Spark Ignition Characteristics of a LO_2/LCH_4 Engine at Altitude Conditions

Julie Kleinhenz, Charles Sarmiento, and William Marshall

The use of non-toxic propellants in future exploration vehicles would enable safer, more cost effective mission scenarios. One promising “green” alternative to existing hypergols is liquid methane/liquid oxygen. To demonstrate performance and prove feasibility of this propellant combination, a 100lb_f LO_2/LCH_4 engine was developed and tested under the NASA Propulsion and Cryogenic Advanced Development (PCAD) project. Since high ignition energy is a perceived drawback of this propellant combination, a test program was performed to explore ignition performance and reliability versus delivered spark energy. The sensitivity of ignition to spark timing and repetition rate was also examined. Three different exciter units were used with the engine’s augmented (torch) igniter. Propellant temperature was also varied within the liquid range. Captured waveforms indicated spark behavior in hot fire conditions was inconsistent compared to the well-behaved dry sparks (in quiescent, room air). The escalating pressure and flow environment increases spark impedance and may at some point compromise an exciter’s ability to deliver a spark. Reduced spark energies of these sparks result in more erratic ignitions and adversely affect 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 1-6mJ, though multiple, similarly timed sparks of 55-75mJ were required for reliable ignition. An optimum time interval for spark application and ignition coincided with propellant introduction to the igniter and engine. Shifts of ignition timing were manifested by changes in the characteristics of the resulting ignition.

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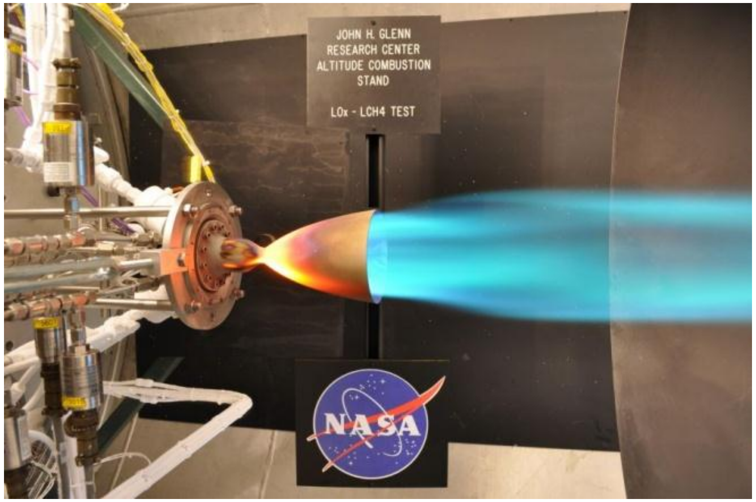
Propulsion and Cryogenic Advanced Development Project: LO_2/LCH_4 Performance study

- Examine the feasibility and performance characteristics of non-toxic (liquid oxygen/ liquid methane) propellant systems.
- Evaluate a 100 lb_f Reaction Control Engine at altitude conditions
- Vary propellant inlet temperature over liquid regime cold (170 ˚R LCH_4, 163 ˚R LO_2), nominal (204 ˚R), and warm (224 ˚R)



- Previously reported test series focused on determining Specific Impulse and Impulse Bit performance.

- **<u>Objective of Ignition test series</u>**:
  - Explore ignition performance and reliability versus delivered spark energy
  - Characterize spark behavior in an engine environment

Facility: GRC Altitude Combustion Stand

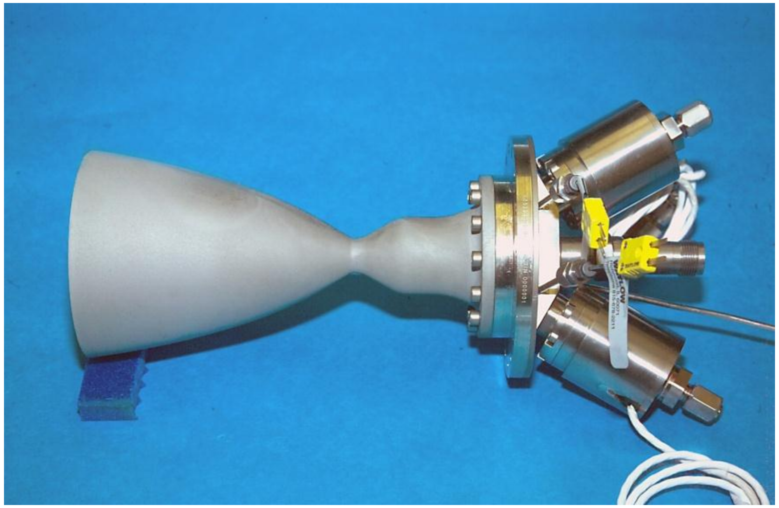
- Accommodates up to 2000-lb_f class engine
- Simulates altitude up to 130,000 ft
- $LO_2/GO_2/LH_2/GH_2/LCH_4$ and RP
- Chamber pressures up to 1000 psia
- Multi-stage ejector driven vacuum system, water spray cart/water cooled diffuser
- Propellant Conditioning Feed Systems to enable control of propellant inlet temperatures
  - Capable of maintaining propellant temperature +/- 5 °R

Engine: LO_2/LCH_4 RCE

- 100-lb_f (445-N) Reaction Control Engine (RCE) designed by Aerojet Corp.
- Chamber and nozzle are radiatively cooled columbium with oxidation resistant coating
- Nozzle is 45:1 exit ratio

Nominal Operating conditions

- P_c = 175 psia (1.2 MPa)
- O/F = 2.5
- Augmented (Torch) Igniter
- Integrated Igniter, 2.5% of total flow, ~1.82 O/F



Exciters

- Variable Energy Exciter (VEE):
  - Developed in-house to permit variation of spark rate and energy
- Champion* Exciter:
  - Commercial unit used during the Specific Impulse test program
  - Data from this unit will not be presented here
- Unison* Exciter
  - Commercial unit used during the Impulse Bit test program

* Commercial units "Champion" and "Unison" chosen based on availability and convenience, and the results presented here should not be construed as an endorsement of these units

	VEE	**Unison**	**Champion**
Type	Uni-polar	Uni-polar	Bi-polar
Spark Rate, sparks/sec	Variable, 125 to 250	200	100
Delivered Spark Energy*, 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
Delivered High Voltage Pulse**, kV	9 to 10	5 to 6	5 to 6
Test program	Ignition only	I-bit	Isp

* As measured for quiescent air spark gap.

