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Experimental Investigation of Augmented Spark Ignition of a LO_2/LCH_4 Reaction Control Engine at Altitude Conditions

Julie Kleinhenz, Charles Sarmiento, and William Marshall
Glenn Research Center, Cleveland, Ohio

June 2012

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Abstract

The use of nontoxic propellants in future exploration vehicles would enable safer, more cost-effective mission scenarios. One promising “green” alternative to existing hypergols is liquid methane (LCH_4) with liquid oxygen (LO_2). To demonstrate performance and prove feasibility of this propellant combination, a 100-lbf LO_2/LCH_4 engine was developed and tested under the NASA Propulsion and Cryogenic Advanced Development project. A series of three test programs were performed at the NASA Glenn Research Center Altitude Combustion Stand in a low pressure environment: specific impulse and impulse bit performance tests (covered in previous publications) and ignition margin testing.

High ignition energy is a perceived drawback of this propellant combination; one goal of the ignition margin test program was to explore ignition performance and reliability versus delivered spark energy. The other goal was to examine the sensitivity of ignition to spark timing and repetition rate. Three different exciter units were used with the engine’s augmented (torch) igniter. Captured waveforms indicated spark behavior in hot fire conditions was inconsistent compared to the well-behaved dry sparks (in quiescent room air). This suggests that rising pressure and flow rate increase spark impedance and may at some point compromise an exciter’s ability to complete each spark. If encountered prior to ignition, the reduced spark energies of such quenched deliveries results in more erratic ignitions and adversely affects ignition probability. Although nonessential, sparks delivered after ignition were particularly susceptible to quenching. This occurred when the exciter output, or driving voltage, was inadequate to tolerate the accelerated pressure rise effects on spark impedance. However, ionization created by the flame did appear to lower the breakdown voltage, thus decreasing the high-voltage pulse requirements to initiate sparks after ignition.

The timing of the sparks relative to the pressure/flow conditions also impacted the probability of ignition. Sparks occurring early in the flow could trigger ignition with energies as low as 1 to 6 mJ, though multiple, similarly timed sparks of 55 to 75 mJ were required for reliable ignition. Delayed spark application and reduced spark repetition rate both correlated with late and occasional failed ignitions. An optimum time interval for spark application and ignition therefore coincides with propellant introduction to the igniter and engine. Shifts of ignition timing were manifested by changes in the characteristics of the resulting ignition.

1.0 Introduction

Next generation propulsion systems are currently being developed to enable future exploration missions. Cryogenic bi-propellants are attractive for their high performance. Traditionally hydrogen has been favored as the fuel, but its thermal storage requirements (low boiling point) create additional vehicle dry mass, reducing potential payload capacity. Hypergolic propellants, such as hydrazine, are a common alternative but are highly toxic. The rigid handling and containment procedures are not cost efficient. Hydrocarbon fuels, methane in particular, are gaining appeal for their high performance potential (when paired with oxygen) and moderate thermal storage requirements. This combination is also nontoxic, enabling simpler handling and storage methods. Methane is also available from local resources on some exploration destinations, such as Mars. For example, it could be produced from the atmospheric Carbon Dioxide on Mars using Sabatier processes.

Prior work with this propellant combination is limited, so a goal of the NASA Propulsion and Cryogenic Advanced Development (PCAD) project was to examine the feasibility and performance characteristics of these systems (Refs. 1 to 3, and 13). A 100-lbf Reaction Control Engine (RCE) was developed by Aerojet Corporation to study liquid oxygen/liquid methane (LO_2/LCH_4) combustion (Ref. 4) and was tested at altitude conditions using the Altitude Combustion Stand (ACS) at NASA Glenn Research Center. In particular, there was interest in demonstrating repeatable and reliable ignition of an engine for a wide range of propellant inlet temperatures.

The first series of tests (Refs. 5 and 6) explored the specific impulse (I_{sp}) performance with burn times up to 7 s. The engine met its I_{sp} goal, and demonstrated that performance improved as propellant temperature increased or as mixture ratio decreased, which is consistent with previous studies. The next test series examined the impulse bit (I-bit) performance for pulsed mode operation (Ref. 7). Again, the engine met its goals, achieving I-bits <4 lbf-s with pulse durations under 80 ms. As many as 30 consecutive pulses at a 5-percent duty cycle were repeatedly achieved.

In the final test series, which will be covered in this document, ignition characteristics were examined during engine hot fires at altitude conditions. Since one of the perceived drawbacks of this propellant combination is a need for higher ignition energy (relative to oxygen/hydrogen), the goal was to explore ignition performance and reliability versus delivered spark energy. Aerojet adopted an augmented, or spark torch, igniter configuration in this engine to enable better control of the spark environment (versus a direct spark ignition within the main chamber), as demonstrated in their previous oxygen/hydrocarbon engine designs. Based on this previous engine work (Refs. 8 and 9), it was expected that 40- to 50-mJ sparks would be required to obtain reliable ignition of the oxygen/methane propellants, especially at low inlet temperatures where liquid/liquid spray injection can prevail. A Variable Energy Exciter unit was developed in-house to explore the ignition energy limits. Exciters used in the previous I_{sp} and I-bit test series were also tested in order to help interpret the ignition behaviors observed in those tests. Here, the exciter units were instrumented to obtain high fidelity spark current and voltage waveform information. By coupling such data to the pressure and flow measurements in the engine, it was possible to identify the ignition spark in terms of energy and timing.

Nomenclature

ACS	Altitude Combustion Stand
BDV	breakdown voltage
DSO	digital storage oscilloscope
HV	high voltage
I_{sp}	specific impulse(s)
I-bit	impulse bit (lbf-s)
MR	Mixture Ratio (oxidizer/fuel)
PCAD	Propulsion and Cryogenic Advanced Development
PCFS	Propellant Conditioning Feed System
PLC	Programmable Logic Controller
RBD	reverse breakdown
RCE	Reaction Control Engine
sps	sparks per second
Vdc	Volts direct current
VEE	Variable Energy Exciter

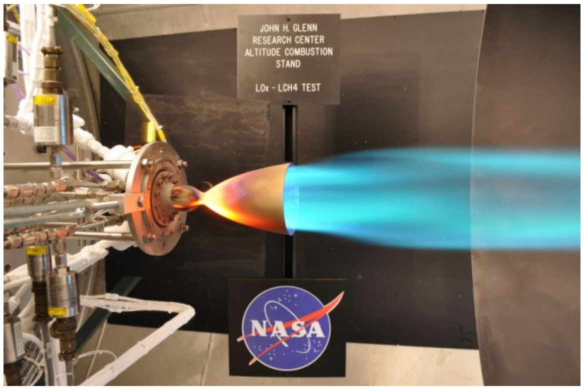

Figure 1: The 100-lbf RCE operating at altitude conditions in the ACS facility.

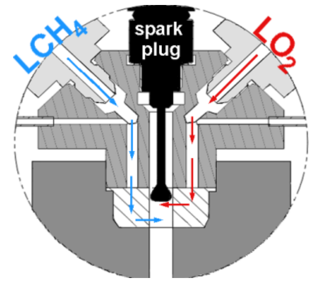

Figure 2: A schematic of the igniter cavity.

2.0 Hardware

2.1 Reaction Control Engine

All ignition tests were performed using the Aerojet 100-lbf RCE (Ref. 4 and Figure 1). This radiative-cooled 45:1 columbium nozzle was designed to operate at a nominal mixture ratio of 2.5 and a chamber pressure of 175 psia. The details of the configuration are described in detail in Reference 5. With the exception of exciter units, the tested engine configuration remained unchanged throughout all the test series.

The engine is designed for use with an augmented, or spark torch, igniter with a capacitive discharge exciter (Figure 2). Ignition therefore consists of lighting the spark torch, which then ignites the main chamber. Unlike traditional augmented ignition systems, propellant flow to the igniter in this engine was integrated into the main feed system and not independently controlled. This approach minimized engine mass and manifold volumes, while reducing dribble volumes and increasing pulse performance. Therefore, ignition tests necessarily involved a main chamber burn. Approximately 2.5 percent of the total propellant flow to the engine was directed to the igniter cavity, where the nominal mixture ratio was approximately 1.82.

2.2 Test Facility

The ACS facility is located at the NASA Glenn Research Center. The recently restored facility became operational with this RCE test program. The facility can accommodate a 2000-lbf-class engine with chamber pressure up to 1000 psia and can accommodate liquid and gaseous oxygen, liquid and gaseous hydrogen, LCH_4, and other hydrocarbon propellants. A water spray cart and a water-cooled diffuser/multistage ejector system are used to condense the products of combustion and draw vacuum conditions inside the test capsule to simulate altitudes up to 130,000 ft.

The system is well instrumented, with over 100 channels dedicated to the research hardware alone. The data is logged at 1000 Hz using a National Instruments module. Data can be streamed to multiple displays simultaneously for quick turnaround. All system timing is controlled using a Programmable Logic Controller (PLC) which has a 10 ms resolution.

To accommodate the propellant temperature control needed in this investigation, the standard feed system was replaced with two propellant conditioning feed systems (PCFSs). These were developed by Sierra Lobo, Inc., to provide precise control of propellant conditions (Refs. 10 and 11). The oxygen PCFS utilized liquid nitrogen as the conditioning fluid whereas the methane PCFS used liquid argon with a recirculation loop.

Table 1: Specifications of the three exciters used in the Ignition Margin Program.

	Variable Energy Exciter (VEE)	Unison	Champion
Spark rate, sparks/sec	Variable, 125 to 250	200	100
Delivered spark energy,[a] mJ	30 to 50	55 to 65	12
Spark discharge time, µs	100 to 400	200	50
Time to first spark, ms	21	6.5	3 to 9

[a]As measured for quiescent air spark gap contents.

2.3 Exciter Units

As mentioned, three exciter units were used in the course of the ignition margin test program. All were variants of the capacitive discharge ignition type. The first unit, called the Variable Energy Exciter (VEE), was developed in-house to permit energy and spark rate variation. The other two units, made by Champion and Unison, had been used in the I_{sp} performance and I-bit test programs, respectively. The three exciters provided a good mix of exciter types and capabilities. Note that the Champion and Unison units were chosen based on availability, and the results presented here should not be construed as an endorsement of these units. The same spark plug was used with all exciters.

All units were instrumented with voltage and current probes, which were located on the ignition cable near the exciter. The same cable was used for all exciters. These probes were not vacuum compatible, therefore, the exciters were located outside the vacuum vessel. The high-voltage ignition cable penetrated the vessel within a pressurized sleeve to prevent corona discharge. The voltage and current data were captured by a digital storage oscilloscope (DSO) for high-speed waveform data acquisition.

Historically, spark ignition systems have been operated using spark trains, which is a series of sparks triggered over a specified time. This is done to ruggedize the system against variations in propellant flow. The presence of a flow field, especially a turbulent one, can reduce ignition probability for a single spark (Ref. 12). For most of these tests, the exciter was active for 60 ms, where the number of sparks occurring in that time varied depending on the spark rate of the exciter (Table 1).

2.3.1 Variable Energy Exciter

The VEE was an unsealed, breadboard version ignition unit. It used capacitor energy storage and discharge to drive unipolar sparks at its output. Distinct from most such capacitive discharge designs, it employed inductive (transformer flyback) high-voltage (HV), or ionization pulse generation to initiate the sparks. The VEE’s open-circuit HV pulses (approx. 20 kV) were reduced to 9 to 10 kV at the spark plug due to the capacitive loading of the ignition cable. Once initiated, sparks were driven by the voltage and energy available from a 4.4-µF storage capacitor via a resistor-inductor path bypassing the output transformer. Available spark energy was adjusted by variation of the storage capacitor charge voltage (160 to 280 Vdc (volts direct current)) using a digipot control. After transmission losses, the corresponding stored energy (56 to 172 mJ) yielded a 30 to 50 mJ delivered spark energy range at the spark plug tip in benchtop tests. Deliberate selection of lower (<160 V) charge voltages and stored energies was avoided due to an inadequacy of such low capacitor voltages to sustain sparks until most of the stored energy could be discharged. The duration of individual sparks, or spark discharge time, increased as the spark energy setting was decreased. Spark rate was adjusted by variation of capacitor charging duty cycle and ionization pulse repetition rate using a second digipot. The VEE was powered by a preapplied 28 Vdc input and triggered to fire by a separate command signal that resulted in a first spark 21 ms later.

This exciter unit was developed specifically for this ignition test program. With variable spark rate and energy, ignition margins (limits) could be explored. This unit was not used in any prior engine testing, but had undergone checkout testing in a vacuum environment.

2.3.2 Champion

The Champion exciter (model number CH92111, which was a modified 305131 single channel design) was a hermetically sealed, vacuum-compatible, capacitive-discharge unit. Operable from a 26 to 30 Vdc input, it generated bipolar sparks from a capacitor with 94 mJ of stored energy. Delivered spark energies were 12 mJ, as measured at the spark gap in room air conditions. The unit produced a spark rate of 100 sparks per second (sps) as it periodically generated ionization pulses rated for 20 kV, but reduced to 9 to 10 kV at the spark plug due to ignition cable loading. It was triggered to fire (commanded) by application of 28 Vdc input power that resulted in a somewhat jittery 3 to 9 ms time to first spark.

This exciter unit was used during the I_{sp} test program where several nonignition events occurred (Ref. 5). Potential causes for these nonignition events were sought using the additional instrumentation available in this ignition program.

2.3.3 Unison

The Unison exciter (part number 500700–1) was another hermetically sealed, vacuum-compatible, capacitive-discharge unit. It had a welded 1.37 m length of shielded ignition cable that was spliced to the unshielded facility cable. From a 23 to 36-Vdc input voltage, it delivered 55 to 65 mJ unipolar sparks from a capacitor with 160 mJ of stored energy at a rate of 200 sps. Sparks were initiated by the unit's 13-kV ionization pulses (5 to 6 kV at spark plug due to cable loading). The Unison was commanded by a switched application of 28 Vdc input power, yielding a 6.5 ms time to first spark.

This exciter unit was used during the I-bit test program, where a few nonignition events were observed (Ref. 7). Like the Champion exciter, the Unison exciter was characterized here with additional instrumentation to explore possible causes for these events.

2.4 Spark Plug and Ignition Cable

A single modified Champion spark plug that featured a button-tipped electrode with a 0.64-mm igniter annular spark gap was used for all exciters. It was connected to the exciters using a 3.65-m, unshielded, silicone-insulated, and atmosphere-sleeved ignition cable. Cable shielding was eliminated to facilitate insertion of diagnostic probes and to avoid its substantial capacitive load on the exciter output. Despite this measure, the remaining capacitive load on the exciter outputs by the long cable still significantly attenuated open-circuit HV pulse magnitudes delivered to the igniter spark gap. Spark current return path was provided by a low-inductance engine and facility ground structure to which the exciters were externally bonded.

2.5 Diagnostics

A Tek P6015A, 1000:1 voltage probe was used to monitor spark discharge voltage. Its large attenuation ratio was needed to protect the oscilloscope amplifiers from the multi-kV breakdown, or ionization, pulses that initiate each spark. Because the probe was not vacuum compatible, it was necessary to locate it exterior to the test cell, hence at the exciter output rather than at the spark plug, during tests under altitude conditions. The voltage drop across this ignition cable length for the 30- to 80-V sparks were verified to be negligible (≤2 V) by room air gap spark calibrations using a pair of probes that monitored exciter and spark gap ends of cable.

Spark current pulses were monitored with a Pearson model 110 current transformer threaded by a single pass of the ignition cable. It had a 0.1 V/A output and 20 MHz bandwidth. Spark pulses were verified to be well within the probe's current-time maximum limit, which ensures that the coil does not saturate or distort the waveform.

Waveform data were recorded using a Tek 3054B, 500-MHz bandwidth, four-channel DSO with a 9-bit vertical resolution and a memory length of 10,000 samples per channel. Both exciter output (discharge voltage and current) and input signals were logged. DSO vertical and horizontal time scales were set to capture spark trains with adequate resolution to discern individual spark details. As an example, the 4 ms/division, or a 40-ms span used for most runs corresponded to a 250-kHz sample rate. For the Unison and VEE exciters, seven sparks were captured for each spark train. For the champion, only one or two sparks could be captured with adequate resolution. The oscilloscope was triggered by the spark command signal from the PLC so that the data could be synchronized with the engine data. However, the accuracy of this synchronization was limited to the nearest millisecond as a result of the lower 1 kHz engine data sample rate.

3.0 Experiment

3.1 Test Procedure/Operations

Ideally, the engine would be fired in pulsed operation mode, where multiple ignition opportunities would be possible per test. However, the data from the digital oscilloscope could not be output to memory quickly enough to permit this. Therefore, each ignition test was a single engine cycle. Typically, 10 tests could be performed in 1 day, though as many as 23 were possible depending on the test matrix. Once ignited, the burn duration was 1 s at a simulated altitude of 75,000 to 120,000 ft (0.2 to 0.5 psia).

Timing of exciter command signals was constrained by the facility PLC to 10 ms steps coinciding with, or offset from, the thruster valve commands that activated propellant flow. As with the previous test series (Refs. 5 and 7), the LO_2 flow was initiated first, with LCH_4 flow initiation 10 ms later. The exciter was commanded using four different timing scenarios: simultaneous with the LCH_4 valve command, 10 ms after LCH_4 valve command, 20 ms after LCH_4 valve command, and simultaneous with the LO_2 valve command. These scenarios were chosen to help identify the igniting spark within the spark train and to explore different ignition behaviors. Note that in the previous test series, the exciter was always initiated prior to propellant flow (10 ms before the LO_2 valve command).

