake thermal efficiency values for laser ignition.

12. DEFINITIONS, ACRONYMS AND ABBREVIATIONS
Table 1 provides the definitions and associated parameters for abbreviations or acronyms used within this manuscript.

Table 1: Definitions, Acronyms and Abbreviations
14. REFERENCES CITED
Ma, J.X., Ryan, T.W., Buckingham, J.P.,
Nd:YAG Laser Ignition of Natural Gas.
Schmieder, R.W.,
Laser Spark Ignition and Extinction of a Methane-Air Diffusion Flame.
Ma, J.X., Alexander, D.R., Poulain, D.E.,
Laser Spark Ignition and Combustion Characteristics of Methane-Air Mixtures,
Combustion and Flame.
Weinberg, F.J. and Wilson, J.R.,
A Preliminary Investigation of the Use of Focused Laser Beams for Minimum Ignition
Energy Studies,
Tran, P.X.,
Laser Spark Ignition: Experimental Determination of Laser-Induced
Breakdown Thresholds of Combustion Gases,
Optics Communications.
Ronney, P.D.,
Laser verses conventional ignition of flames,
Optical Engineering.

Reference: http://www.seminarprojects.com