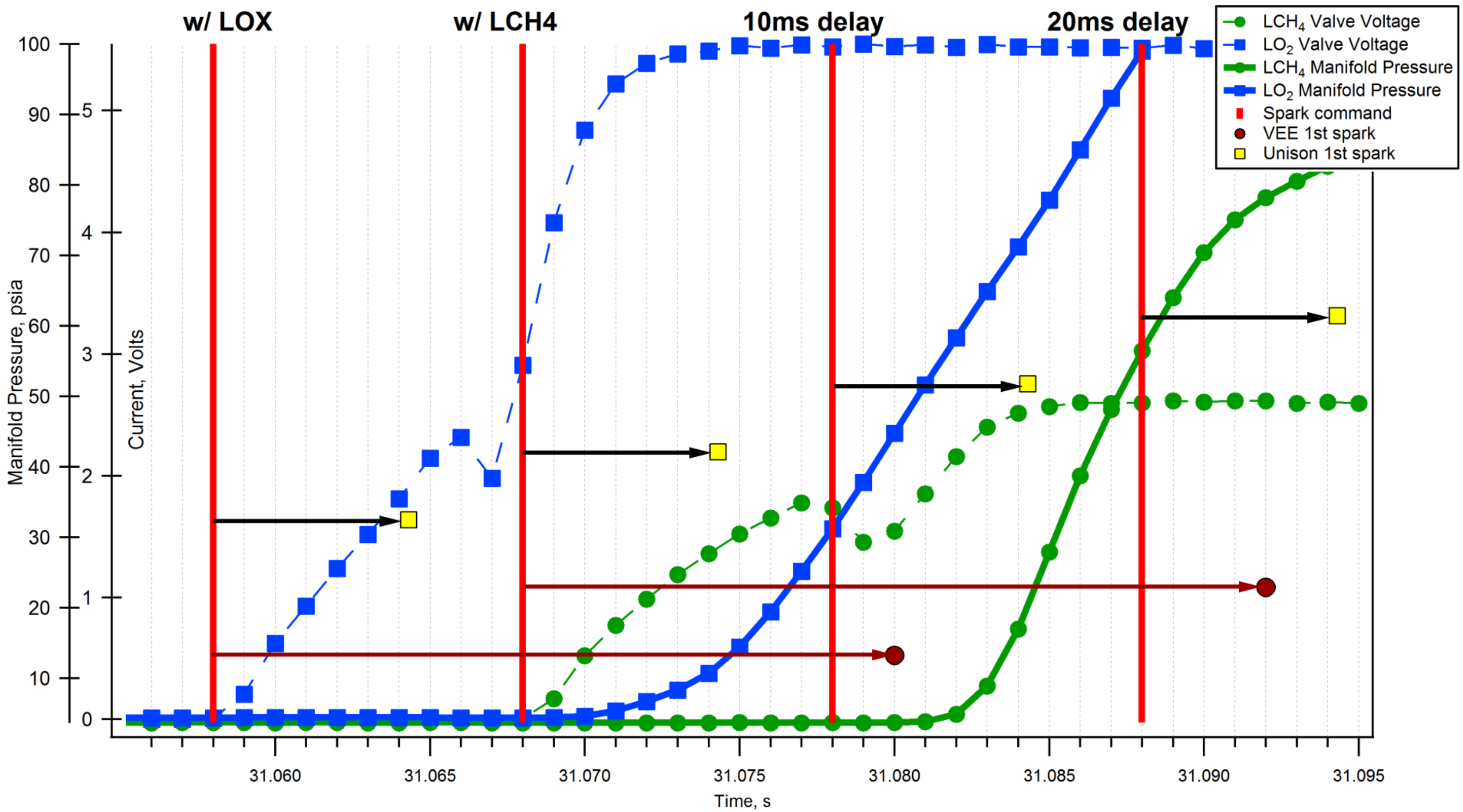
** High voltage pulse measured after cable attenuation

Exciters

- Units located outside vacuum, connected via 11.8 ft (3.6 m) unshielded, atmospherically sleeved cable
  - Signal attenuation resulted from length
- Spark plug: button tipped electrode with a 0.025 in. (0.64 mm) igniter annular spark gap
- Voltage and current probes located near exciter unit (outside vacuum)
  - Waveform data collected with a Digital Oscilloscope at 250,000 Hz (40 ms span)
  - Synchronized with engine data (pressures, temperatures, etc) which was logged at 1000 Hz

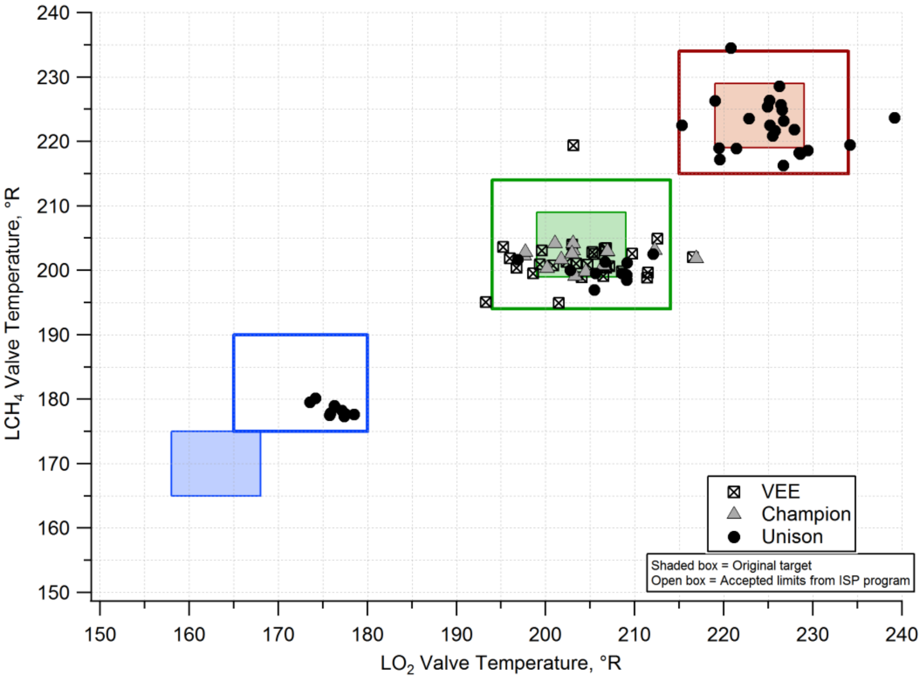
Timing

- PLC allowed 10 ms resolution
- LO_2 initiated 10 ms before LCH_4
- Igniter active for 60 ms (spark train)



Test summary

- Variable Energy Exciter (VEE)
  - 28 hot fire tests over 2 days
  - Energy set point varied on day 1
  - Spark rate varied on day 2
  - Nominal propellant temperature
- Unison Exciter
  - 44 hot fire tests over 3 days
  - Propellant temperature varied
- Champion Exciter
  - 15 hot fire tests
  - Bipolar spark waveforms required a high data acquisition rate to resolve. Only 1-2 sparks within the train could be captured using available DAQ system.
  - Data from this exciter is presented in:
    - Ref. 10: Kleinhenz, J.E., Sarmiento, C.J., and Marshall, W.M., "Experimental Investigation of Augmented Spark Ignition of a LO_2/LCH_4 Reaction Control Engine at Altitude Conditions," NASA TM-2012-217611, 2012