Because spark timing and ignition events occur on time scales of milliseconds, it is important to consider the system response. Figure 3 and Table 2 illustrate the timing relationships accounting for the response times of the exciter and flow valves. Feedback signals from the propellant valves are shown by the dashed lines. The rise in voltage (nonzero) indicates the valve has been commanded open, while the dip (approx. 10 ms later) indicates the valve response. When the voltage leveled off about 6 ms later, the valve was fully open. This coincided with a pressure rise in the propellant manifolds, shown by the thick solid lines, which confirmed that propellant was flowing. The vertical lines show the exciter command timings for the Unison and VEE. The symbols represent the average first spark times for the VEE (circle) and Unison (square), while the arrowed lines indicate the time to first spark for each timing scenario. As can be seen, the different exciter command timings yielded first sparks that occurred at various stages of propellant flow, including during LO_2-only flow, and various mixed propellant conditions.

Historically, spark ignition systems have been operated using spark trains, which is a series of sparks triggered over a specified time. This has presumably been done to ruggedize the system against variations in propellant flow and local mixture ratio. Typically, the exciter was commanded ‘on’ for 60 ms. The number of sparks occurring in that time varied depending on the spark rate of the exciter and the time to first spark. Spark command durations longer than 60 ms were not used in order to avoid potential late, or hard-start ignitions, particularly when employing delayed spark initiation timings. In addition, DSO memory limitations would have precluded capture of any longer spark trains with adequate resolution to discern individual spark details.

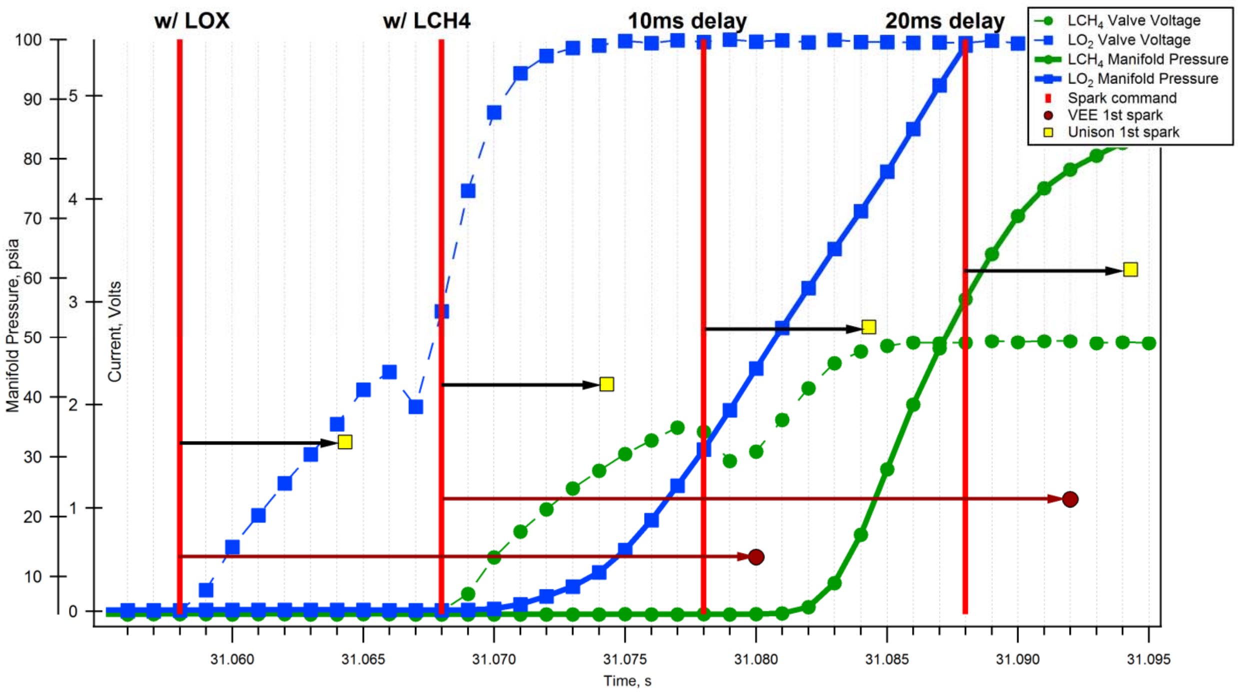

Figure 3: The command timing of the propellants and exciter are shown. The dotted lines represent the valve feedback signals. It takes approx. 15 ms from the command until the valve is fully open. The solid lines show the manifold pressure response, where an increase indicates propellant flow. The vertical lines indicate the exciter activation and the arrows represent the time until the first spark occurs.

Table 2: Command times are shown for propellant flow (top) and exciter (bottom). All numbers were taken from the data, as opposed to the programmed setpoint. Test to test variations are ±2 ms for any given value. The champion exciter experienced variability in response time and will be discussed later.

Propellants	**Valve command, s**	**Valve full open, s**	**Manifold pressure rise, s**
Oxygen	31.058	31.073	31.071
Methane	31.068	31.084	31.082

Spark commands	**Command signal, s**	**VEE first spark, s**	**Unison first spark, s**
With oxygen command	31.058	31.080	31.064
With methane command	31.068	31.092	31.074
10 ms after methane command	31.078	NA	31.084
20 ms after methane command	31.088	NA	31.094

3.2 Test Matrix

A total of 87 runs were performed during the ignition margin test program using the three exciter units. While the exciter conditions were varied according to each exciter’s capabilities, the engine conditions were kept constant. The mixture ratio, which is governed by the run tank pressures, was set according to the I_{sp} test program. Therefore, if the engine was fired long enough to reach steady-state flow conditions, these setpoints would result in a mixture ratio (O/F) of 2.5. Likewise, the propellant timing scenarios were retained from the previous test programs; the oxidizer flow was initiated 10 ms prior to the fuel, and the fuel was shut down 20 ms after the oxidizer. The oxidizer lead was shown in early testing to reduce the risk of hard starts, and was maintained as a safety precaution. Likewise, the fuel lag on

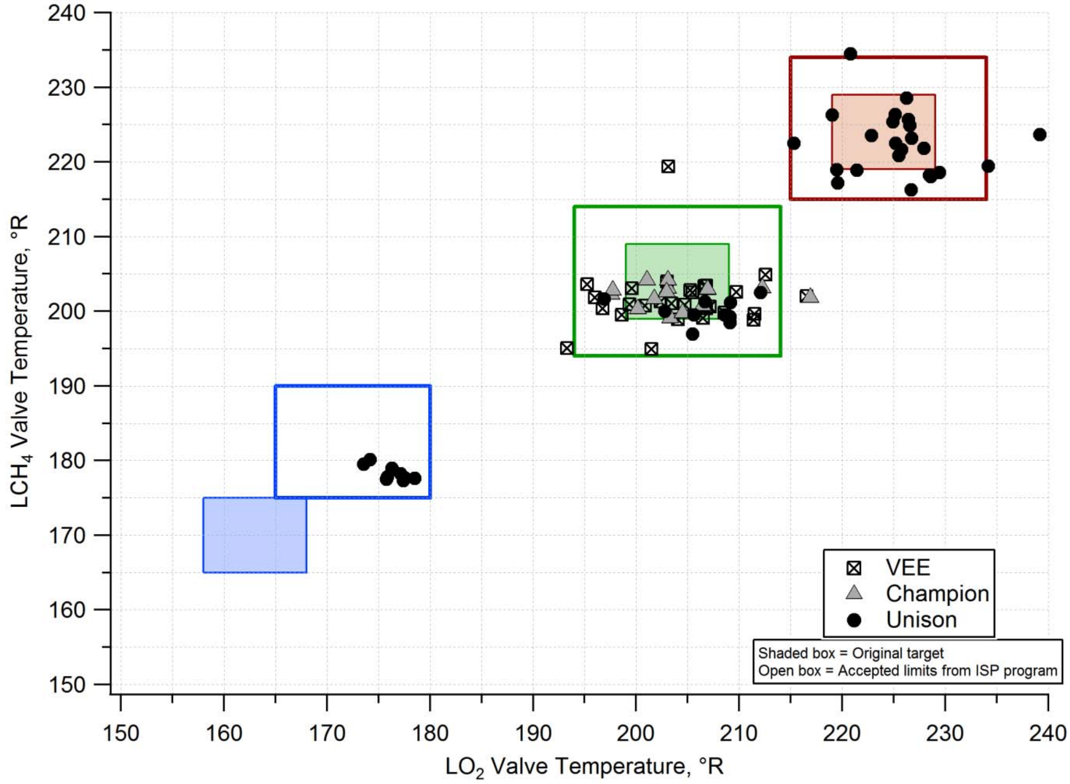

Figure 4: The propellant temperature conditions, as measured at the thruster valve, are shown for all tests. These are average temperatures over the ignition interval: starting at the initiation of methane flow (31.082 s) and ending 60 ms later. The target temperature ranges are shown, including the expanded target from the specific impulse test program (Ref. 7).

shutdown reduced the risk of oxidation on the hot chamber walls. During tests with the Unison exciter, propellant temperature (measured at the fire valve) was varied among the previously established setpoint conditions; cold (170 °R LCH_4 and 163 °R LO_2), nominal (204 °R), and warm (224 °R). Figure 4 shows the temperatures that were achieved for the tests.

The test record for all tests is listed in Appendix A. The VEE was used in 28 hot fire tests over the course of 2 days, encompassing run numbers 293 to 329 (span includes cold flow and calibration runs). During the first day, only the energy setpoint was varied, while both energy and spark rate were varied the second day. The Champion exciter was tested for just 1 day, with 15 hot fire tests encompassing run numbers 330 to 348. Since only one to two sparks could be captured within the data resolution of the oscilloscope, the oscilloscope timing was the sole variable in these tests. The final 3 test days employed the Unison exciter, using a different propellant temperature each day. A total of 44 hot fire tests were performed with run numbers from 349 to 401. Spark command timing was the varied within each test day.

3.3 Data Reduction Method

3.3.1 Energy Calculation

Spark energies were calculated using the discharge voltage and current data from the digital oscilloscope. The following method is applicable for the VEE and Unison exciters, but is not practical for the Champion exciter due to the difficulties of adequately sampling and processing its short-duration bipolar waveform. Although single spark capture could be resolved using a high DSO sample rate, the Champion's erratic time to first spark in this application, the low duty cycle of its spark pulse trains, and the limited DSO memory (10 kS/waveform) precluded a workable approach for obtaining spark energies in ignition test runs (section 4.2).

Figure 5 shows an example waveform for a single spark from the Unison exciter. (A VEE waveform was similar**.**) The discharge voltage (circles) and current (triangles) waveforms for a single spark are shown at the bottom. A spark discharge is indicated when the current level rises above its zero level. Energy was determined by calculating and then integrating the power level during this period, as shown in Equation (1) (where V is voltage, I is current, and t is time). For the Unison exciter, the “zero” level for the current was 3 amps (Figure 5 , upper right insert) and for the VEE it was 0.4 Amps. (Note that the Unison signal was unfiltered resulting in a higher zero offset.)

$$E_{spark} = \int (V * I)\, dt \tag{1}$$

All data reduction was performed using Igor™ graphing software with its programming interface. Power was calculated only when the current exceeded a threshold value (zero offset), and the resulting array was scanned to determine spark times. A spark began when the power level exceeded zero for more than two time steps and ended when power dropped below zero for two time steps. These regions were then integrated to obtain energy for each spark. The squares at the top of Figure 5 show the power calculation for each time step and the shaded region indicates the integration time. The energy for this spark was 63 mJ.

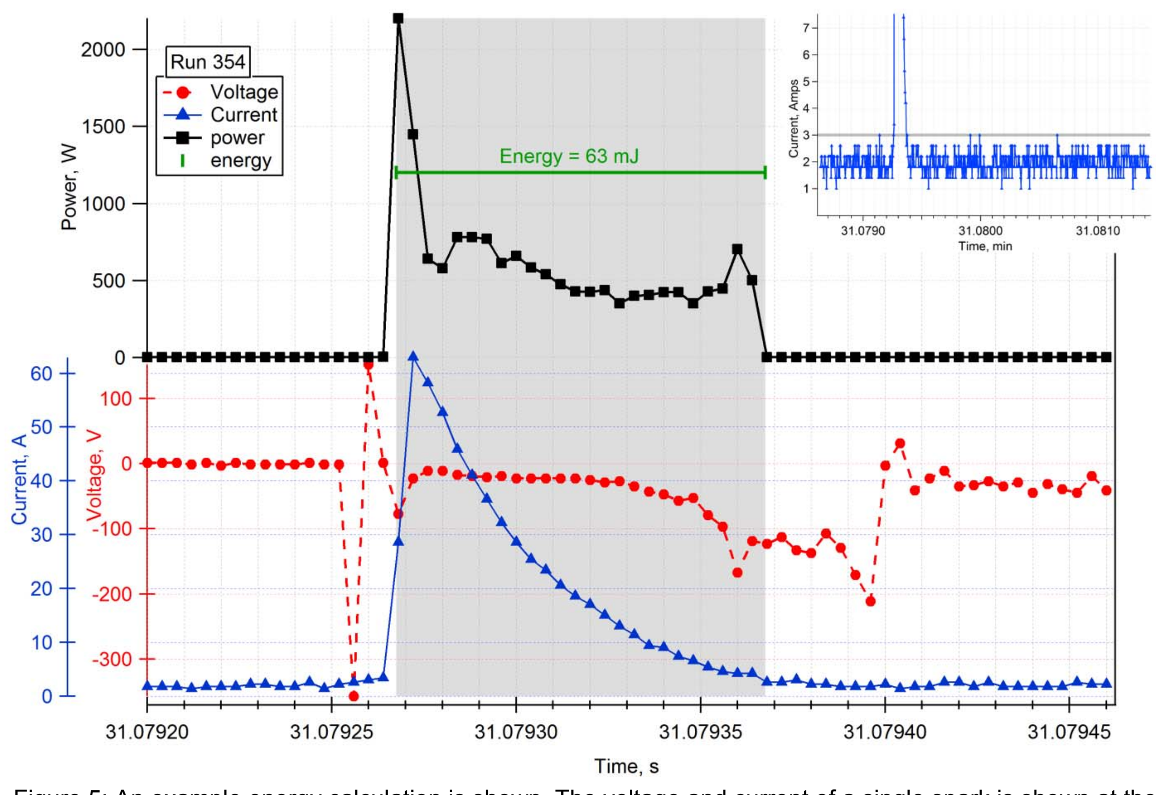

Figure 5: An example energy calculation is shown. The voltage and current of a single spark is shown at the bottom, with the power at the top. Energy is calculated by integrating the power curve during the time the current exceeds its noise floor, represented by the highlighted region. The insert graph illustrates the noise level for the Unison exciter.

3.3.2 Identification of Ignition Spark

Since the individual spark energies in a spark train may vary, determining ignition energy required the identification of the ignition spark. For the Unison exciter, there were as many as seven consecutive sparks per test, while the VEE had up to nine sparks. Ignition was indicated by a rise in pressure in both the igniter cavity and the engine chamber. The spark waveform data was therefore synchronized to the engine pressure data to determine ignition. Figure 6 and Figure 7 show examples of this overlaid data. The sparks are indicated by spikes in the voltage and current signals (lower left axis), and the energy levels of each spark are indicated at the top. The dashed lines indicate the initiation of the propellant flow; at approximately 31.074 s for LO_2 and approximately 31.084 s for LCH_4. The squares and circles denote the chamber and igniter cavity pressures, respectively, while the open symbols show cold flow pressures for comparison. Ignition occurs when the igniter and chamber pressures deviate from the cold flow values. In Figure 6, the sparks began 20 ms before CH_4 flow, and ignition occurred at approximately 31.086 s, coinciding with the fifth spark. However, considering a finite response time for the pressure measurement, it is likely that the fourth spark triggered the ignition. This is evidenced by Figure 7, which is a VEE test using a low spark rate (the VEE is the only unit that permitted this variation). It is clear that the first spark triggered the ignition, but the pressure response lagged the spark by about 4 ms. Another indicator is the temperature in the igniter cavity, represented by the solid line, which begins to rise about 8 to 10 ms after the ignition spark. When these delays are applied to Figure 6, it indicates that the fourth spark caused ignition. This is corroborated by other tests with the VEE at varying spark rates as well as a Unison test with a shortened spark command time.

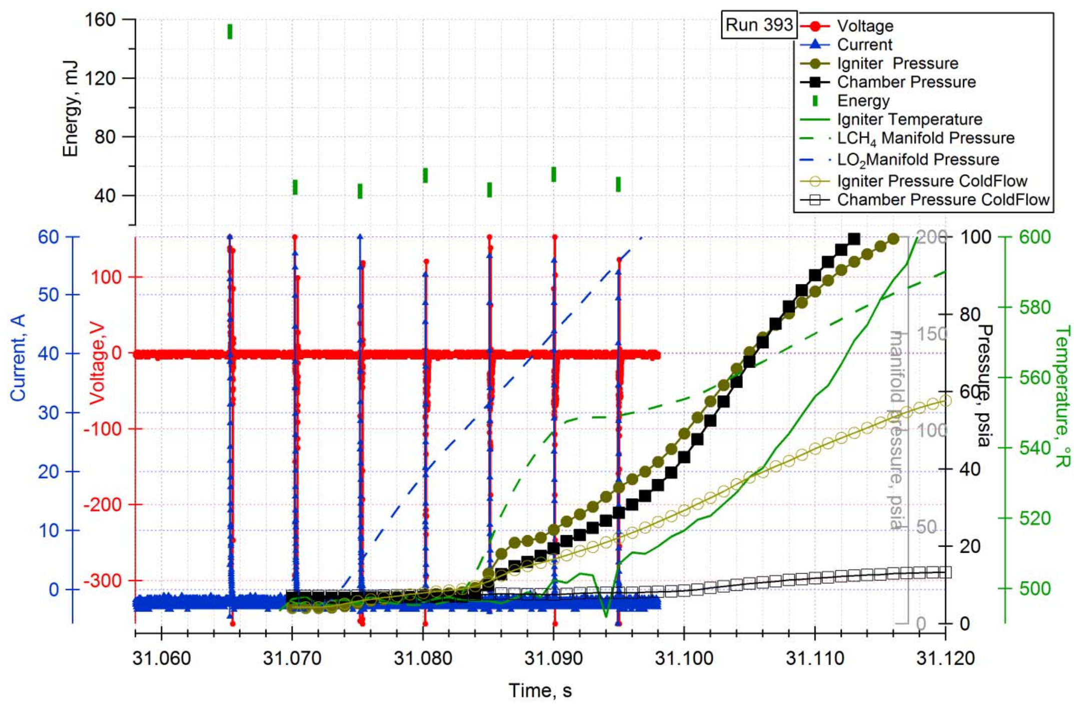

Figure 6: An example of a unison exciter run with pressure traces plotted against the waveforms. Ignition occurs when the chamber and igniter cavity pressures exceed their cold flow (nonignition) levels. This is correlated to the spark waveforms to determine which spark triggered ignition.