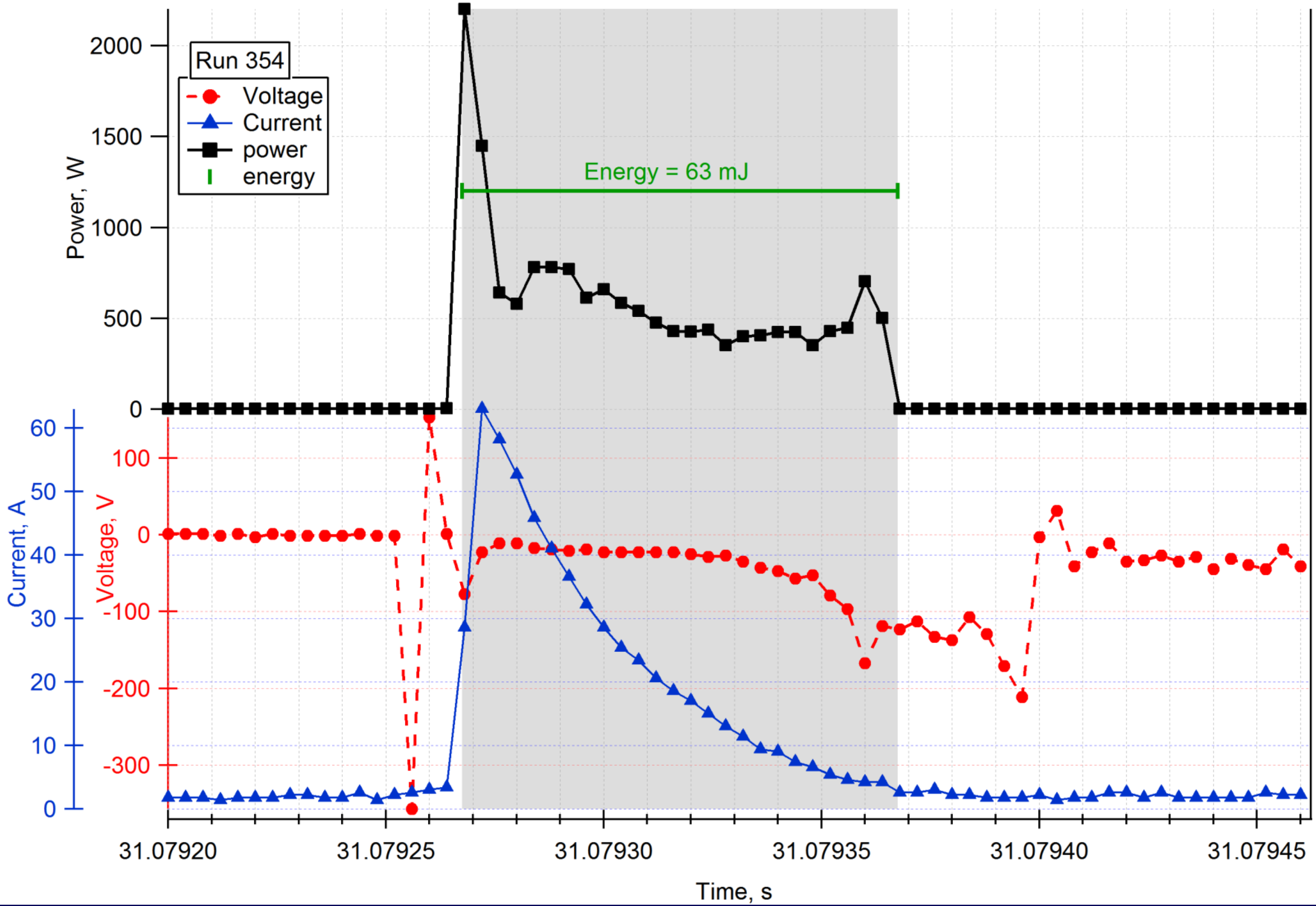
Results Summary

Results will show:

1. Waveform examples highlighting the effect of engine environment on individual spark behavior
2. Energy calculations for each spark, including the identification of the ignition spark
3. The effect of spark timing relative to the propellant flow/pressure conditions
   - How spark timing also affects the nature of ignition, as represented by the pressure rise in the igniter cavity and main chamber

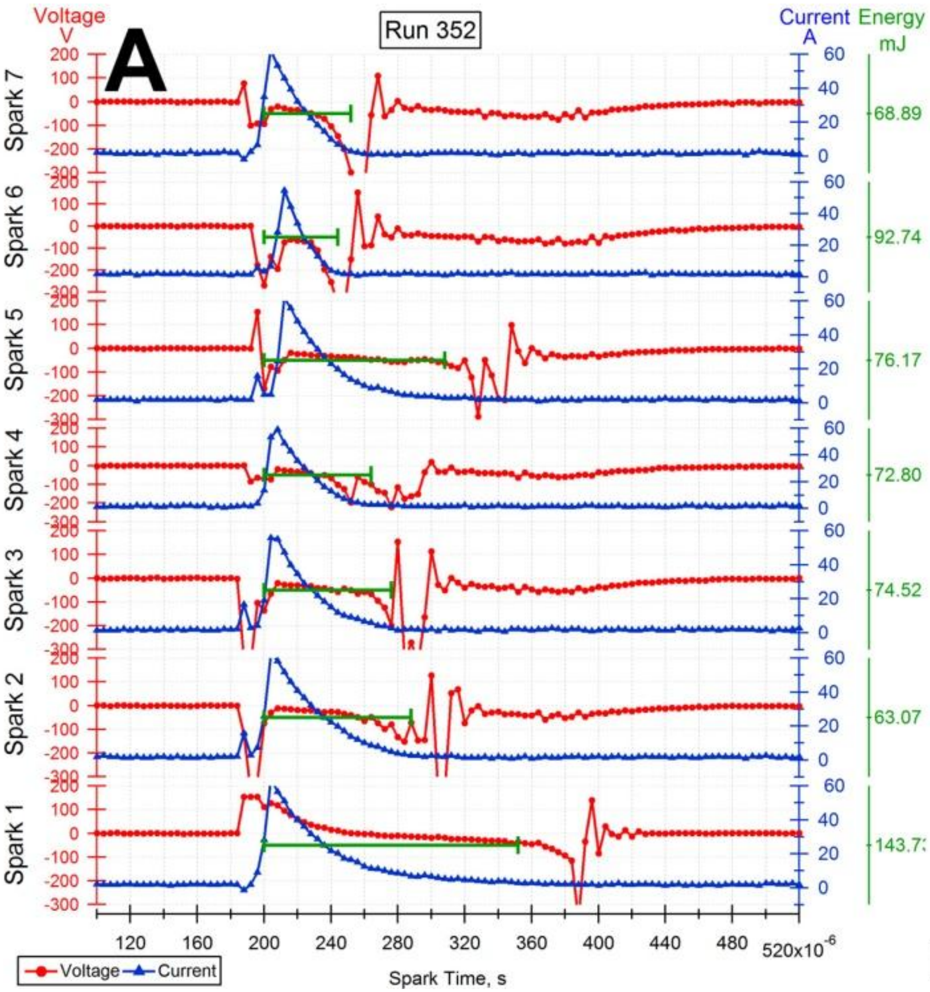
Energy Calculation

$$E_{spark=} \int |V * I| dt$$

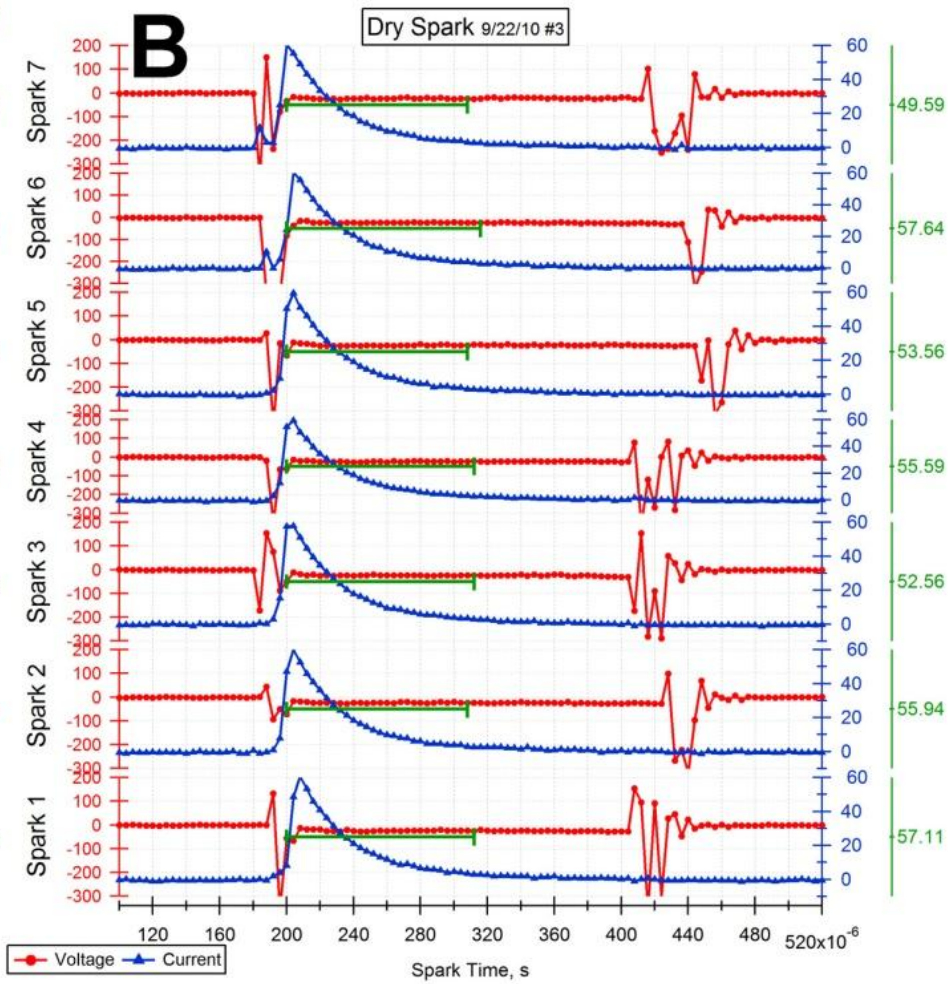


Waveforms -Unison

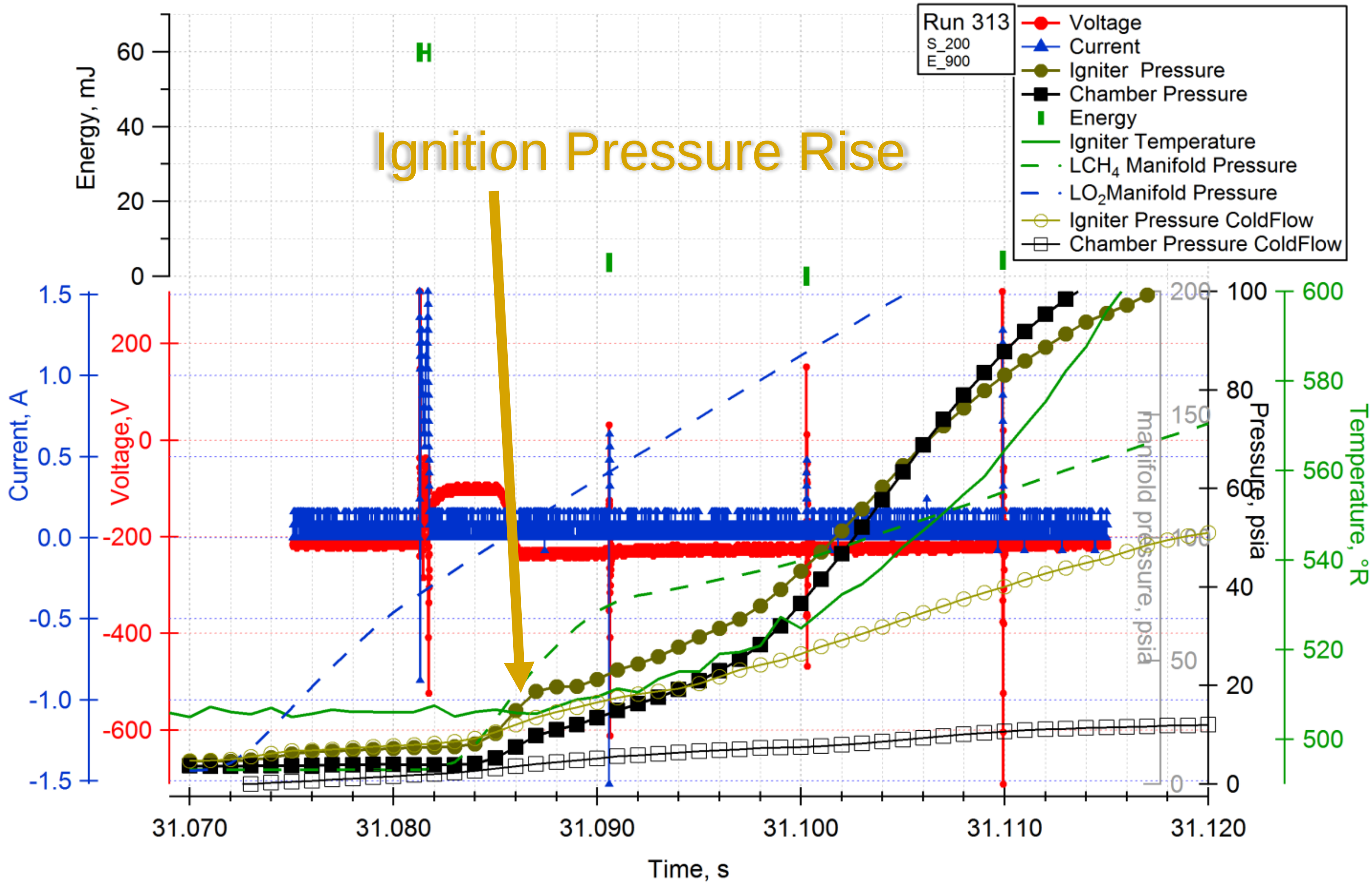
Hot Fire



Dry Spark



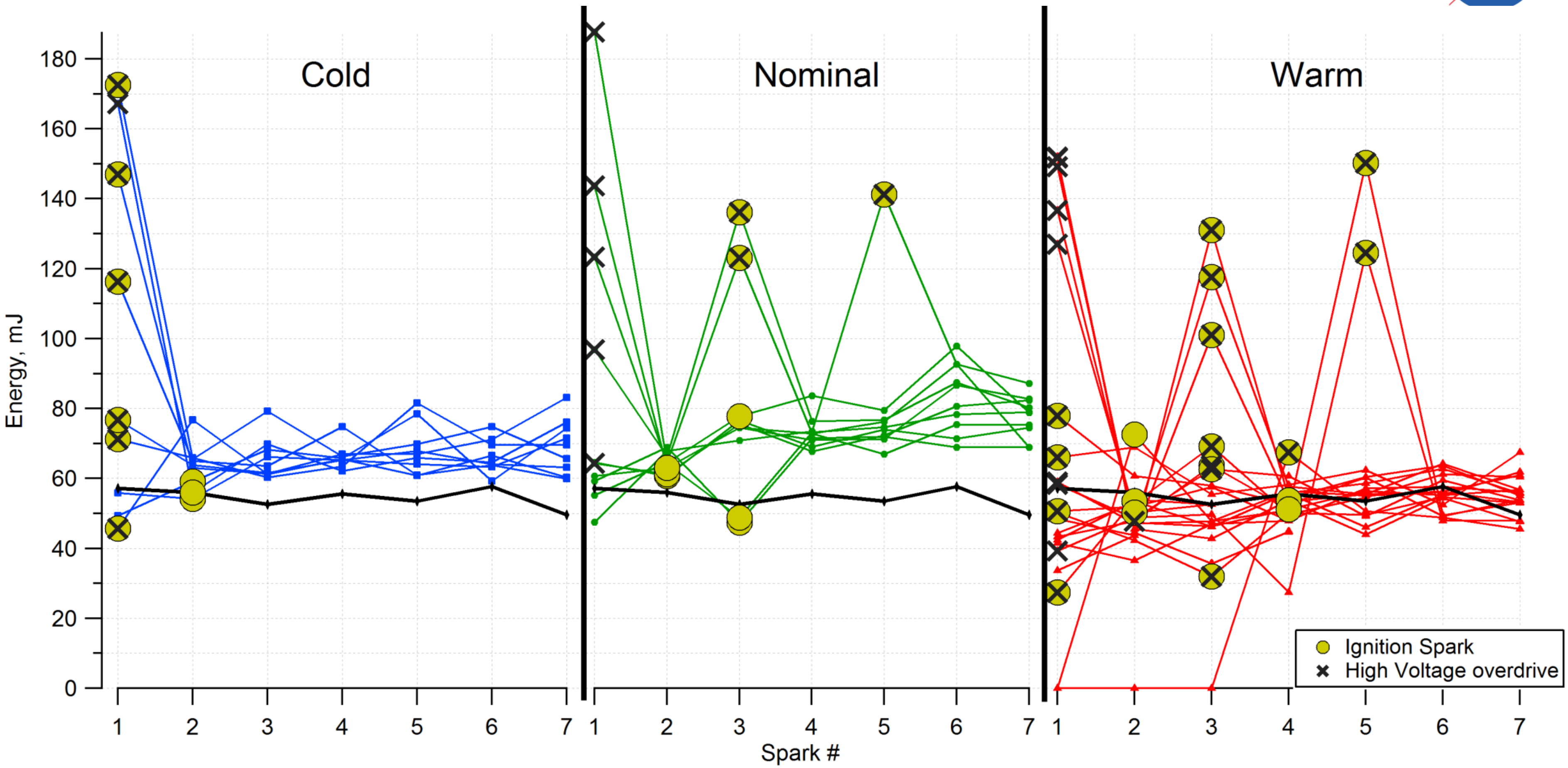