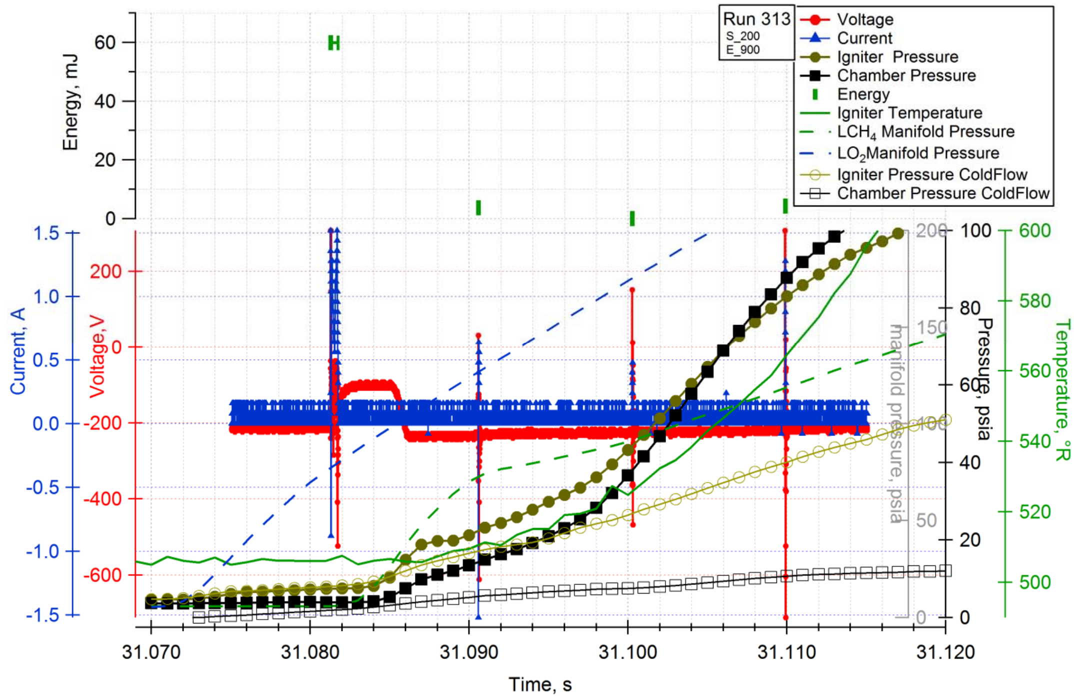

Figure 7: An example data set taken from the VEE with a low spark rate. The pressures rise occurs between the first and second sparks, so the first spark must have triggered the ignition. The pressure response is delayed by approx. 4 ms relative to the ignition spark and igniter cavity temperature has an 8- to 10-ms delay.

4.0 Results

4.1 Variable Energy Exciter

The VEE underwent a total of 28 runs over 2 test days. This unit was designed such that stored spark energy and spark rate could be adjusted using digital potentiometers (digipots). Originally, the digipot settings were calibrated using air spark gap tests performed at room conditions with no propellant flow, namely “dry spark” tests. These calibrations were performed on the engine test stand, thus the configuration was identical to hot fire tests. Although the spark rates shown in Figure 8 are accurate, the delivered spark energy exhibited a dependence on the engine (hot fire) environment. Therefore, the dry spark energy calibration was not transferable to the hot fire tests. In the following sections, test conditions are identified by the digipot setpoint. Energy was varied between “E_900” and “E_500” while spark rate was varied between “S_850” to “S_200.” The resulting spark energies and rates in test runs were then determined from the actual hot fire data.

While the energy range shown in Figure 8 was smaller, and lower, than anticipated based on initial benchtop testing, it indicates that resulting spark energies should scale with the digipot setpoint for a fixed spark gap. This holds true as long as the setpoint is above a minimum capacitor charge voltage that is sufficient to sustain sparks without quenching. For the dry spark conditions of Figure 8, this threshold appears to be E_500, corresponding to 15 mJ delivered energy (from 180 V capacitor charge, 71 mJ stored). However, as the data presented below will suggest, under the variable hot fire conditions this minimum VEE setpoint changes substantially and renders the digipot settings ineffective for controlling delivered spark energy. This behavior is attributed to inadequate capacitor charge or driving voltage for the desired energy range. It could likely be mitigated by modifying the VEE to maintain higher storage capacitor voltages for the target energy range.

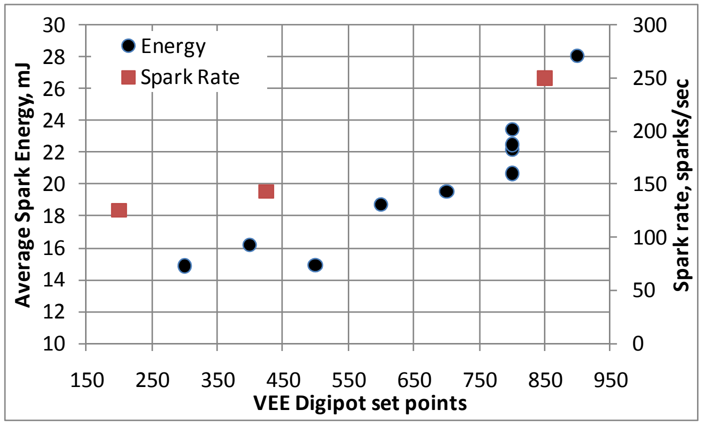

Figure 8: Calibration of the VEE digipot settings for dry sparks. The energy calibration is shown on the left axis, but is not applicable to hot fire tests. The spark rate is shown at right (squares) and is universal.

4.1.1 Waveforms

Examples of waveform and pressure data from a VEE test are shown during a hot fire engine test Figure 9(a) and in stagnant air at room conditions, or dry spark, Figure 9(b). As with the previous graphs, voltage, current, and pressure data are displayed on the bottom and calculated spark energies at the top. Spikes in the voltage and current signals indicate a spark occurrence. Figure 10 shows expanded views of the individual sparks of Figure 9. Only the first seven sparks (out of nine) are shown due to size restrictions.

Comparison of the hot fire and dry spark runs show significant irregularities in spark behavior during hot fire conditions relative to the repeatable spark energy and waveform behavior in the dry spark situation. For the nominal dry spark behavior in Figure 10(b), the voltage is steady during the discharge, with spikes (ringing) at the beginning and end. In Figure 9(b), the voltage is an “h” shape with the spike(s) representing the spark discharge and a gradual voltage decline (the hump of “h” shape) marking the capacitor recharge. These patterns are evident in all of the dry sparks, but only for the first five hot fire sparks (Figure 9(a)). The latter sparks of the hot fire run clearly exhibit an absence of capacitor recharging cycles and little to no spark discharge current. The lack of voltage recharge indicates that the capacitor never fully discharged. In the case of spark 6, there was no current draw or recharge cycle at the end, indicating a dropped or absent spark. However, spark 7 shows a brief current draw but no substantial voltage recharge. This indicates that the spark was quenched, or truncated, with only a partial discharge of the capacitor occurring.

4.1.2 Energy Results

Figure 11 shows the energy results from two sparks in each VEE test: the ignition spark and the spark with the highest energy. The data are grouped by the energy setpoint (indicated at top) while the size of the symbol represents spark rate. Raising the energy setpoint appears to increase the range of observed spark energies, although the high energies themselves are inconsistent. Ignition spark energy is similarly inconsistent, making it difficult to establish whether the notion of minimum ignition energy applies, or could be resolved, within the available VEE energy range. Surprisingly, in some cases such as run 318, the ignition energy appeared to be <1 mJ.

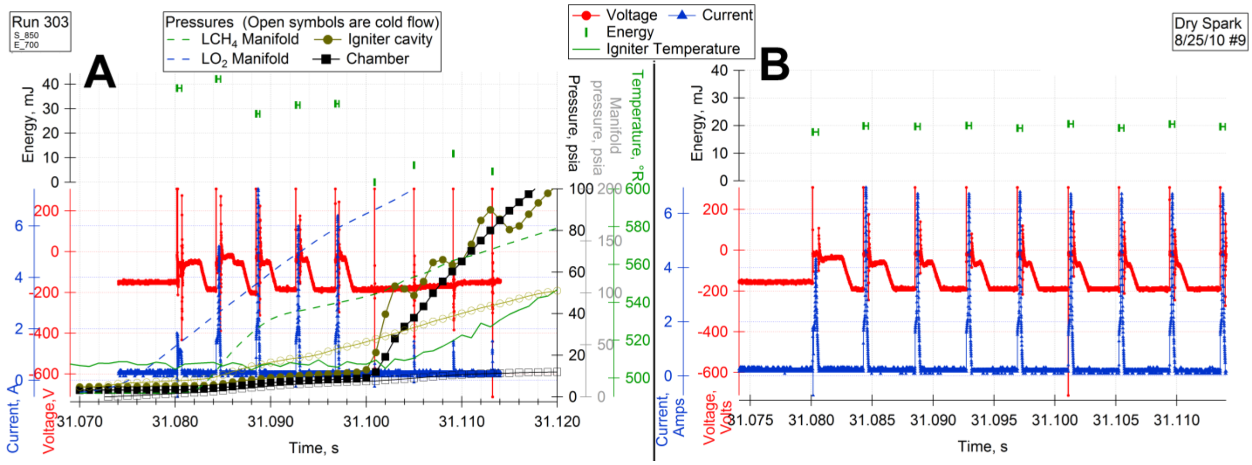

Figure 9: Example waveforms from the VEE. (a) A hot fire test indicates inconsistent spark behavior and (b) a dry spark test (no propellant flow so no pressure data) shows repeatable, consistent spark performance.

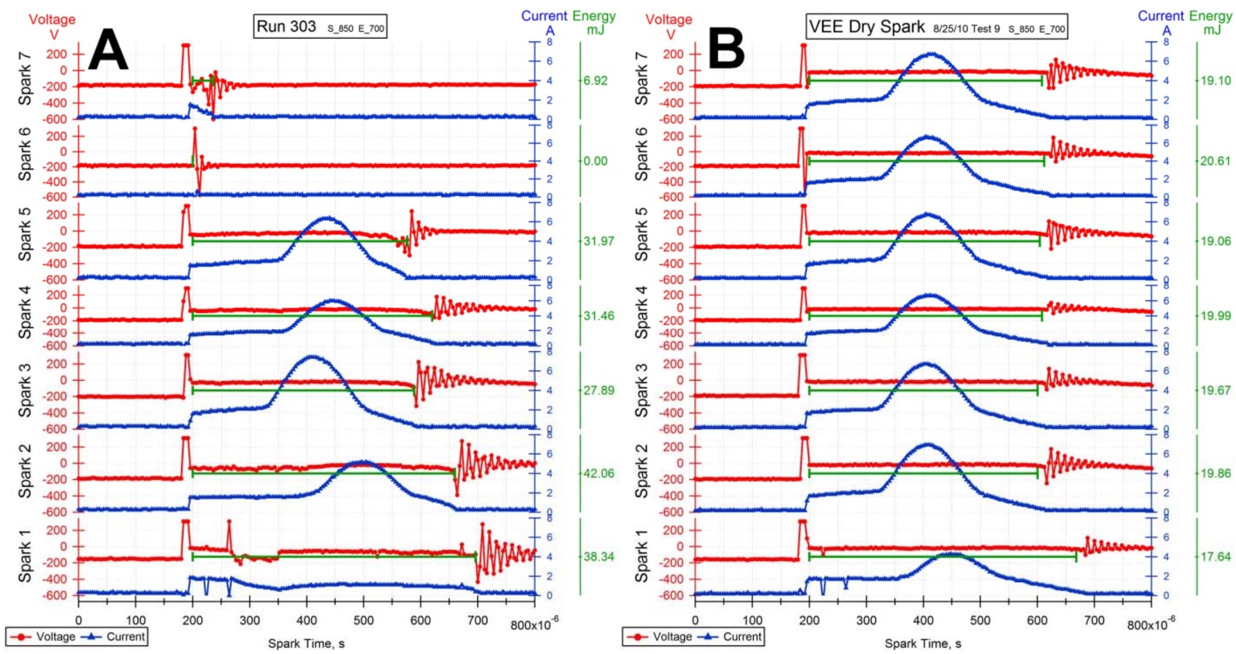

Figure 10: Closeup plots of individual spark waveforms for the VEE. (a) A hot fire run showing irregular behavior and (b) the dry spark data shown which is very repeatable.

These energy fluctuations also are clear in Figure 12, which shows spark trains for a group of tests with the same spark rate, but different energy setpoints. The ignition sparks in each run are outlined. The inconsistency in spark behavior over the course of the spark train is evident. Overall, the spark energies appear to decrease later in the spark train. In several tests, this decrease seems to be triggered by the ignition spark. An example is shown in Figure 9 (left), where the ignition occurred on spark 5, and sparks 6 to 9 were quenched. Also note that the igniting spark was not always the highest energy prior to ignition.

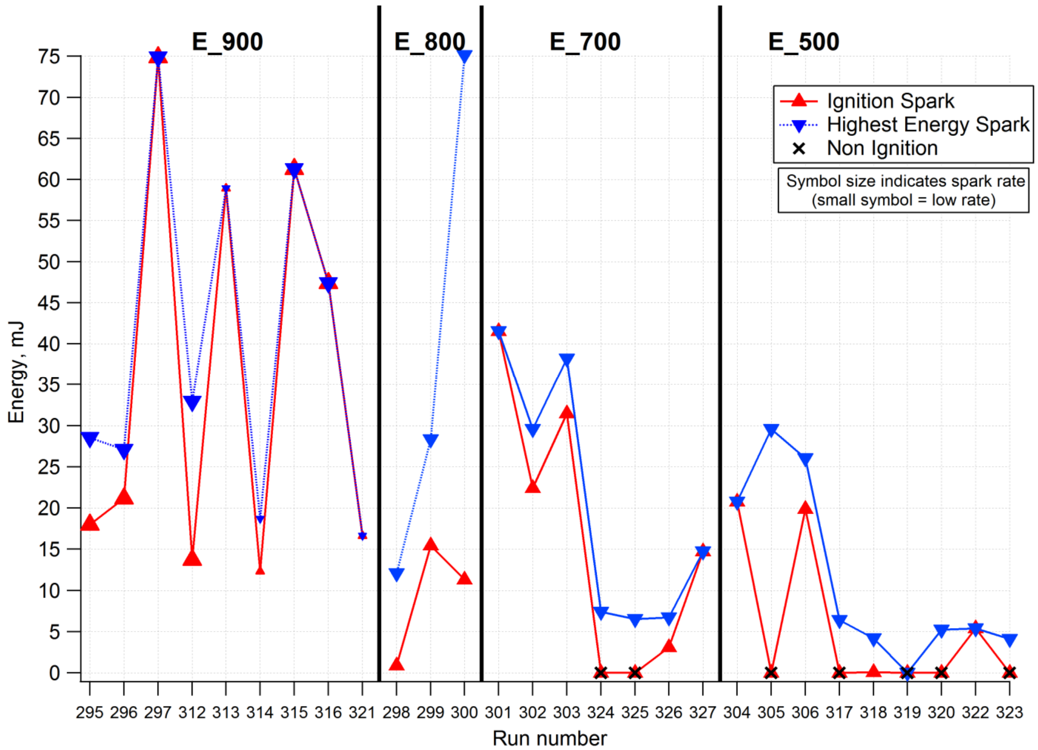

Figure 11: Ignition spark energy is shown for each VEE run along with the highest spark energy. Data is divided according to the setpoint energy. The higher energy setpoint had a larger range of resulting energies. Ignition energy is very inconsistent.