Ignition Spark Identification



Pressure response: 4 ms

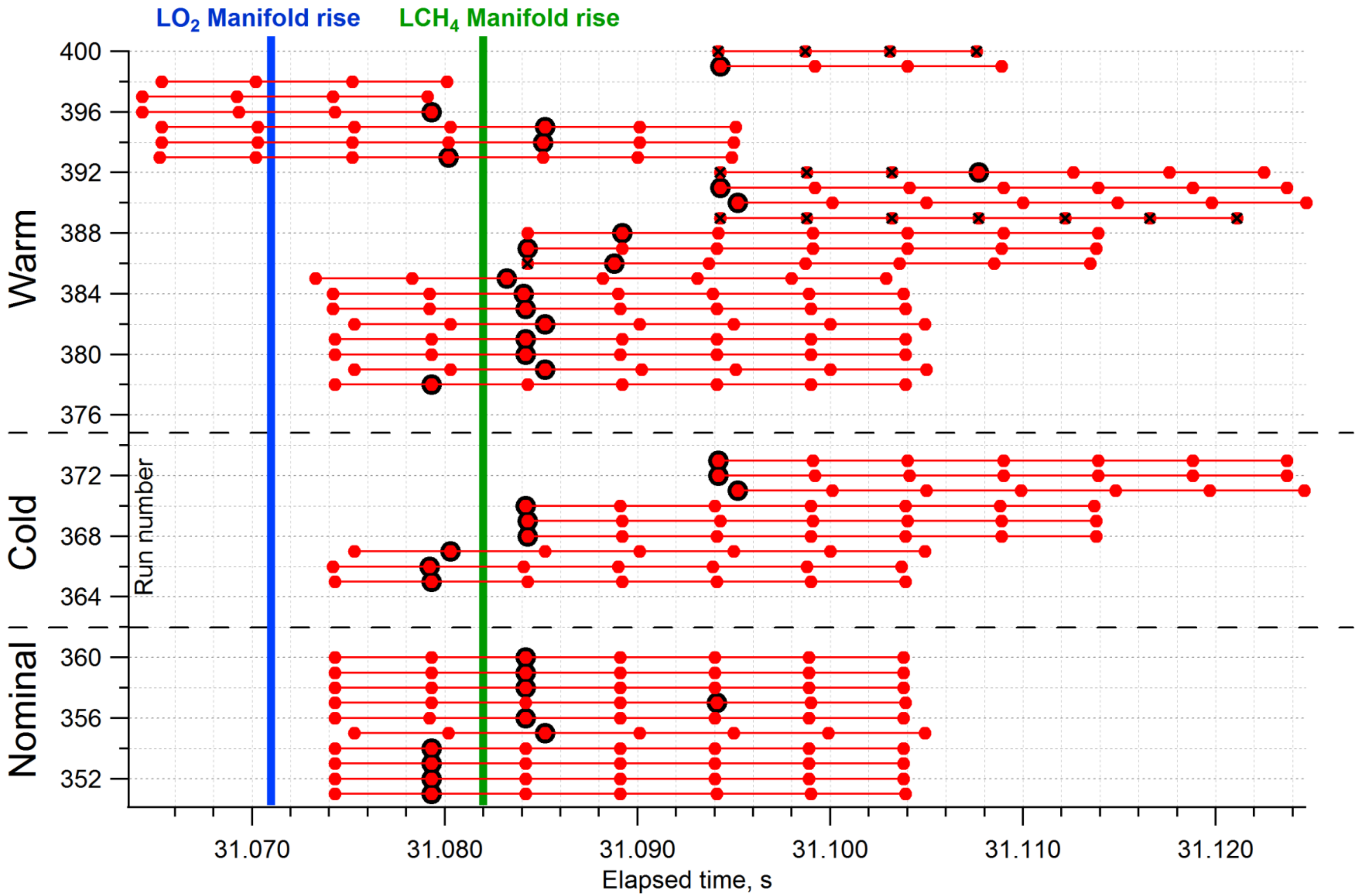
Temperature response: 8-10 ms

Unison- Energy



- Highest energies are not valid. This was due to an overdrive of the digital oscilloscope amplifier (indicated by X)
- Circles indicate ignition spark
- Energies are consistent, with slight increase at end of train.

Unison- Timing



- Earliest combustible mixture is when methane flow is introduced: Ignition occurs on sparks timed nearest to this
- Spark drop outs occur when activated late in the flow ramp up