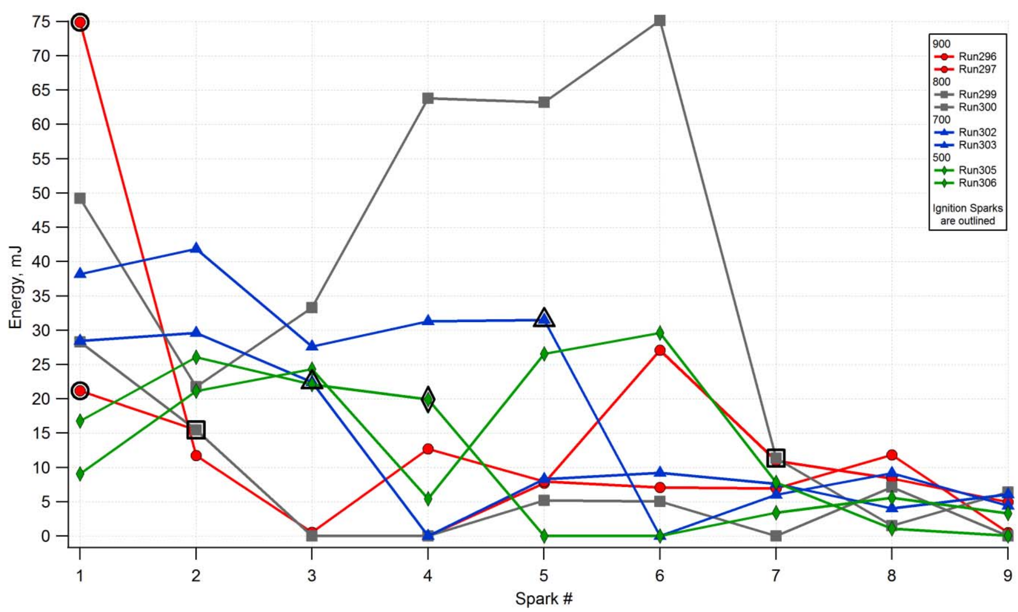

Figure 12: Spark energies are shown for a group of VEE tests at the same spark rate but varying setpoint energy. Ignition sparks are outlined. The energies over the spark train vary widely but appear to decrease late in the spark train and after ignition has occurred.

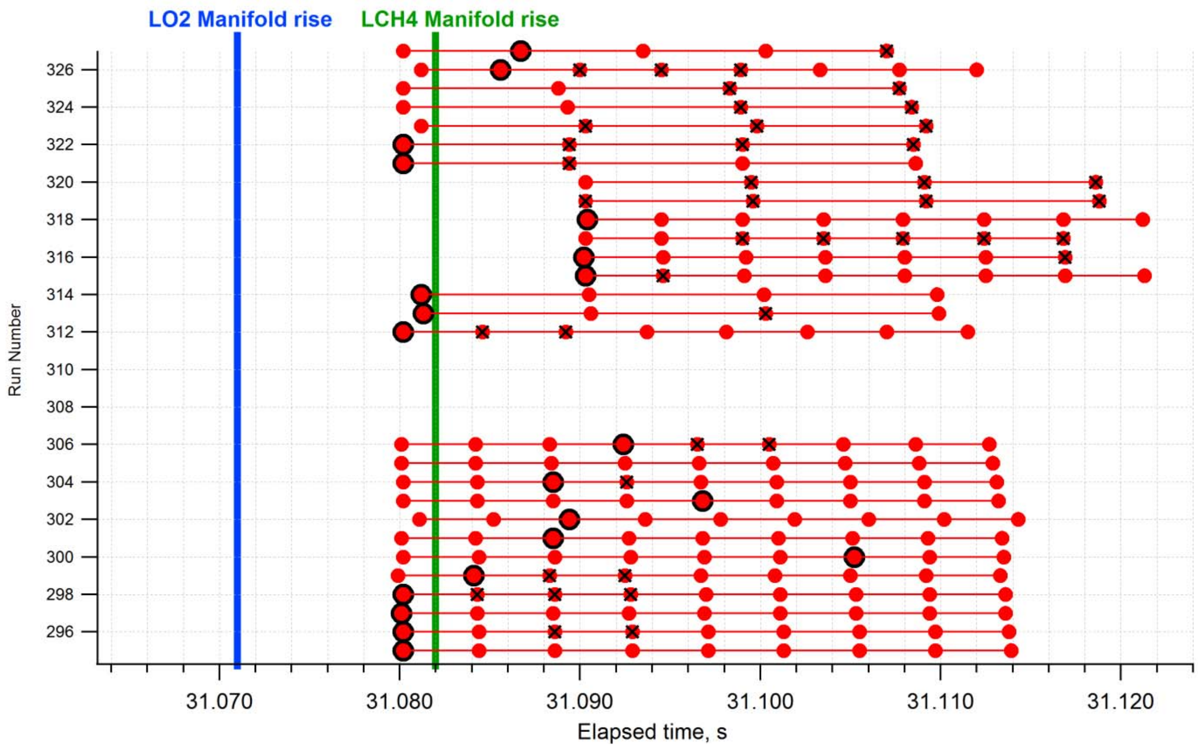

Figure 13: The VEE spark occurrences for each run are shown as a function of test time. Vertical lines denote first indications of propellant flow. The ignition spark is circled, and dropped sparks are crossed out.

Figure 13 illustrates the timing of the ignition spark relative to the propellant flow. The spark trains for all the tests are plotted relative to the elapsed test time. The ignition sparks are circled. The vertical lines represent the response of the manifold pressure transducers, indicating propellant flow initiation. Note that the propellant valve open command is sent approximately 14 ms prior to this (it takes approx. 10 ms for the valve to respond and another approx. 4 ms until the manifold pressure rises). The dropped sparks, which are crossed out, often occurred immediately after ignition.

4.2 Champion

One day of testing was performed using the Champion exciter with a total of 15 tests. There were several logistical difficulties that limited the scope of this test matrix. First, the bipolar spark waveforms were difficult to resolve. Any noise in the signal made it difficult to distinguish the voltage shifts. Numerous dry spark tests revealed that the voltage probe needed to be within 6 in. of the spark plug igniter to obtain a clean signal. However, the voltage probe was not vacuum compatible and therefore could not be used in this position during hot fire testing.

The other issue concerned the data resolution of the digital oscilloscope, which could store 10,000 data points for a variable time-base span. With the VEE, this recording time was chosen as 40 ms (250 points/ms) so that seven of the maximum nine sparks could be resolved. However, the spark discharge time for the Champion exciter was much shorter (30 to 50 μs) and its spark rate lower (100 sps) than the VEE (200 μs, 250 sps). Therefore, using the same time base as the VEE would mean that four

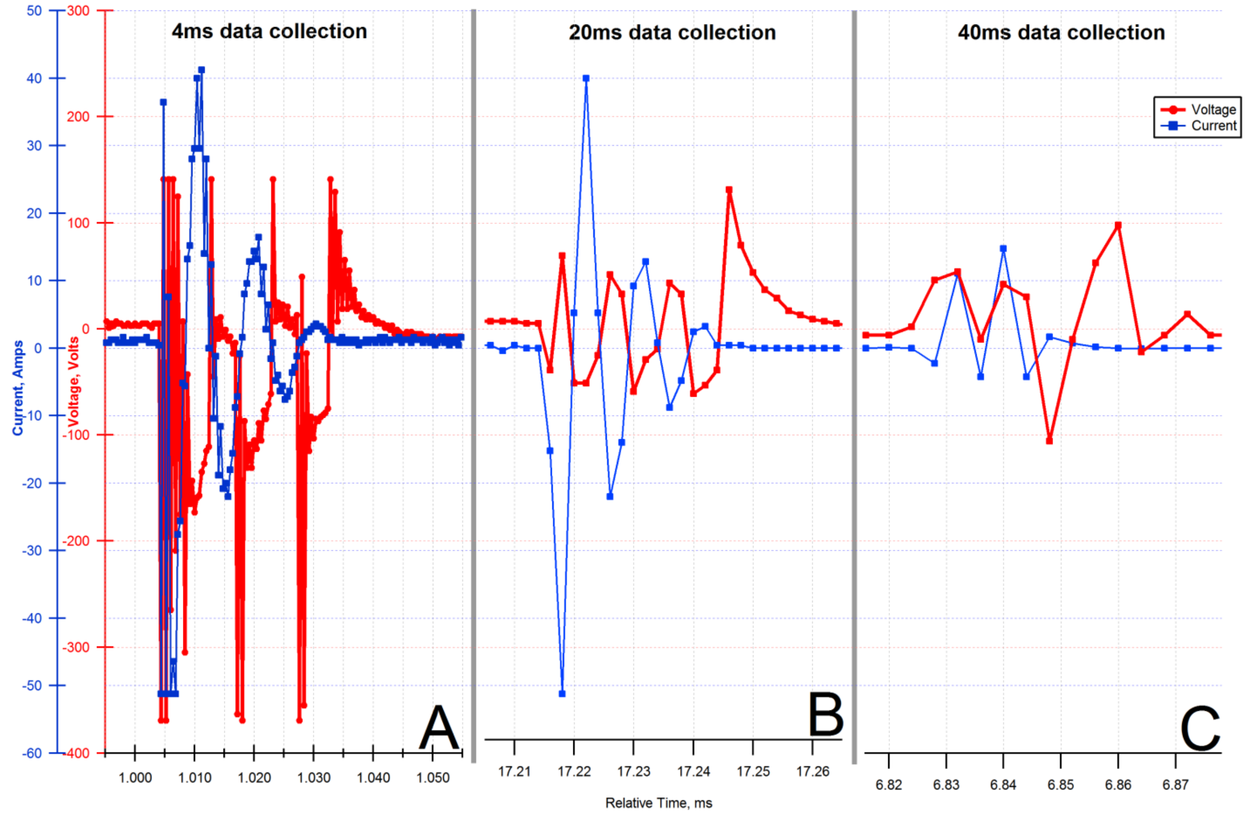

Figure 14: Examples of dry spark waveforms from the Champion exciter. The oscilloscope data rate was adjusted to resolve the waveform. (a) A fully resolved waveform is shown but only permitted 4 ms of data collection. (b) A 20 ms window was sufficient to confirm an unquenched spark, but not for energy calculations. (c) The same data rate used with the VEE does not have sufficient resolution.

spark waveforms could be obtained, but would only be represented by 12 data points each. Figure 14(c) illustrates a spark waveform captured with this sample rate. The bipolar voltage peaks cannot be distinguished. Figure 14(a) shows a similar spark waveform captured using a shorter time base (higher sample rate) resulting in multiple points for each polarization shift. Using this time base, only 4 ms of data was collected so only one spark in the train could be captured. However, due to a 7-ms variability in Champion exciter response to the spark command signal (i.e., in the time to first spark), it was not possible to repeatedly capture a single spark within this 4-ms window.

Since significant modification would be required to correct the noise on the voltage probe and/or extend the memory of the oscilloscope, energy measurements for the Champion exciter were abandoned. The hot fire tests were ultimately performed with a 20-ms oscilloscope time base (Figure 14(b)) that generally captured two sparks at low resolution. This compromise sample rate was chosen solely for qualitative observation of spark fidelity (i.e., nominal vs. quenched or dropped sparks). DSO trigger delay was shifted in each test to capture different sparks in the train of five to six sparks, as shown in Figure 15. The solid circle symbols represent sparks that were captured by the oscilloscope (±2 ms), while the open symbols are the predicted times for the remaining sparks based on a 100 sps rate. The ignition time, as indicated by a rise in the chamber pressure, is indicated by the black squares. No quenched sparks or dropouts were observed in the oscilloscope data, and the waveform behavior appeared repeatable. Nevertheless, 2 of the 15 tests (runs 337 and 347) failed to ignite. The energy of the spark shown in Figure 14(a) is approximately 16 mJ. The results suggest this spark energy is insufficient for repeatable ignition in an igniter/thruster environment, at least for a bipolar type of spark with a 100-sps rate.

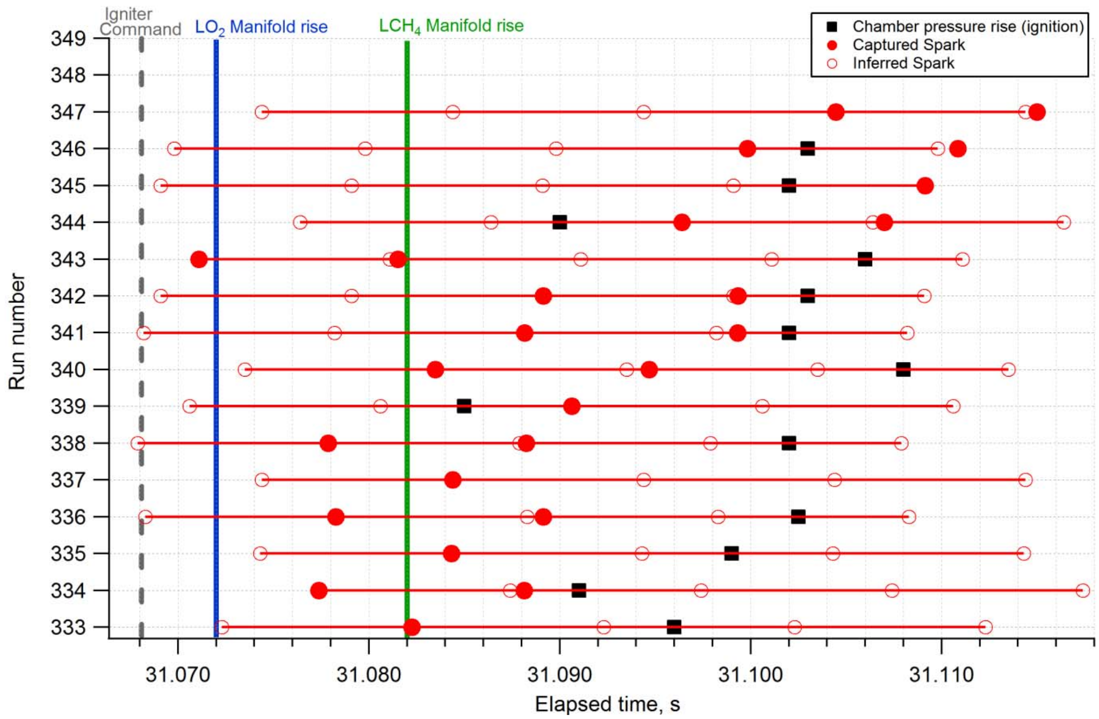

Figure 15: The spark timing of the Champion exciter is shown. The solid symbols represent those recorded by the oscilloscope (±2 ms), while the open symbols are inferred assuming a 100 sparks per second rate. The black squares show the time of the chamber cavity rise, indicating that ignition was likely caused by the preceding spark.

It is also evident in Figure 15 that the spark timing was inconsistent (especially time to first spark). Likewise, ignitions tended to occur later relative to fuel introduction than with the VEE and Unison (section 4.3.3), where ignitions approximately coincided with the methane manifold pressure rise. Taking into account the approximately 4-ms LCH_4 manifold response time (section 3.3.2), Figure 15 indicates that ignition usually was triggered by the first to third spark following methane entry (at approx. 31.078 s). This ignition delay is likely attributable to the Champion's lower spark rate combined with a less than 100 percent ignition probability for each spark.

4.3 Unison

The Unison exciter underwent a total of 44 tests in 3 test days. The characteristics of this exciter's sparks proved to be the easiest to examine relative to the previous units. Therefore, this was the only unit to be tested at all three propellant temperature conditions. Because the unit was unipolar, like the VEE, energy calculations were straightforward. However, hot fire spark behavior was more consistent than with the VEE. The duration and duty cycle of the spark discharges were long enough such that the DSO could resolve the waveforms for all sparks in the train.

Since the energy level was fixed for the Unison exciter, it was not useful for exploring energy margins. Therefore, the primary test goal was to examine ignition performance. The timing of the first spark with respect to propellant flow was varied in order to investigate its impact on ignition behavior.

4.3.1 Waveforms

Example waveforms are shown in Figure 16 and Figure 17. Figure 16 shows spark occurrence with respect to propellant flow, while Figure 17 shows closeups of each individual spark. As with previous plots, spikes in the voltage and current indicate a spark occurrence. In both figures, a hot fire test at nominal propellant temperature is shown in image (a) while a dry spark test is shown in image (b). The dry spark test shows very repeatable results, both in terms of energy (50 to 55 mJ) and discharge time. Indeed, individual dry spark waveforms in Figure 17(b) are nearly identical, but in the hot fire test, the waveforms are inconsistent. Spark 6, for example, almost appears to be quenched based on its short discharge time. However, its energy is quite high at 92 mJ whereas most of the others are around 60 to 75 mJ. This suggests that a full spark did occur, but with a higher than usual spark impedance or discharge voltage (approx. 64 V). As a result, energy transfer from the storage capacitor to spark was more efficient, yielding the higher spark energy and reduced discharge time.

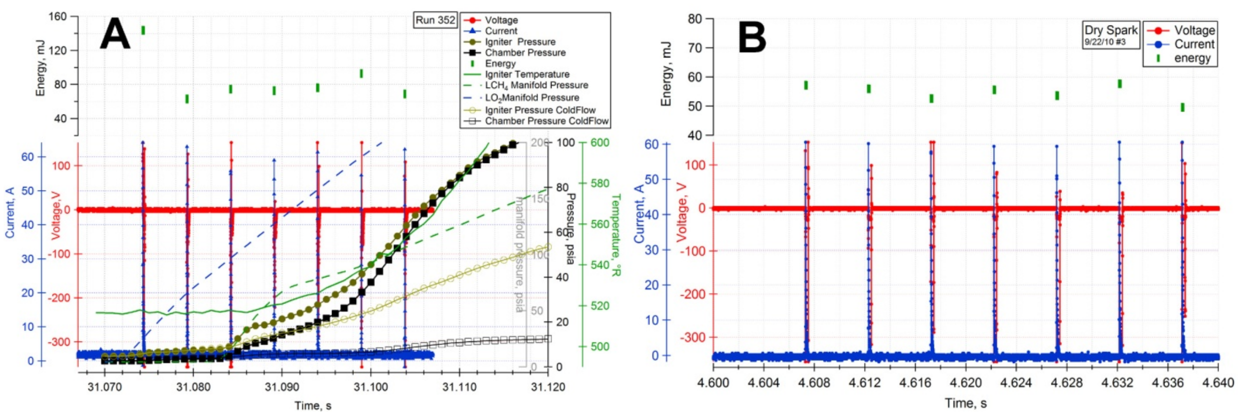

Figure 16: Example waveforms from the Unison. (a) A hot fire test indicates inconsistent spark behavior and (b) a dry spark test (no propellant flow so no pressure data) shows repeatable, consistent spark performance.

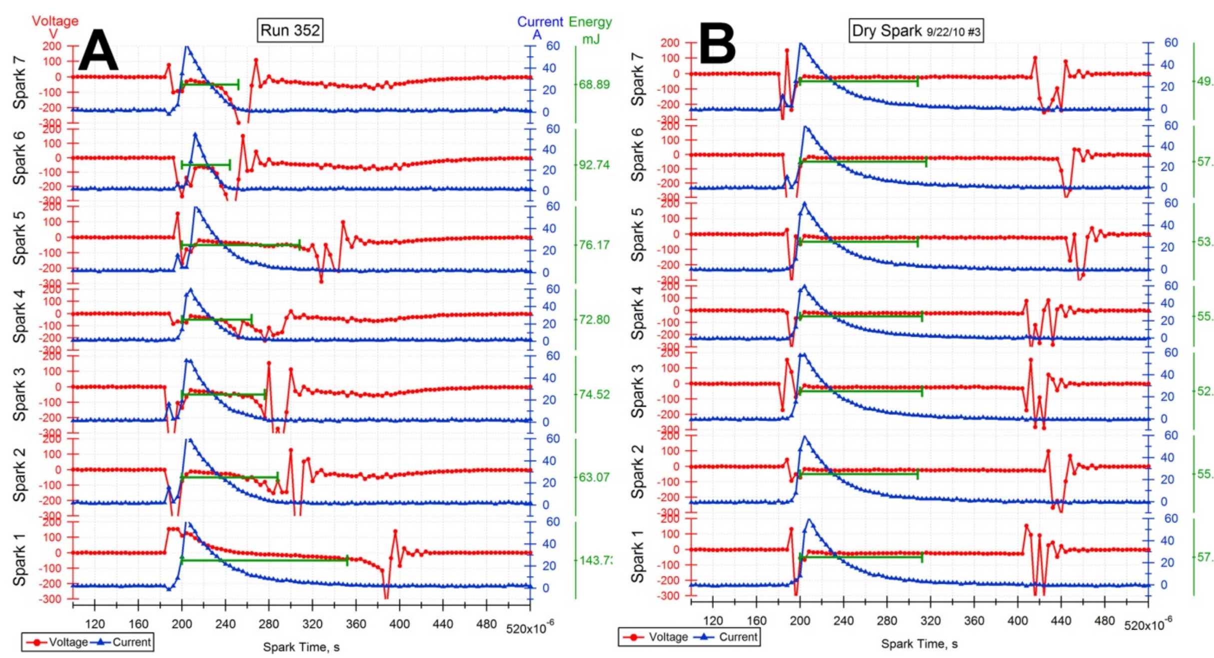

Figure 17: Closeup plots of individual spark waveforms for the Unison. (a) A hot fire run showing irregular behavior and (b) the dry spark data shown which is very repeatable.

However, many of the highest spark energies were not valid, for example, the highest indicated energy in this test was the first spark, at 143 mJ (Figure 17(a)). The gap breakdown voltage (BDV) for the exciter HV/ionization pulse tends to be significantly higher for the first spark of train when there is no residual ionization from previous sparks or from a flame kernel. This voltage spike frequently overdrives the HV probe DSO amplifier, retarding its recovery after the overshoot induced by this abrupt gap voltage collapse. This artifact is apparent by the slowly relaxing, inverted (positive) polarity of the spark voltage for the initial approximately 1/3 of the discharge (Figure 17(a), spark 1). Given the unipolar spark current output of the Unison exciter, an inverted (positive) polarity for spark voltage cannot be valid. Since this period is when most of the spark energy is deposited, the initial inaccurate voltage reading can have a large impact on indicated spark energy. This effect was not always present due to the typical statistical fluctuations in first spark BDV. Likewise, this effect was also found to arise occasionally for other sparks in the train, presumably when their BDVs spiked either randomly or as a result of flow conditions. This first spark artifact was observed for the Unison and the VEE. For this reason, all spark waveforms were checked and their energies flagged as suspect when their initial polarity indicated a HV probe amplifier overdrive condition.

4.3.2 Energy Results

The spark energies for all the Unison exciter tests are shown in Figure 18, grouped by propellant temperature conditions. The dry spark energies are shown at each condition (thick black line) for reference. Some sparks energies were questionable due to the HV overdrive artifact discussed in a previous section. These are indicated by an "X" in the figure, while the sparks that triggered ignition are circled. In many cases it was an overdrive spark that caused ignition. In fact, the frequency of this coincidence suggests that higher BDVs and/or associated gap conditions may increase the ignition probability of a given spark. The energies in the cold and nominal cases were consistently higher than the dry spark baseline of 55 mJ, while the warm condition was similar to the dry spark. The data scatter is widest in the warm case, which may be due to the larger sample size (23 tests). Conversely, the energies were quite consistent at cold propellant conditions. There is a slight energy increase as the train proceeds, which is

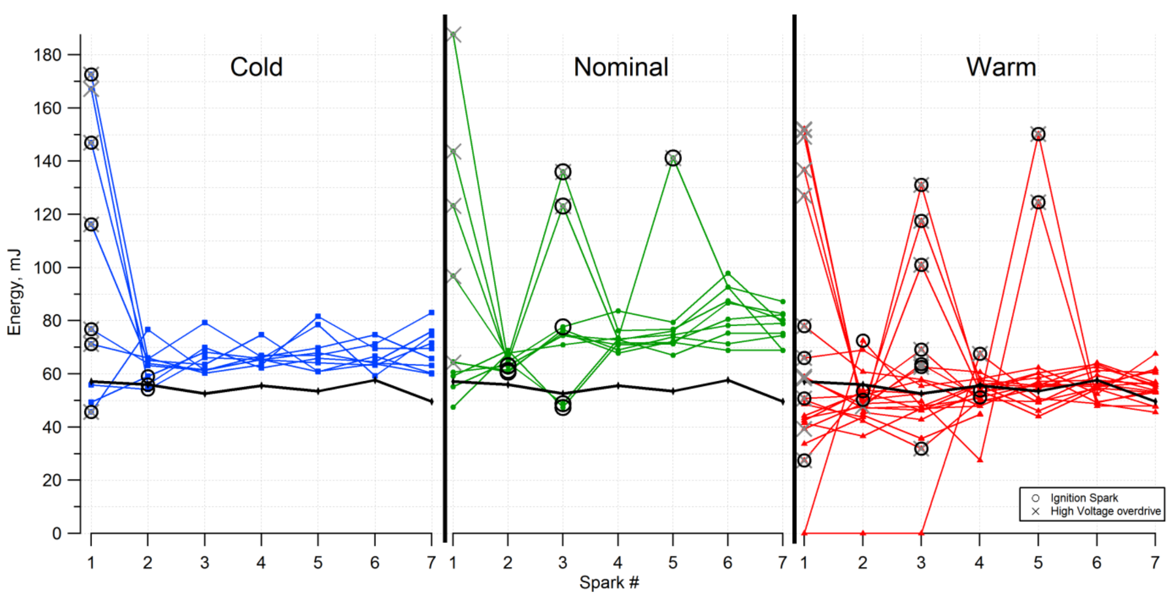

Figure 18: The spark energies are plotted for all the Unison exciter tests. Results are grouped by propellant temperature conditions with 9 cold runs, 12 nominal, and 23 warm. The thick line represents the dry spark energies, which are consistent at approx. 55 mJ. The igniting spark for each run is circled. Energies that are suspect due to a high-voltage overdrive issue are crossed out.

particularly noticeable in the nominal temperature case. This may be due to the higher pressure/flow conditions late in the spark train, which drives up the spark impedance. This results in a higher energy transfer efficiency, and shorter spark duration.

4.3.3 Ignition Spark

The ignition sparks are highlighted in Figure 18. Many ignitions were triggered by sparks that experienced the HV overdrive artifact, which makes it difficult to draw conclusions about the ignition energy, therefore, instead of looking at energy, Figure 19 illustrates the dependency on spark timing. This plot is analogous to Figure 13 for the VEE where ignition sparks are circled and vertical lines indicate propellant flow initiation (the valve was commanded approx. 14 ms prior to flow initiation). The majority of igniting sparks occurred within ±3 ms of the methane manifold pressure rise, which indicates methane flow introduction. The pressure transducer response can lag the valve open command by as much as 3 to 4 ms (section 3.1) even though it appears that some sparks occurred in an oxygen-only flow regime, this cannot be definitively proven within the uncertainties of the system response. All ignitions, but one, were triggered off the spark that immediately preceded or followed the methane manifold pressure rise. Even when the spark command was delayed until 20 ms after the methane valve (runs 371 to 373), it was the first spark, thus the first one after methane flow introduction, that triggered ignition. The exception was run 357, which will be discussed later as a unique ignition event termed a "rumbling ignition." It is interesting to note that the first tests of the day were ignited by the spark immediately prior to methane flow, while the latter tests were ignited by the spark immediately following methane flow. At the warm propellant condition, most ignitions were triggered immediately after the methane flow, despite earlier opportunities. Such behavior possibly hints at an ignition pattern relating to propellant temperature, with warmer propellants tending to correlate with slightly later ignition. The trend seems to hold in the

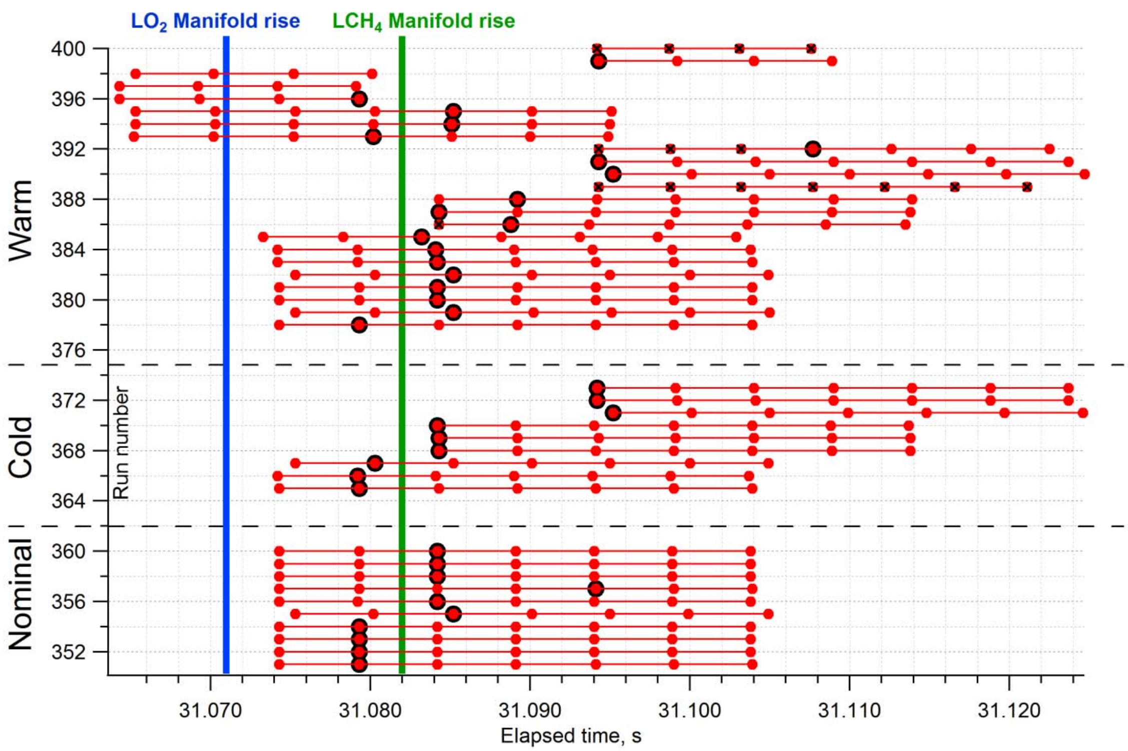

Figure 19: The Unison spark occurrences for each run are shown as a function of test time. Propellant flow initiation is indicated by vertical lines. Three propellant temperature conditions are represented, where each condition represents 1 test day. The ignition spark is circled. Dropped sparks are crossed. Generally, the spark at, or immediately following, the methane flow triggers ignition.

Table 3: Unison tests with spark dropouts are summarized.

Run	Command timing	Time of first spark, s	Duration, ms	Total sparks	Dropout spark no.
386	10 ms after CH4	31.0843	60	7	1
389	20 ms after CH4	31.0952	60	7	All
392	20 ms after CH4	31.0652	60	7	1 to 3
400	20 ms after CH4	31.0942	20	4	All

nominal case, but the change in spark command timing after the third run of the cold propellant case excludes it as a reference to confirm this pattern of ignition behavior. This could be related to hardware temperature, which affects the injected propellant temperatures, and will be discussed in section 5.2.

Only four tests failed to trigger ignition. All occurred at warm inlet conditions and all were attributable to deliberately unorthodox (early and late) spark command timings. Runs 397 and 398 both used a shortened spark train (only four sparks) applied prior to methane flow. Even though the sparks were successfully discharged, the propellant/flow conditions were insufficient for ignition. In runs 389 and 400, no sparks were discharged. More detail is shown in Table 3, which indicates the spark command timing relative to the methane valve open command, the total duration of the spark train, and which sparks in the train were dropped. These tests were all performed at warm propellant conditions. The common factor is that these sparks were commanded to begin late in the test, well after propellant flow introduction. The igniter cold flow pressures already exceeded 20 psia before the first spark attempt. At this pressure, the gap's estimated Paschen (DC) breakdown threshold is approximately 3.5 kV (for pressure*gap of 66 torr-cm) (Refs. 14 and 15), therefore, the cable-degraded Unison HV pulse capability of approximately 6 kV was marginal. This considers that microsecond HV pulse breakdowns, as used here, often substantially exceed Paschen thresholds due to the statistical time-lag effect[1] in absence of ambient ionization. Faster rise and shorter duration HV pulses can exaggerate this (fluctuating) overshoot of the Paschen limit.

5.0 Discussion

The following discussion primarily encompasses the VEE and Unison exciters. Discussion of the Champion exciter will be limited because of the previously described issues in obtaining high-resolution waveforms. Since its sparks were also bipolar, its waveforms could not be directly compared to the two unipolar units.

5.1 Engine Environment—Effect on Spark

It was observed in sections 4.1.1 and 4.3.1 that the spark behavior in an engine environment was significantly different than a dry spark (room air and no propellant flow). Both the VEE and Unison demonstrated repeatable spark waveforms in terms of discharge time, profile, and energy during dry spark tests. During hot fire engine tests, however, the waveforms and resulting energies were inconsistent within a single spark train. This suggests that the propellant flow field has a significant impact on spark behavior.

[1]Even with sufficient voltage, breakdown may be delayed due to the absence of avalanche initiating free electrons in the electrode gap. Without an artificial source (e.g., photoelectron emission by UV illumination), the rate at which free electrons randomly appear in this region is typically less than or comparable to the time scale of a 10 to 50 µs duration HV pulse. The HV pulses involved here are insufficient for electrode field emission of electrons. Thus, breakdown can be delayed until a free electron is available in the gap. This delay is known as statistical time lag. For fast-rising HV pulses, it often results in substantial "overshoot" of DC Paschen levels before breakdown is obtained.

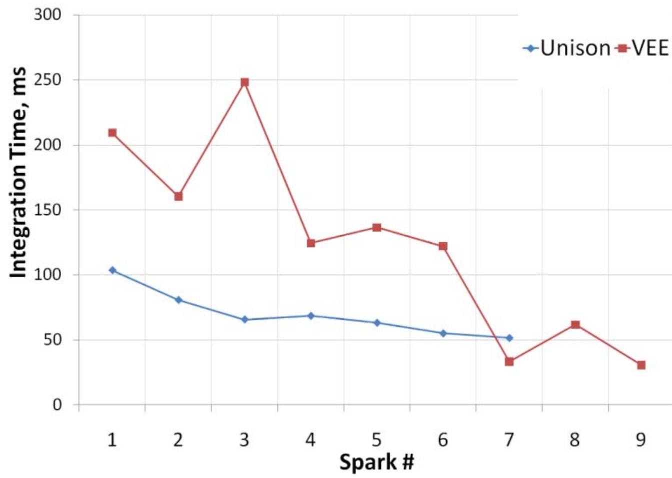

Figure 20: Average energy integration times indicate spark discharge time for the Unison and Variable Energy Exciter (VEE).

Glassman (Ref. 12) noted that minimum ignition energy is higher in flowing mixtures due to a reduction in deposited energy density (energy per volume or per spark column length) as the spark is stretched downstream. Likewise, previous experiments (Refs. 16 and 17) of ignition in turbulent premixed methane and air mixtures noted that the strain rate fluctuations at the spark location prevented stabilization of the flame kernel. For turbulent nonpremixed flows, local mixture ratio fluctuations also affect ignitability near the spark. The randomness of these fluctuations causes ignition success to be probabilistic, therefore, a higher energy is typically needed to ensure ignition.

Here, the flow effects are evident in the spark waveforms themselves, namely the spark discharge times. Figure 20 shows the average energy integration time for each spark over all VEE and Unison tests. In both cases, the discharge time decreased as the spark train proceeded. Since the spark train was applied coincident with the introduction and ramp up of propellant flow, this reduction in individual spark duration correlates with an increasing flow rate and pressure. This trend is more severe in the VEE, where ignition also seems to adversely impact spark behavior.