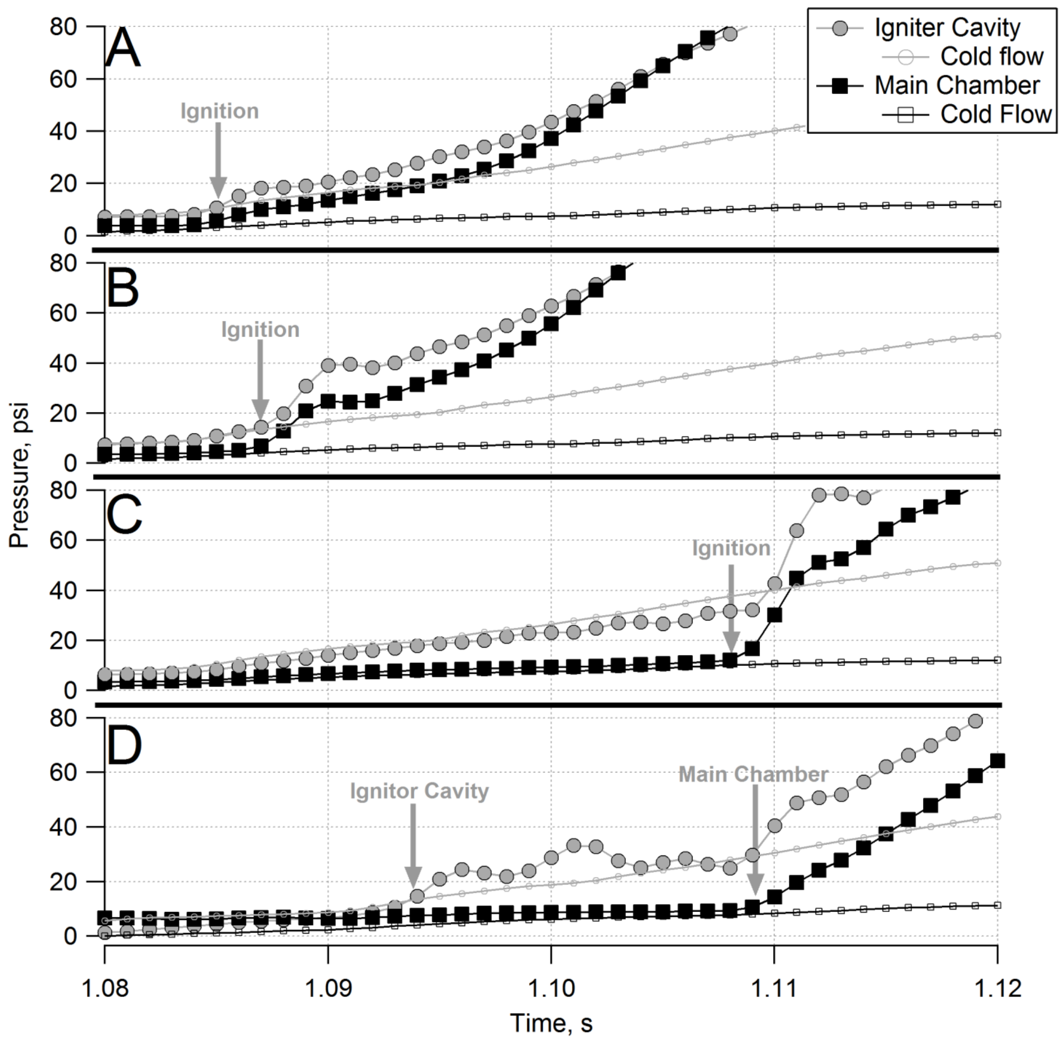
Timing – Ignition Characteristics

A. Gradual Ignition
- Occur earliest in combustible flow regime

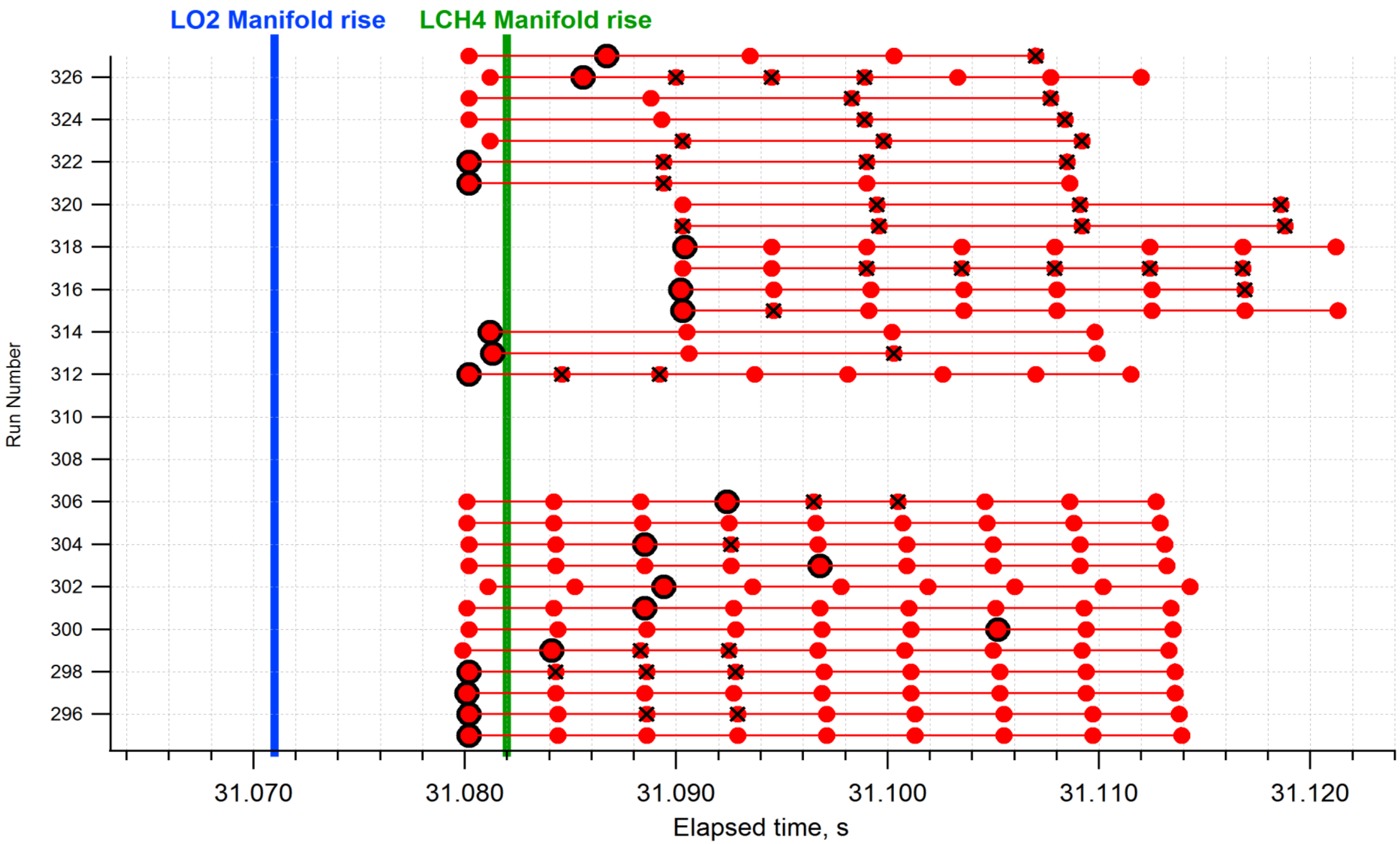
B. Abrupt Ignition
- Most common

C. Late Ignition
- Occur at least 10ms after fuel entry

D. Rumbling Ignition
- Occur randomly. Indicates ignition in igniter cavity, but not main chamber.

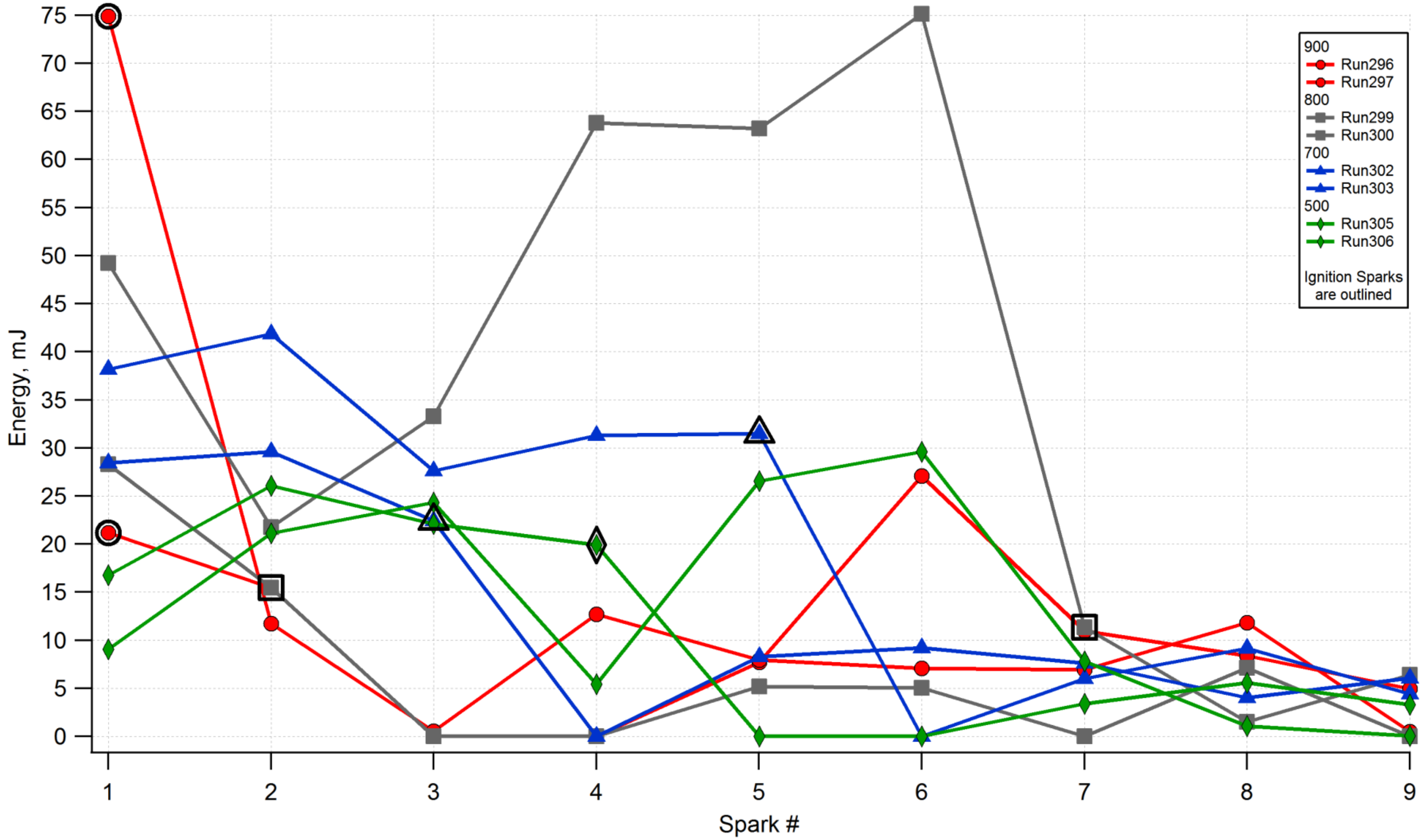


VEE- Timing



- More variation in ignition spark timing, also more variability in spark energies
- Spark drop outs tend to occur after ignition

VEE- Energies

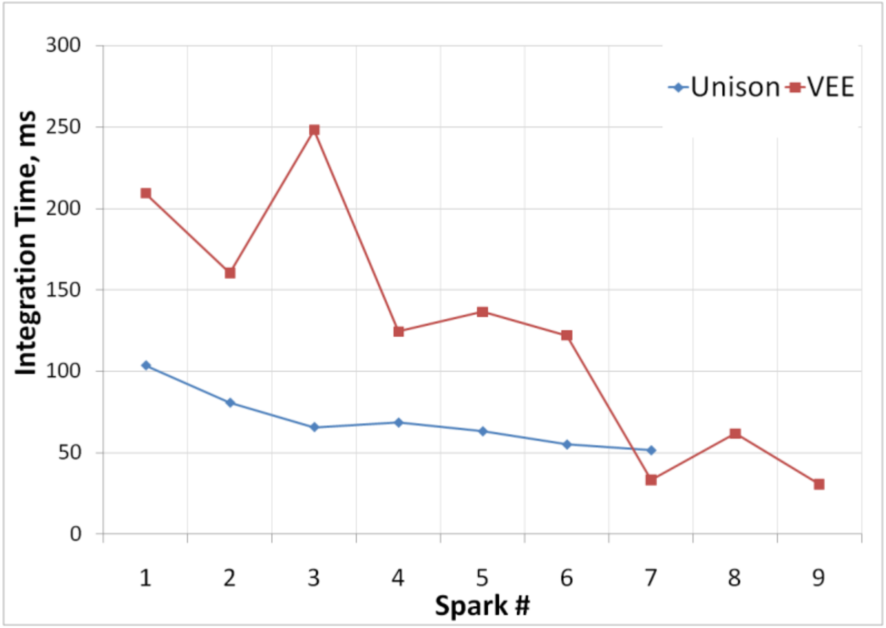


- Energy is inconsistent
- Spark drop outs/quenches tend to occur after ignition

Discussion: Engine environment

Dry Sparks behaved repeatable, whereas hot fire sparks demonstrated more variability

- Propellant flow stretches spark downstream, reducing deposited energy density[11]
- Turbulent flow prevent stabilization of flame kernel, and may create local mixture ratio fluctuation[12,13]
- Ignition is probabilistic, higher spark energy can increase probability
- Higher pressure environment results in higher impedance. Spark discharge time is therefore shorter



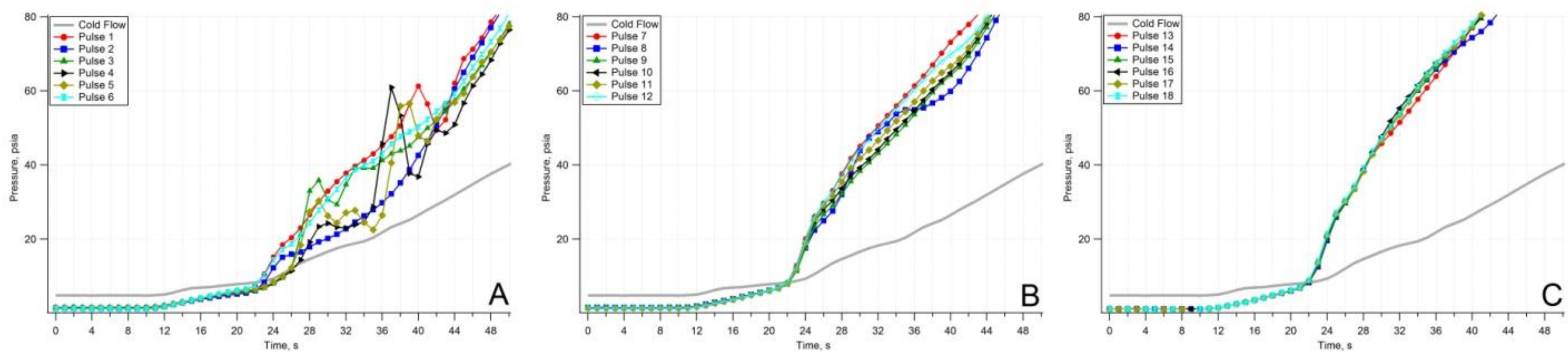
- [11] Glassman, I. Combustion. 3rd Edition. Academic Press. 1996. (pg 347)
- [12]Mastorakos, E. "Ignition of turbulent non-premixed flames", Progress in Energy and Combustion Science,35:57-97, 2009.
- [13]Huang, Shy, Liu, Yan, "A transition on minimum ignition energy for lean turbulent methane combustion in flamelet and distributed regimes", Proceedings of Combustion Institute. 2007; 31:1401-9

Discussion: Spark timing

Sparks early in flow had higher success probability.

Ignition characteristics changed based on timing.

- Unison tests at different propellant temperatures indicate a possible propellant temperature effect to ignition characteristics.
  - Could not be fully resolved in this test set
- During I-bit program, hardware had chance to ‘chill in’ during long pulse trains.
  - Transition apparent: Gradual ignition in first pulses, a few rumbling ignitions intermittent), then abrupt ignition at end.



Conclusions

- Testing exciter in room conditions is not fully representative of its performance in an engine
  - Spark behavior in an engine environment is highly variable as compared to room conditions.
- Sparks occurring early in the combustible flow environment have a higher probability of ignition
  - **Increasing spark rate during this time will increase probability of success**
  - Ignitions later in the flow are possible but have a lower probability of success.
- Spark energies of 55-75 mJ sparks regularly yielded ignition.
  - Well timed sparks with energies as low as 1-6 mJ were shown to trigger ignition but with a lower probability of success