As observed in section 4.1.2, quenched and dropped sparks frequently occurred immediately after ignition when using the VEE. These patterns of spark behavior may be primarily attributed to the effect of increasing pressure on spark discharge impedance and associated power dissipation. (While increased flow rate has a similar effect, flame kernel development after ignition would not be expected to accelerate flow through the spark gap.) Higher pressure raises spark voltage and power (I*V) for each discharge. Ultimately, there is a limit to an exciter's capability to drive higher impedance sparks. This is governed by the combination of its storage capacitor voltage and internal series inductance, hereafter referred to as "capacitor driving voltage." When exciter capacitor voltage is sufficient (as with Unison) to sustain higher voltage sparks, the corresponding higher spark power dissipation yields faster discharge of capacitor stored energy and shorter duration sparks. However, if exciter capacitor voltage is already marginal (as with VEE), then the higher spark voltages prevent full discharge of capacitor energy before sparks get interrupted, or quenched. This tendency is exacerbated when the VEE's spark energy (capacitor voltage) is further reduced via the digipot setpoint.

Another contributing factor, particularly for the VEE post-ignition apparent dropped sparks, could be flame-induced ionization. The level of flame-induced ionization is small compared to the ionization in the spark channels, therefore, it is unlikely to significantly affect discharge impedance. However, it is sufficient to significantly reduce pulse BDVs of the gap that initiate sparks. Under such circumstances, a weakness of the inductive flyback method (used by the VEE to produce HV pulses) is that it is susceptible to reverse polarity breakdown (RBD) at its output over the (pre-HV pulse) transformer “charging” interval. During this period, ramping of current through the transformer primary generates a moderate (approx. 800 V for VEE) reverse polarity voltage on the transformer secondary (VEE output). Normally, this remains open-circuit while its polarity flips upon deliberate, abrupt interruption of the transformer primary current. The induced collapse of transformer magnetic field then produces a desired HV pulse on the VEE output. However, if the VEE output is shorted (e.g., by a premature gap breakdown) during the transformer “charging” interval, this has been found to prevent the subsequent intended (correct polarity) HV pulse generation, gap breakdown, and discharge of the storage capacitor energy into a spark. (A possible example of this is evident in Figure 9 (left). The typical “h” shape of the voltage that would indicate a capacitor recharge is not present in later sparks. This indicates that the capacitor never discharged.) For these igniter gap dimensions, these moderate voltage RBDs have only been identified to occur for attempted sparking in post-ignition situations with the VEE. It has not been observed with flow prior to ignition, when gap cold flow pressures typically preclude triggering of any breakdowns by sub-kV transient voltages. (Note: RBV was observed in preflow conditions, when the low/vacuum pressures similarly reduced the Paschen limit.) Although a RBD still produces a short-duration (approx. 2 μs), weak (<1 mJ), reverse polarity spark powered by collapse of the exciter output transformer’s magnetic field (and not by a capacitor discharge), it manifests as an apparent dropped spark for the data acquisition sample rates (1 sample/4 μs) used here.

Therefore, while reduced spark durations and quenched sparks are readily explained by pressure-induced elevation of spark impedance, it is also possible that post-ignition ionization conditions facilitated some RBD (at <800 V) dropped sparks for the VEE tests. Although the latter supposition might be argued to conflict with Paschen breakdown limits for the gap and pressures involved, the level of post-ignition ionization was likely sufficient to suppress or render invalid such limits. The presence of the flame-induced ionization could be sufficient to counter the pressure increase induced either by flow ramp up or by the ignition flame kernel itself. This is supported by the Unison data, for which no dropped sparks occurred after ignition, despite its lower delivered HV pulses (approx. 6 kV).

The few Unison spark dropouts all occurred prior to ignition, typically only in late spark application conditions (Figure 15, runs 386, 389, 392, and 400). By these times, pressure in the igniter cavity had risen to a level that rendered the cable-attenuated Unison HV pulses (approx. 6 kV) marginal relative to the effective Paschen breakdown threshold (Refs. 14 and 15) for the gap. A similar explanation may apply to VEE dropped sparks that occurred late in instances of nonignition (Figure 15, runs 317, 319, 320, and 323 to 325). However, unlike the VEE, the pressure rise caused by ignition did not cause dropped sparks for the Unison. This suggests that the post-ignition ionization may have been sufficient to make the gap mildly conductive, facilitating breakdown at the higher pressures by lowering BDVs substantially below the Paschen curve levels. The Unison had a higher capacitor driving voltage than the VEE, so provided its lower HV pulse could achieve breakdown and thereby initiate each spark, it was able to sustain these sparks to completion despite their elevated discharge impedances caused by the ignition pressure rise.

In terms of minimum ignition energy, the lowest observed ignition was approximately 1 mJ with the VEE (run 318). This suggests a well-timed spark, even at low energy, can trigger ignition. However, the mix of ignitions and nonignitions for similarly timed 1 to 6 mJ quenched VEE sparks indicates that ignition for these low-energy sparks is less than reliable. Other studies involving turbulent and/or nonpremixed flows have noted a similar probabilistic nature with regard to minimum ignition energy (Ref. 16). The limitations of the current test program did not permit statistical significance to quantify such probabilities. While the Unison exciter did not permit energy variation, it was able to reliably ignite the flow. The majority of sparks occurred at or above the dry spark baseline of 55 mJ. The timing of the sparks was critical; the only failed ignitions occurred when sparks were limited to an interval before methane flow (runs 397 and 398) or delayed until after igniter pressure exceeded a level corresponding to Paschen breakdown constraints (runs 389 and 400).

The limited Champion exciter appears to support these observations. None of the captured sparks from this unit appeared to be quenched, yet 2 of the 15 runs failed to ignite. The dry spark energy was lower than the other units at approximately 16 mJ, with the hot fire spark unlikely to be significantly higher. This, combined with the low spark rate, would decrease the probability of ignition. It should also be noted that the ignitions that were achieved frequently occurred late in the train.

5.2 Ignition Types

The timing of spark train relative to propellant flow was shown to influence spark performance, but also could impact the nature of the ignition itself. Four distinct ignition patterns were identified based on the pressure rise in the chamber and igniter cavity upon ignition. These are represented in Figure 21, which shows the igniter cavity pressure and chamber pressure rise. The open symbols indicate the cold flow pressures, so deviation from this indicates an ignition event. The first ignition type, termed a "gradual" ignition, is represented in Figure 21(a). The deviation from cold flow is marked by a gradual slope increase of the pressures in both the chamber and igniter cavity. This contrasts with an "abrupt" ignition (Figure 21(b)) where there is a sudden, sharp slope change in both pressure traces. A "late" ignition (Figure 21(c)) has the same basic characteristics as an abrupt ignition, but occurs at least 10 ms after fuel entry, when the cold flow pressure is higher. The pressure spike is also more severe than for the abrupt ignition. The final scenario is a "rumbling" ignition (Figure 21(d)), which was an unusual case. In all other scenarios, the chamber and igniter cavity pressure departures are nearly simultaneous. In the rumbling ignition, igniter cavity pressure begins to deviate from cold flow while main chamber pressure continues to track its cold flow profile. Rumbling ignition was only observed in one test of this series. However, it was also observed in the previous I-bit test series, where the behavior was more pronounced. Rumbling ignition will be discussed in more detail in section 5.2.1.

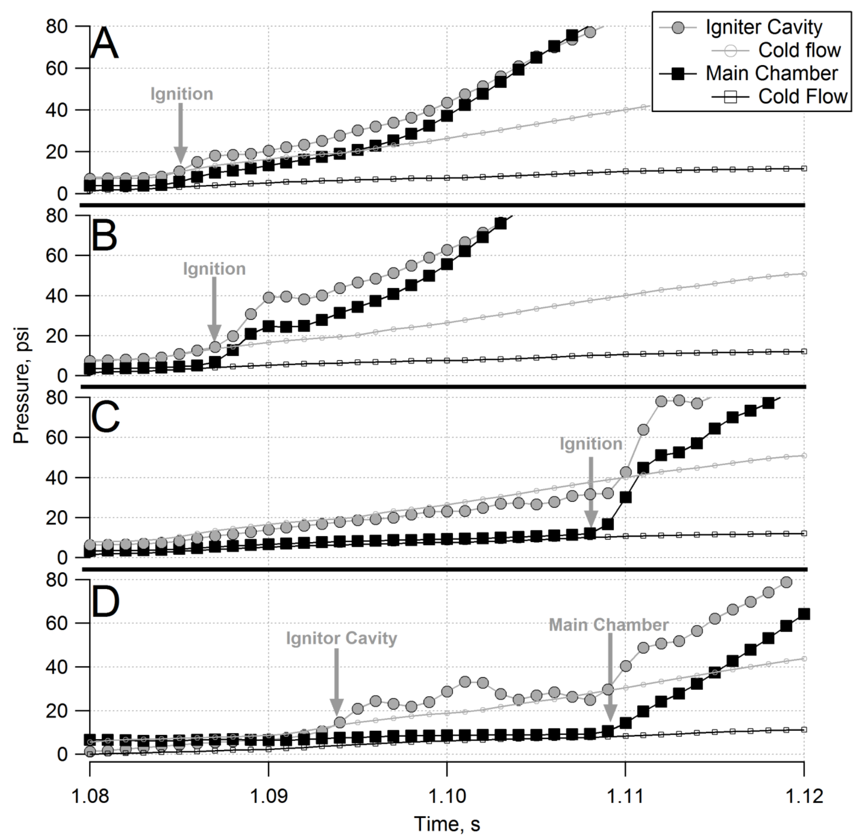

Figure 21: Ignition types are represented by the igniter cavity pressure and chamber pressure traces. Deviation from the cold flow indicates ignition. (a) Gradual ignition, (b) Abrupt ignition, (c) Late ignition, and (d) Rumbling ignition.

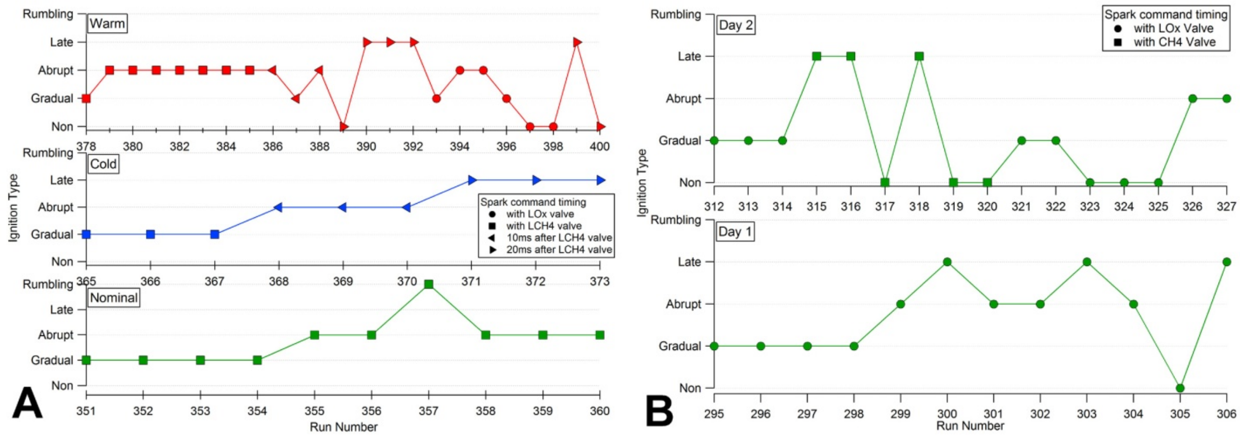

Figure 22: The ignition types are shown for each test of the (a) Unison and (b) VEE. Data are grouped according to test day. The first tests of each day have a gradual ignition while late tests have an abrupt ignition.

In Figure 22 the different ignition types are correlated to spark timing (symbols) and time of day (X-axis) for both the Unison (a) and VEE (b) exciters. For the Unison, there were 3 test days, each at a different propellant temperature. Both of the VEE test days were at nominal temperature. Generally, the first test of every day yielded a gradual ignition. Relating back to Figure 13 and Figure 19, these were also the runs that ignited on the spark just prior to methane flow. At the nominal and cold conditions this persisted for the first 3 to 4 runs, typically the point when a change in spark train parameters was implemented. Ignition then usually shifted to the spark after methane flow, which resulted in an abrupt ignition. When spark initiation was delayed beyond approximately 8 ms after methane entry (e.g., spark command with LCH_4 valve, unless prevented by timing as with VEE day 2, or 20 ms after CH_4 valve as in Unison warm and cold tests), late-type ignition resulted. Other changes made to spark train settings as each test day progressed, including reductions in capacitor driving voltage (reduced VEE spark energy), spark rate, and spark train duration were generally associated with more erratic ignition timing and some nonignitions. For example, VEE late ignitions occurred intermittently despite early spark initiation when lower spark energies (capacitor driving voltages) were selected (as in runs 300, 303, and 306).

The ignition behavior shifts observed appears to be primarily a consequence of test sequence. While propellant temperature may have contributed a secondary influence, it had no clear effect on ignition characteristics for the ignition margin testing. Yet, for the pulse strings (sequential short engine burns) of I-bit testing (Ref. 7), propellant temperature did exhibit a distinct effect on ignition behavior, especially in regard to the incidence of rumbling ignition (section 5.2.1). The differing influence of propellant temperature between the two test series can be attributed to the hardware temperature operating conditions.

In the single-shot ignition margin tests, a warm nitrogen purge through engine manifolds and igniter was maintained between each engine firing. This kept the hardware at relatively warm temperatures (approx. 480 to 500 °R) prior to each run, effectively resetting hardware conditions. Given the short duration of each run and the hardware temperatures relative to the much colder fluid temperatures, it is likely the propellant injected into igniter was ultimately gaseous regardless of initial propellant temperature or state upstream. Additionally, only minor MR variations would result. Valve propellant temperatures therefore had little effect on ignition.

In contrast, pulse strings in the I-bit test series were commanded without intervening purge cycles. Igniter hardware was able to chill-in as each pulse string progressed. This allowed the hardware to achieve temperatures more comparable to the propellants, permitting the possibility of transition, or mixed-phase propellant injection into the igniter. Consequent changes of ignition behavior that occurred during the progression of each pulse string could thereby have been triggered by the developing spray injection and/or associated MR fluctuations.

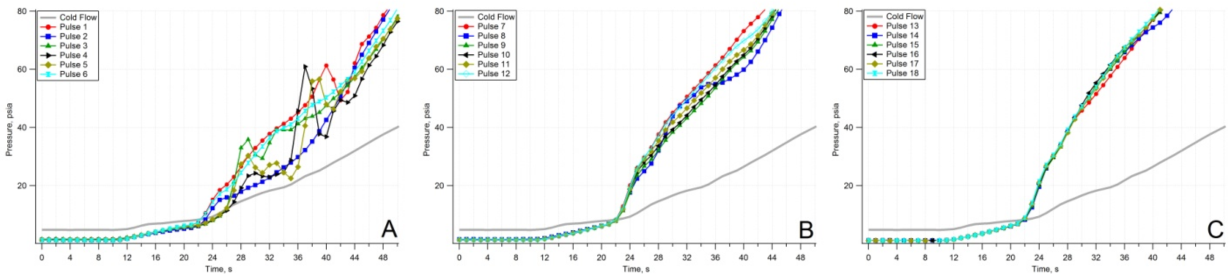

Figure 23: These three images show the igniter pressures from 18 consecutive pulses. The first six pulses in the left image have fluctuations indicative of a rumbling ignition. In the middle image the behavior becomes more consistent, culminating in very repeatable abrupt ignitions by the last six pulses at the right.

These ignition behavior transitions are evident in Figure 23, which shows ignitions for 20 sequential pulses at nominal propellant conditions. The igniter cavity pressure traces for each pulse are plotted against a relative time scale in milliseconds. Cold flow pressure is also shown as the solid line. Figure 23(a) shows the first six pulses. The first pulse was a stable, gradual ignition but the next three pulses showed fluctuations in the igniter cavity, indicative of a rumbling ignition. The behavior then began to stabilize as abrupt ignitions for pulses 7 to 12, shown in Figure 23(b). The last six pulses (Figure 23(c)) show very repeatable abrupt ignitions. The transition from gradual ignition early in the test to abrupt ignition late for a pulse train in the I-bit test series exhibits the same trend observed for ignition tests over the course of a test day (Figure 22).

5.2.1 Rumbling Ignition—I-Bit Test Series

Perhaps the most interesting ignition case is that of the "rumbling" ignition. The data suggest that sparking initiated a reaction in the igniter torch cavity, possibly an unstable flame kernel that did not immediately induce ignition of the main chamber. While this ignition type only occurred once in this ignition margin test series, a revisit of the previous I-bit test series (Ref. 7) provides more evidence.

During the I-bit test series, the engine was pulsed (short fired) up to 30 consecutive times. While no spark waveform data were captured for those tests, the igniter cavity pressure and chamber pressures were recorded and can be examined. Figure 24 shows a closeup of several rumbling ignitions during one of these pulse trains. Igniter cavity and chamber pressures are shown near the time of ignition, along with the cold flow baselines, for five successive pulses. A cold flow departure and fluctuation in the igniter cavity pressure is evident in all five pulses, but in the top three plots (pulses 8, 9, and 10) there is a 10- to 15-ms delay before a corresponding rise in chamber pressure. For these cases, chamber pressure remains at the cold flow pressure, indicating the activity is initially isolated to the igniter cavity. Since these ignitions typically display mild oscillations in igniter pressure until main chamber ignition, they are referred to as rumbling ignitions.

The majority of the rumbling ignitions observed during the I-bit test series occurred within the first 10 pulses. It was most commonly encountered for cold propellant conditions where 15 percent of the 131 pulses performed were classified as rumbling ignitions. Only two of those occurred at the end of the pulse train (after pulse 20). A total of 218 pulses were performed at nominal temperature, with 11 percent demonstrating this ignition type. At warm conditions, only 1 of the 170 total pulses exhibited a rumbling ignition, suggesting that propellant temperature and its relation to injection hardware temperature are key factors affecting its incidence.

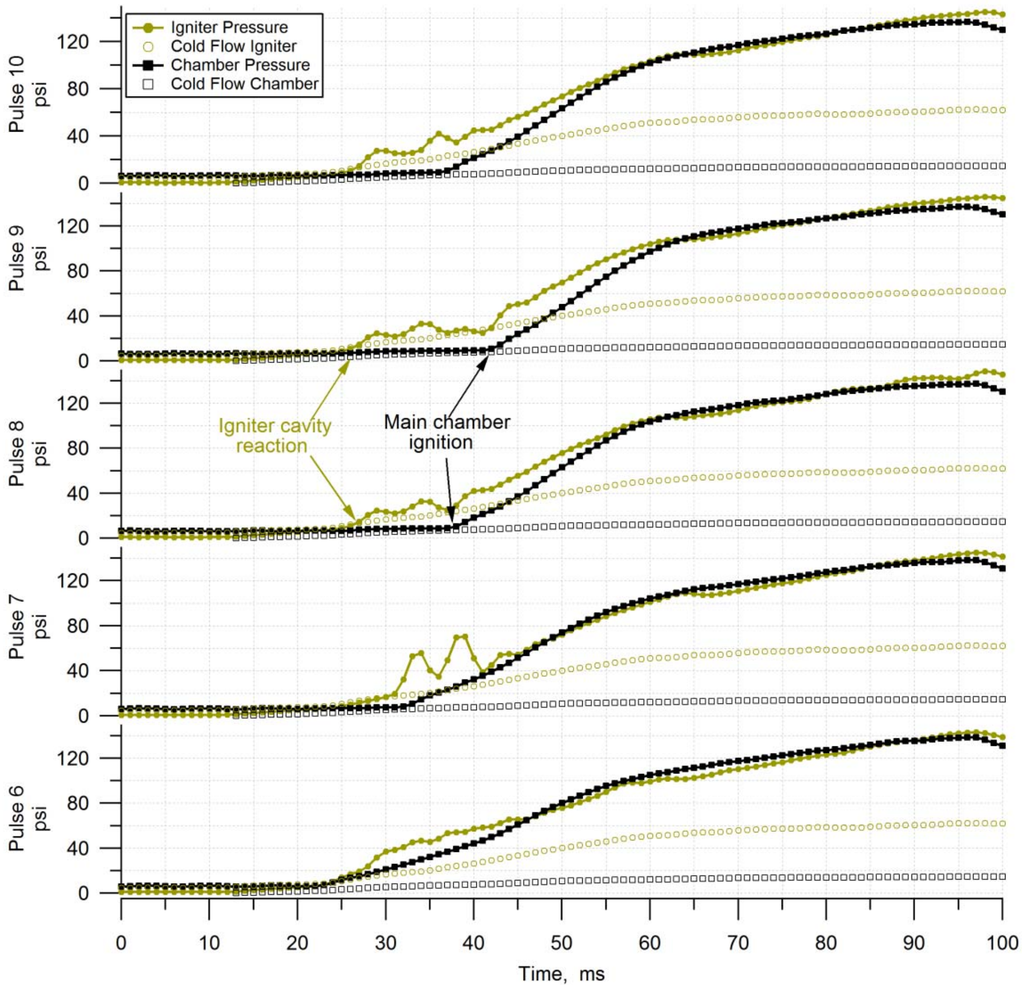

Figure 24: Ignition pressure traces illustrate rumbling ignitions (top three plots). Fluctuations in the igniter pressure indicate a reaction, but the chamber pressure does not respond. The data are taken from a pulsed fire engine test from the previous test program (run 255), where this type of ignition was more commonly observed.

6.0 Conclusions

The ignition margin test series was performed at NASA Glenn Research Center's Altitude Combustion Stand using the 100-lbf LO_2/LCH_4 RCE. With the goal of exploring minimum energy requirements for this propellant combination, a total of three exciters were tested. All were instrumented with a high-speed digital oscilloscope to resolve current and voltage waveforms of the spark discharges. These data were synchronized with the engine pressure and temperature data to enable identification of the ignition spark.

For all exciter units, spark waveforms in the hot fire, engine environment differed from those of dry spark tests (room condition, no-flow environment). The dry sparks demonstrated repeatable waveforms and consistent spark energies; whereas the hot fire tests had changing waveforms and inconsistent energies within a single spark train. As igniter pressure and flow rate increased during progression of each spark train, spark discharge voltages tended to increase and result in shorter spark durations. This indicates that rising pressures and flow rates substantially increase spark impedance, which, at some point, can affect an exciter's ability to complete sparks without quench. That is, higher pressures and cross flows in the spark gap region can raise spark voltage to levels that exceed the limit that a particular exciter can tolerate. When an exciter is able to sustain sparks of increased voltage, the energy transferred to the sparks is marginally improved over that for baseline spark voltage levels. However, if spark voltages reach exciter limits, premature extinctions and/or reductions of spark energy (i.e., quenched sparks) typically result. If these features occur prior to ignition, this has an adverse impact on ignition promptness and reliability.

After ignition, the accelerated pressure rise caused by the flame kernel had the most obvious effect on spark discharge characteristics. The Variable Energy Exciter (VEE), which had a higher (9 to 10 kV) high-voltage (HV) pulse, was able to achieve breakdown and initiate sparks at elevated pressures, but its low capacitor driving voltage was often unable to sustain, or complete each spark. Sparks occurring after ignition therefore tended to quench. This was not the case for the Unison which, with its higher capacitor driving voltage, always delivered full sparks after ignition. It might be surprising that the Unison's lower HV pulse (6 kV) was sufficient to obtain breakdown in the higher post-ignition pressure environment. However, this may be attributed to ignition-induced flame ionization, which facilitated reduced breakdown voltages (BDVs), effectively invalidating Paschen-law pressure effects. By this same mechanism, flame ionization may have caused some post-ignition dropped sparks for the VEE, due to its circuit design. During preparation for HV pulse generation, moderate voltage on the VEE's output transformer secondary may have been sufficient to yield breakdown in the mildly ionized gap environment. As a result, a very weak, inductive, reverse polarity spark occasionally replaced and prevented the intended capacitor discharge spark, resulting in an apparent dropped spark.

Spark energies were obtained for two of the three units. With the third unit, the Champion exciter, spark energy capture proved to be incompatible with the data system capabilities. While the VEE was designed to allow precise control of spark energy, the engine environment caused a great deal of variability in waveform behavior and delivered energies. The unit's energy adjustment only served to limit the overall range of spark energies, but the sparks themselves were not repeatable, primarily due to erratic spark quenches. The individual sparks that triggered ignition were identified, but also exhibited a large scatter in energies. In some cases ignition was triggered by quenched sparks of energies as low as 1 to 6 mJ, although ignition by such sparks (in same time interval) was not reliable. By comparison, similarly timed, higher energy Unison sparks (55 to 75 mJ) regularly yielded ignition.

Yet, a spark of this higher energy did not always trigger ignition, so no distinct energy threshold can be presented for reliable ignition by a spark in a given time interval. Despite this, relatively reliable ignition was experienced with an appropriately timed train of Unison sparks. Evidently, a sequence of several sparks over an appropriate time interval is required such that their cumulative probability of ignition approaches 100 percent. Ignition probability thus depends not just on spark energy, but also on spark timing relative to propellant flow introduction. This was further supported by the Unison exciter tests in which the timing of the spark train was adjusted. The spark nearest to the initiation of propellant flow (either immediately before or after) tended to trigger ignition.

This ignition timing also impacted the nature of the ignition, as indicated by the pressure behavior in the igniter cavity and chamber. Four ignition scenarios were identified; the earlier ignitions caused a gradual pressure rise, while the later ignitions caused a more severe pressure rise. This was supported by data from the previous test series, which examined engine performance in pulsed mode operation. The pulses early in the train showed a gradual ignition, while the later pulses had abrupt ignitions. In the unique case of a "rumbling" ignition, which was primarily observed during pulse testing, the chamber pressure was unaffected by pressure fluctuations in the igniter cavity. In most cases, pressure response in the igniter cavity and chamber were simultaneous. The rumbling ignition suggests that an unstable flame kernel can develop in the igniter cavity. However, all rumbling ignitions did ultimately trigger main chamber ignition, albeit delayed.

From the standpoint of future LO_2/LCH_4 engine design, these RCE tests have demonstrated that reliable ignition of the propellants is possible. While spark energy was found to exhibit a significant influence on this reliability, no distinct minimum spark energy for reliable ignition was found. Rather, ignition displayed a stochastic dependence on spark energy. Note that it is delivered spark energy that is relevant in this regard. For the dynamic environment of the engine torch igniter, delivered spark energy did not always correspond to the rated output spark energy of the exciter. It is therefore important to verify that exciter design characteristics, such as capacitor driving voltage, are sufficient to guarantee unquenched spark delivery under actual igniter conditions. While higher spark energies tend to increase ignition probability, spark timing and repetition rate also play a critical role. Lower energy sparks that are well timed with respect to propellant entry often achieve ignition. Observations indicate that sparks early in the flow ramp-up (in this case –4 to +10 ms relative to methane flow initiation) have the highest probability of success. Yet, a single well-timed higher energy spark alone does not guarantee ignition. Several sparks over the optimum time interval appear to be necessary to ensure an adequate cumulative probability of ignition. Thus, a high spark rate (here, 200 to 300 sparks per second) yielding more sparks in this optimum interval helps facilitate ignition reliability. Later sparks, timed after the optimum interval, can still trigger ignition, but do so with reduced probability.

Appendix A.—Test Logs

The following tables list all tests that were performed as part of this study. The information is abbreviated with respect to JANNAF standards to facilitate easier viewing of the parameters referenced in this document. Raw data is available upon request.

- Run: The number of the test run as referenced to the first facility tests in the 100-lb RCE test program.
- Test description: This column indicates whether or not an ignition occurred within each run. "Hotfire" refers to a successful ignition.
- Target temperature: This column indicates the propellant temperature setpoint condition: cold (170 °R LCH_4, 163 °R LO_2), nominal (204 °R), and warm (224 °R).
- Exciter timing: When the exciter was activated, relative to the propellant valve commands. "Simultaneous with LOX" or "with Lox cmd" indicates the exciter was commanded on at the same time the LOX valve was commanded open. The actual response times of the valves are described in section 3.1.
- First captured spark: This indicates the time in which the first recorded spark occurred. For the VEE and Unison, this is the first spark of the train. But since only one or two sparks could be captured for the Champion, this indicates when the first captured spark occurred. This is the elapsed time relative to the PLC start. For all tests, both propellants were flowing at 31.082 s.
- Spark duration: The exciter remained active for the amount of time specified here.
- Number of sparks: The total number of sparks in the train.
- *(VEE ONLY)* Energy Digipot setting: A digital potentiometer was used to vary spark energy. The setpoint value on the digipot dial is indicated here. (The resulting energies varied, so a calibration between setpoint and energy could not be represented.)
- *(VEE ONLY)* Spark rate Digipot setting: A digital potentiometer was used to vary spark rate. The setpoint value on the digipot dial is indicated here as well as the resulting spark rate (in parentheses).
- *(Champion ONLY)* Scope delay: This is the trigger delay used on the digital oscilloscope so the different sparks in the train could be captured. A higher delay would allow the capture of a spark late in the train. This number does not correlate directly to other DAQ times used in this paper, and is shown for completeness.
- *(Champion ONLY)* Scope resolution: This is another oscilloscope setting, displayed here for completeness. This setting governs the data rate.
- *(Champion ONLY)* Captured sparks: Only one to two sparks could be captured for the champion. This indicates which sparks in the train were captured.
- Run tank pressures: The pressure in the propellant holding tanks. This is a pressure-driven flow system, so these pressures govern the mass flow rate of the propellants. Engine flow rates were highly transient during the ignition time.
- Run tank temperature: The temperature of the propellant in the holding tanks. The desired conditions (cold, nominal, and warm) were judged based on the temperature at the thruster valve. Thus, the run tank temperatures were chosen to account for line losses. Note the temperatures are given in Fahrenheit, since this was the convention of the propellant conditioning systems.
- Valve temperature: The temperature at the propellant thruster valves.
- Ignition type: These designate the ignition characteristics as described in section 5.2.
- Notes: Test specific notes.
- Likely ignition spark: This indicates which spark in the train is believed to have triggered ignition.
- Spark energy: The calculated energy for each spark in the train.

Variable Energy Exciter

Run	Test description	Target temperature condition	Exciter timing	First captured spark, s	Spark duration, ms	Number of sparks	Energy - Digipot setting	Spark rate digitpot and (spark rate)	Ignition type	Run Tank Pressure, psig LO_2	Run Tank Pressure, psig LCH_4	Run Tank Temperature, °F LO_2	Run Tank Temperature, °F LCH_4	Valve Temperature, °R LO_2	Valve Temperature, °R LCH_4	NOTES	Likely Ignition Spark	Spark energy, mJ 1	2	3	4	5	6	7	8	9
8/12/2010																										
293	Abort thrust cal																									
294	Thrust cal																									
295	Hotfire	Nominal	simulataneou with LOX	31.0802	60	9	900	850 (250spark/s)	grad	325	265	-263	-264	193.3	195.0	Start at a high energy, and adjust timing	1	18.00	12.23	3.21	0.29	5.91	28.52	7.08	53.56	17.55
296	Hotfire	Nominal	simulataneou with LOX	31.0802	60	9	900	850 (250spark/s)	grad	325	265	-263	-264	201.5	194.9		1	21.18	15.45	0.00	0.00	7.68	27.08	10.95	8.38	4.93
297	Hotfire	Nominal	simulataneou with LOX	31.0801	60	9	900	850 (250spark/s)	grad	325	265	-262	-267	203.1	219.4	Methane temp was high	1	74.91	11.71	0.55	12.70	7.93	7.08	6.91	11.80	0.48
298	Hotfire	Nominal	simulataneou with LOX	31.0802	60	9	800	850 (250spark/s)	grad	325	265	-262	-268	198.6	199.5		1	0.88	0.00	0.00	0.00	0.00	12.08	8.98	0.00	3.54
299	Hotfire	Nominal	simulataneou with LOX	31.0799	60	9	800	850 (250spark/s)	abrupt	325	265	-262	-268	209.7	202.6		2	28.31	15.46	0.00	0.00	5.19	5.04	0.00	7.13	0.00
300	Hotfire	Nominal	simulataneou with LOX	31.0802	60	9	800	850 (250spark/s)	late	325	265	-262	-268	196.0	201.8		7	49.22	21.74	33.30	63.80	63.22	75.14	11.32	1.48	6.40
301	Hotfire	Nominal	simulataneou with LOX	31.0801	60	9	700	850 (250spark/s)	abrupt	325	265	-263	-266	196.8	200.4		3	23.73	12.03	41.53	10.33	14.86	5.46	4.76	7.02	3.55
302	Hotfire	Nominal	simulataneou with LOX	31.0811	60	9	700	850 (250spark/s)	abrupt	325	265	-263	-266	203.5	201.0		3	28.43	29.59	22.41	0.00	8.29	9.21	7.61	4.04	6.04
303	Hotfire	Nominal	simulataneou with LOX	31.0802	60	9	700	850 (250spark/s)	late	325	265	-263	-265	195.2	203.6		5	38.19	41.88	27.61	31.27	31.48	0.00	5.99	9.15	4.42
304	Hotfire	Nominal	simulataneou with LOX	31.0802	60	9	500	850 (250spark/s)	abrupt	325	265	-261	-264	202.4	201.3		3	13.21	14.96	20.77	0.00	4.84	5.90	3.97	3.15	4.44
305	Nolight	Nominal	simulataneou with LOX	31.0801	60	9	500	850 (250spark/s)	non	325	265	-261	-264	199.6	203.1		0	9.07	21.12	24.33	5.40	26.53	29.59	7.81	1.09	0.05
306	Hotfire	Nominal	simulataneou with LOX	31.0801	60	9	500	850 (250spark/s)	late	325	265	-261	-265	200.9	200.7		4	16.76	26.06	22.11	19.89	0.00	0.00	3.39	5.58	3.30
307	Thrust cal																									
8/26/2010																										
308	Aborted Thrust cal																									
309	Thrust cal																									
310	Cold flow	Nominal	simulataneou with LOX							325	265	-265	-265			Pcign purge is high... 14psi, should be 5psi										
311	Cold flow	Nominal	simulataneou with LOX							325	265	-265	-265			Corrected Pcign purge										
312	Hotfire	Nominal	simulataneou with LOX	31.0802	60	8	900	850 (250spark/s)	grad	325	265	-264	-268	211.4	198.8		1	13.72	0.00	0.00	32.90	28.90	4.98	7.63	26.40	
313	Hotfire	Nominal	simulataneou with LOX	31.0813	60	4	900	200 (125spark/s)	grad	325	265	-264	-268	199.4	201.0	Ignited on first spark	1	58.94	0.00	0.00	4.32					
314	Hotfire	Nominal	simulataneou with LOX	31.0812	60	4	900	200 (125spark/s)	grad	325	265	-263	-269	203.0	204.0	Repeat previous	1	12.32	0.49	18.66	8.48					
315	Hotfire	Nominal	simulataneou with CH4	31.0903	60	8	900	850 (250spark/s)	late	325	265	-264	-266	206.5	199.1	Spark command with methane; still ignite 1st spark	1	61.29	0.00	4.91	27.40	5.62	30.55	6.42	0.00	
316	Hotfire	Nominal	simulataneou with CH4	31.0902	60	7	900	850 (250spark/s)	late	325	265	-264	-260	208.6	199.8	repeat	1	47.42	14.32	0.13	4.16	13.95	8.58	0.00	0.00	
317	Nolight	Nominal	simulataneou with CH4	31.0903	60	7	500	850 (250spark/s)	non	325	265	-263	-264	211.5	199.7	Energy setpoint reduced	0	6.39	3.34	0.00	0.00	0.00	0.00	0.00		
318	Hotfire	Nominal	simulataneou with CH4	31.0904	60	8	500	850 (250spark/s)	late	325	265	-264	-267	216.6	202.0	repeat	1	0.00	4.17	0.00	3.59	0.00	3.32	3.02	0.00	
319	Nolight	Nominal	simulataneou with CH4	31.0903	60	4	500	200 (125spark/s)	non	325	265	-264	-266	212.6	204.9	Reduce spark rate to clarify which ignites. NO sparks!	0	0.00	0.00	0.00	0.00					
320	Nolight	Nominal	simulataneou with CH4	31.0903	60	4	500	200 (125spark/s)	non	325	265	-263	-264	206.6	203.4	try again	0	5.21	0.00	0.00	0.00					
321	Hotfire	Nominal	simulataneou with LOX	31.0802	60	4	900	200 (125spark/s)	grad	325	265	-263	-266	206.8	203.5	Go back to look at previous (sucessful) conditions.Try one here then reduce spark energy	1	16.63	0.00	4.74	5.42					
322	Hotfire	Nominal	simulataneou with LOX	31.0802	60	4	500	200 (125spark/s)	grad	325	265	-263	-265	204.0	198.9	Energy setpoint reduced	1	5.40	0.00	0.00	0.00					
323	Nolight	Nominal	simulataneou with LOX	31.0812	60	4	500	200 (125spark/s)	non	325	265	-263	-263	204.7	200.9		0	4.10	0.00	0.00	0.00					
324	Nolight	Nominal	simulataneou with LOX	31.0802	60	4	700	200 (125spark/s)	non	325	265	-263	-264	206.8	200.4	Tried to get late ignition again, like in previous test day	0	7.39	0.00	0.00	0.00					
325	Nolight	Nominal	simulataneou with LOX	31.0802	60	4	700	200 (125spark/s)	non	325	265	-262	-264	207.2	200.6	repeat	0	6.54	1.27	0.00	0.00					
326	Hotfire	Nominal	simulataneou with LOX	31.0812	60	8	700	850 (250spark/s)	abrupt	325	265	-259	-264	205.5	202.5	repeat condition from earlier day	2	6.71	3.08	0.00	0.00	0.00	4.07	2.20	2.54	
327	Hotfire	Nominal	simulataneou with LOX	31.0802	60	5	700	425 (143spark/s)	abrupt	325	265	-262	-262	205.2	202.8	try mid range spark rate too see if rate affects ignition	2	5.36	14.75	4.39	3.33	0.00				
328	Cold flow	Nominal	simulataneou with LOX							325	265	-260	-262													
329	Thrust cal																									

Champion Exciter

Run #	Test description	Target temperature condition	Exciter timing	First captured spark, s	Spark duration, ms	Scope delay, ms	Scope resolution, ms/division	Captured sparks, # in sequence	Run Tank Pressure, psig LO_2	Run Tank Pressure, psig LCH_4	Run Tank Temperature, °F LO_2	Run Tank Temperature, °F LCH_4	Valve Temperature, °R LO_2	Valve Temperature, °R LCH_4	NOTES
9/16/2010															
330	Dry spark														
331	thrust cal														
332	Facility abort	Nominal	simulataneous with CH4		60	12	2		325	265	-260	-263			Set pressure error on the ejector train
333	Hotfire	Nominal	simulataneous with CH4	31.0823	60	12	2	2	325	265	-260	-263	206.4	200.8	Only 1 spark captured scope, looks like the next was igniting spark. Will shift scope timing
334	Hotfire	Nominal	simulataneous with CH4	31.0774	60	14	2	1, 2	325	265	-261	-262	203.3	199.1	2 sparks captured, include ignition spark. Both look good -no drop out
335	Hotfire	Nominal	simulataneous with CH4	31.0843	60	14	2	2	325	265	-261	-261	204.5	199.8	Repeat: 1 captured spark, not ignition spark.
336	Hotfire	Nominal	simulataneous with CH4	31.0783	60	16	2	2,3	325	265	-260	-262	200.2	200.3	Shifted scope timing again to catch likely ignition sparks. Late ignition. 2 captured sparks, neither ignition
337	No light	Nominal	simulataneous with CH4	31.0844	60	16	2	2	325	265	-261	-261	197.6	202.2	No ignition. Tign is decreasing so not even late ignition. Gas in both manifolds.
338	Hotfire	Nominal	simulataneous with CH4	31.0779	60	16	2	2,3	325	265	-261	-260	203.1	203.1	Increased input voltage to 29.5V (was 28V) to see if this increases spark rate & try to increase number sparks we see. Spark rate did not change signficantly. Late ignitions seem more regular now, so shift scope delay on next test
339	Hotfire	Nominal	simulataneous with CH4	31.0906	60	22	2	3	325	265	-260	-260	212.2	203.2	Increased scope delay. 1 spark captured after ignition.
340	Hotfire	Nominal	simulataneous with CH4	31.0835	60	22	2	2,3	325	265	-260	-261	201.7	201.7	Turned off powersupply between tests to discharge. See if it effects 1st spark timeing. Did not effect 1st spark.
341	Hotfire	Nominal	simulataneous with CH4	31.0882	60	22	2	3,4	325	265	-260	-261	216.9	201.8	repeat: 2 captured sparks, 2nd ignition spark. Both sparks look good.
342	Hotfire	Nominal	simulataneous with CH4	31.0891	60	30	2	3,4	325	265	-259	-260	203.1	204.1	Increased scope delay. 2 captured sparks, 2nd ignition, both clean sparks.
343	Hotfire	Nominal	simulataneous with CH4	31.0711	60	30	2	1,2	325	265	-258	-260	201.0	204.2	Input voltage(trigger signal) spiked early. Scope time window wrong (too early). Don't know why, repeat to see
344	Hotfire	Nominal	simulataneous with CH4	31.0964	60	30	2	3,4	325	265	-259	-260	197.7	202.8	2 sparks both after ignition, both good.
345	Hotfire	Nominal	simulataneous with CH4	31.1091	60	40	2	5	325	265	-257	-257	206.9	202.9	Shifted scope window to catch last sparks. 1 spark captured
346	Hotfire	Nominal	simulataneous with CH4	31.0998	60	40	2	4,5	325	265	-259	-256	206.9	203.0	2 captured sparks, ignition spark, both good
347	No light	Nominal	simulataneous with CH4	31.1044	60	40	2	4,5	325	265	-258	-256	202.9	202.6	2 captured sparks look fine
348	thrust cal														

Unison "brick" Exciter

Run	Test description	Target temperature condition	Exciter timing	First captured spark, s	Spark duration, ms	Number of sparks	Ignition type	Run Tank Pressure, psig LO_2	Run Tank Pressure, psig LCH_4	Run Tank Temperature, °F LO_2	Run Tank Temperature, °F LCH_4	Valve Temperature, °R LO_2	Valve Temperature, °R LCH_4	NOTES	Likely Ignition Spark	Spark energy, mJ 1	2	3	4	5	6	7
9/23/2010																						
349	Thrust cal																					
350	Abort	Nominal	simulatanous with Ch4		60		non	325	265	-263	-265			There were no sparks-power supply was off								
351	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	grad	325	265	-262	-262	205.5	197.0		2	64.61	60.70	76.64	69.01	73.95	71.38	74.48
352	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	grad	325	265	-263	-261	206.6	201.3		2	143.73	63.07	74.52	72.80	76.17	92.74	68.89
353	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	grad	325	265	-259	-264	209.1	199.3		2	64.34	61.25	75.51	67.81	72.31	80.62	82.32
354	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	grad	325	265	-262	-264	202.8	200.0		2	60.69	63.09	74.47	70.97	71.33	86.70	82.70
355	Hotfire	Nominal	simulatanous with Ch4	31.0753	60	7	abrupt	325	265	-262	-264	208.6	199.5		3	59.25	68.87	47.42	71.58	71.87	68.88	68.89
356	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	abrupt	325	265	-262	-262	205.6	199.5		3	187.70	64.50	77.77	83.73	79.45	97.92	78.82
357	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	rumble	325	265	-260	-264	209.1	198.5		5	47.47	67.82	70.89	73.48	141.24	92.69	87.18
358	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	abrupt	325	265	-261	-264	212.1	202.5		3	96.84	66.29	136.08	76.31	76.77	87.47	80.29
359	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	abrupt	325	265	-261	-262	196.9	201.7		3	123.29	64.23	48.85	73.19	74.71	78.28	79.04
360	Hotfire	Nominal	simulatanous with Ch4	31.0743	60	7	abrupt	325	265	-262	-263	209.1	201.1		3	55.22	64.63	123.11	72.90	67.01	75.42	75.28
361	steady state run														3							
362	Thrust cal																					
9/30/2010																						
363	Thrust cal																					
364	Cold flow	Cold						325	285	-296	-281											
365	Hotfire	Cold	simulatanous with Ch4	31.0743	60	7	grad	325	285	-296	-281	174.2	180.1	Looks like possible"rumbling ignition". Definate quench on spark #3.	2	55.81	54.11	66.12	65.31	64.12	63.26	71.53
366	Hotfire	Cold	simulatanous with Ch4	31.0742	60	7	grad	325	285	-269	-283	173.6	179.6		2	49.38	59.08	68.20	65.77	78.45	59.25	74.40
367	Hotfire	Cold	simulatanous with Ch4	31.0753	60	7	grad	325	285	-296	-282	176.3	179.0		2	167.16	56.00	69.89	62.16	65.90	64.58	76.06
368	Hotfire	Cold	10ms after Ch4	31.0843	60	7	abrupt	325	285	-296	-278	177.1	178.2		1	146.95	63.10	61.36	66.93	67.01	71.14	83.08
369	Hotfire	Cold	10ms after Ch4	31.0843	60	7	abrupt	325	285	-296	-282	175.8	177.8		1	71.26	65.94	60.24	63.38	81.56	69.57	69.56
370	Hotfire	Cold	10ms after Ch4	31.0842	60	7	abrupt	325	285	-296	-283	177.5	177.7		1	76.81	63.88	61.60	65.32	67.89	64.06	63.19
371	Hotfire	Cold	20ms after Ch4	31.0952	60	7	late	325	285	-295	-281	175.8	177.5		1	172.54	65.57	79.22	66.37	69.82	74.75	65.70
372	Hotfire	Cold	20ms after Ch4	31.0942	60	7	late	325	285	-295	-280	177.4	177.4		1	45.63	76.71	61.28	65.53	60.80	66.59	60.26
373	Hotfire	Cold	20ms after Ch4	31.0942	60	7	late	325	285	-294	-280	178.5	177.7		1	116.27	65.04	63.58	74.76	60.89	63.79	59.96
374	Cold flow	Cold								-290	-284											
375	Thrust cal																					
10/21/2010																						
376	Thrust cal																					
377	Cold flow									-240	-239											
378	Hotfire	warm	simulatanous with Ch4	31.0743	60	7	grad	370	265	-240	-238	225.5	220.9	Zero shift in current	2	42.48	53.56	46.19	55.82	58.60	62.78	55.78
379	Hotfire	warm	simulatanous with Ch4	31.0753	60	7	abrupt	370	265	-239	-240	226.2	228.6	Zero shift in current	3	43.40	47.75	63.65	51.13	56.43	55.20	56.82
380	Hotfire	warm	simulatanous with Ch4	31.0743	60	7	abrupt	370	265	-240	-238	226.4	225.7		3	44.32	52.99	69.15	49.74	54.51	61.28	60.46
381	Hotfire	warm	simulatanous with Ch4	31.0743	60	7	abrupt	370	265	-239	-238	228.6	218.1		3	50.29	42.25	31.94	50.18	49.58	54.71	53.02
382	Hotfire	warm	simulatanous with Ch4	31.0753	60	7	abrupt	370	265	-240	-239	226.7	216.3		3	58.34	48.50	62.67	60.65	49.20	59.49	53.80
383	Hotfire	warm	simulatanous with Ch4	31.0742	60	7	abrupt	370	265	-239	-238	225.1	226.3		3	33.68	43.74	101.05	53.37	55.54	56.20	61.01
384	Hotfire	warm	simulatanous with Ch4	31.0742	60	7	abrupt	370	265	-239	-239	219.0	226.3		3	48.49	43.71	131.03	54.47	60.40	63.68	55.10
385	Hotfire	warm	simulatanous with Ch4	31.0733	60	7	abrupt	370	265	-239	-238	225.8	221.7		3	149.20	47.04	117.57	57.72	55.54	64.19	56.81
386	Hotfire	warm	10ms after Ch4	31.0843	60	7	abrupt	370	265	-239	-239	219.5	218.9		2	0.00	72.52	47.72	56.37	55.12	56.18	53.32
387	Hotfire	warm	10ms after Ch4	31.0843	60	7	grad?	370	265	-239	-237	227.9	221.8		1	77.91	60.73	57.90	52.55	60.29	49.20	53.95
388	Hotfire	warm	10ms after Ch4	31.0843	60	7	abrupt	370	265	-239	-238	225.2	222.5		2	127.06	50.26	52.61	55.71	46.08	55.37	61.88
389	Nolight	warm	20ms after Ch4	31.0952	60	7	non	370	265	-239	-238	222.8	223.5	No current draw on any spark -all dropout	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
390	Hotfire	warm	20ms after Ch4	31.0943	60	7	late	370	265	-237	-237	226.7	223.2		1	50.70	51.93	57.51	47.92	57.14	57.71	55.95
391	Hotfire	warm	20ms after Ch4	31.0943	60	7	late	370	265	-239	-237	215.3	222.5		1	66.02	68.93	55.43	58.19	62.41	52.52	67.51
392	Hotfire	warm	20ms after Ch4	31.0652	60	7	late	370	265	-238	-238	226.6	224.9	First sparks dropped out… late ignition. Looks like later ignition means less reliable sparks	4	0.00	0.00	0.00	67.54	50.70	48.76	45.59
393	Hotfire	warm	simulatanous with LOX	31.0653	60	7	grad	370	265	-238	-237	219.5	217.2	The sparks before propellant flow don't tell much. Had hoped to see timing shift with respect to manifold press rise, but not	4	151.64	45.55	42.87	53.78	44.03	54.47	47.63
394	Hotfire	warm	simulatanous with LOX	31.0653	60	7	abrupt	370	265	-238	-236	234.2	219.4		5	39.25	48.85	49.75	27.46	124.55	47.90	47.88
395	Hotfire	warm	simulatanous with LOX	31.0643	40	7	abrupt	370	265	-238	-236	224.9	225.4	(limited train duration). Didn't work because the	5	58.96	47.06	47.72	50.91	150.23	49.53	53.16
396	Hotfire	warm	simulatanous with LOX	31.0943	20	4	grad	370	265	-238	-234	221.4	218.9		4	136.66	47.32	46.31	51.22			
397	Nolight	warm	simulatanous with LOX	31.0943	20	4	non	370	265	-237	-241	229.4	218.6	Voltage on exciter increased from 28 to 32v to try to decrease delay to 1st spark	0	41.55	36.56	47.00	47.96	0.00	0.00	0.00
398	Nolight	warm	simulatanous with LOX	31.0643	20	4	non	370	265	-237	-240	228.5	218.2		0	151.99	44.53	35.68	44.74	0.00	0.00	0.00
399	Hotfire	warm	20ms after Ch4	31.0653	20	4	late	370	265	-237	-237	220.8	234.5	Return previous conditions that had drop outs to try to recreate. Keep reduced spark duration to minimize hard start risk	1	27.42	53.91	52.56	55.23	0.00	0.00	0.00
400	Nolight	warm	20ms after Ch4	31.0942	20	4	non	370	265	-237	-235	239.2	223.7	No current draw on any spark -all dropout	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
401	Thrust cal																					

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14. ABSTRACT The use of nontoxic propellants in future exploration vehicles would enable safer, more cost-effective mission scenarios. One promising “green” alternative to existing hypergols is liquid methane (LCH_4) with liquid oxygen (LO_2). A 100 lbf LO_2/LCH_4 engine was developed under the NASA Propulsion and Cryogenic Advanced Development project and tested at the NASA Glenn Research Center Altitude Combustion Stand in a low pressure environment. High ignition energy is a perceived drawback of this propellant combination; so this ignition margin test program examined ignition performance versus delivered spark energy. Sensitivity of ignition to spark timing and repetition rate was also explored. Three different exciter units were used with the engine’s augmented (torch) igniter. Captured waveforms indicated spark behavior in hot fire conditions was inconsistent compared to the well-behaved dry sparks. This suggests that rising pressure and flow rate increase spark impedance and may at some point compromise an exciter’s ability to complete each spark. The reduced spark energies of such quenched deliveries resulted in more erratic ignitions, decreasing ignition probability. The timing of the sparks relative to the pressure/flow conditions also impacted the probability of ignition. Sparks occurring early in the flow could trigger ignition with energies as low as 1 to 6 mJ, though multiple, similarly timed sparks of 55 to 75 mJ were required for reliable ignition. Delayed spark application and reduced spark repetition rate both correlated with late and occasional failed ignitions. An optimum time interval for spark application and ignition therefore coincides with propellant introduction to the igniter.						
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