Statistical Analysis of Electrostatic Spark Ignition of Lean H_2-O_2-Ar Mixtures

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3rd International Conference on Hydrogen Safety
Ajaccio, Corsica, France
September 16-18, 2009

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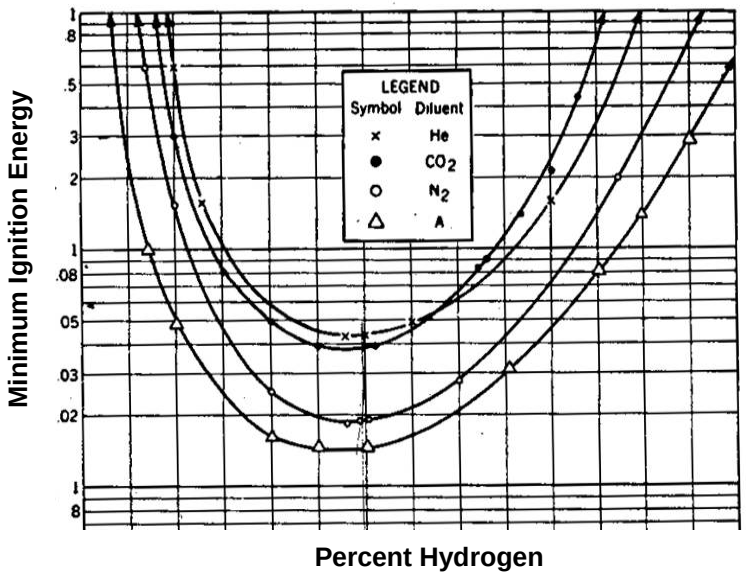
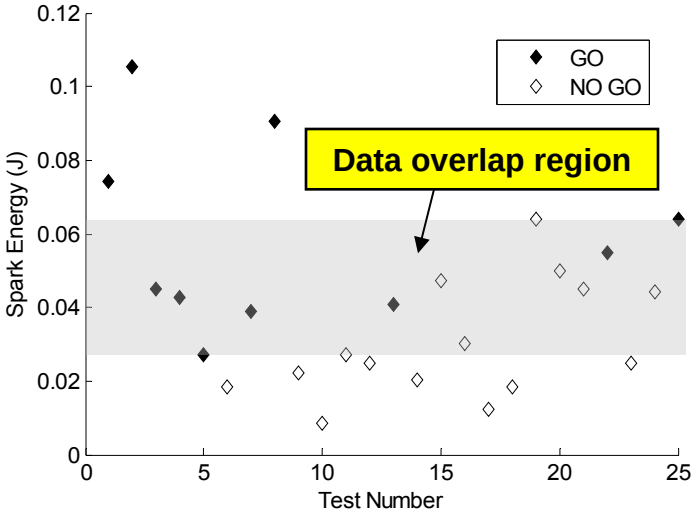
Spark Ignition & Minimum Ignition Energy

- determining risk of accidental ignition extremely important in industry and aviation safety
- ***Minimum Ignition Energy*** (MIE) – traditional basis for quantifying ignition hazards
- experimental work using capacitive spark, tabulations of MIE values

MIE curves, Lewis and von Elbe, 1961



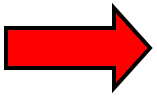
Jet A ignition test data, Lee and Shepherd, 1999



- ***New viewpoint*** – ignition as <u>statistical</u> phenomenon
- previous statistical analysis of Jet A ignition, hot surface ignition
- little work done on statistics of ignition of hydrogen

Statistical View of Ignition

GOAL: isolate and examine statistical nature of ignition with respect to spark energy



Must quantify and minimize other sources of experimental variability

SOME SOURCES OF VARIABILITY:

1) **uncertainties in mixture composition**
   - ➢ Small changes in composition lead to large change in combustion characteristics, MIE
2) **ignition detection method**
   - ➢ false positives or negatives
3) **turbulence**
   - ➢ effect on spark channel formation, flame propagation
4) **spark energy measurement**

Previous work done to assess these sources, improve experimental design

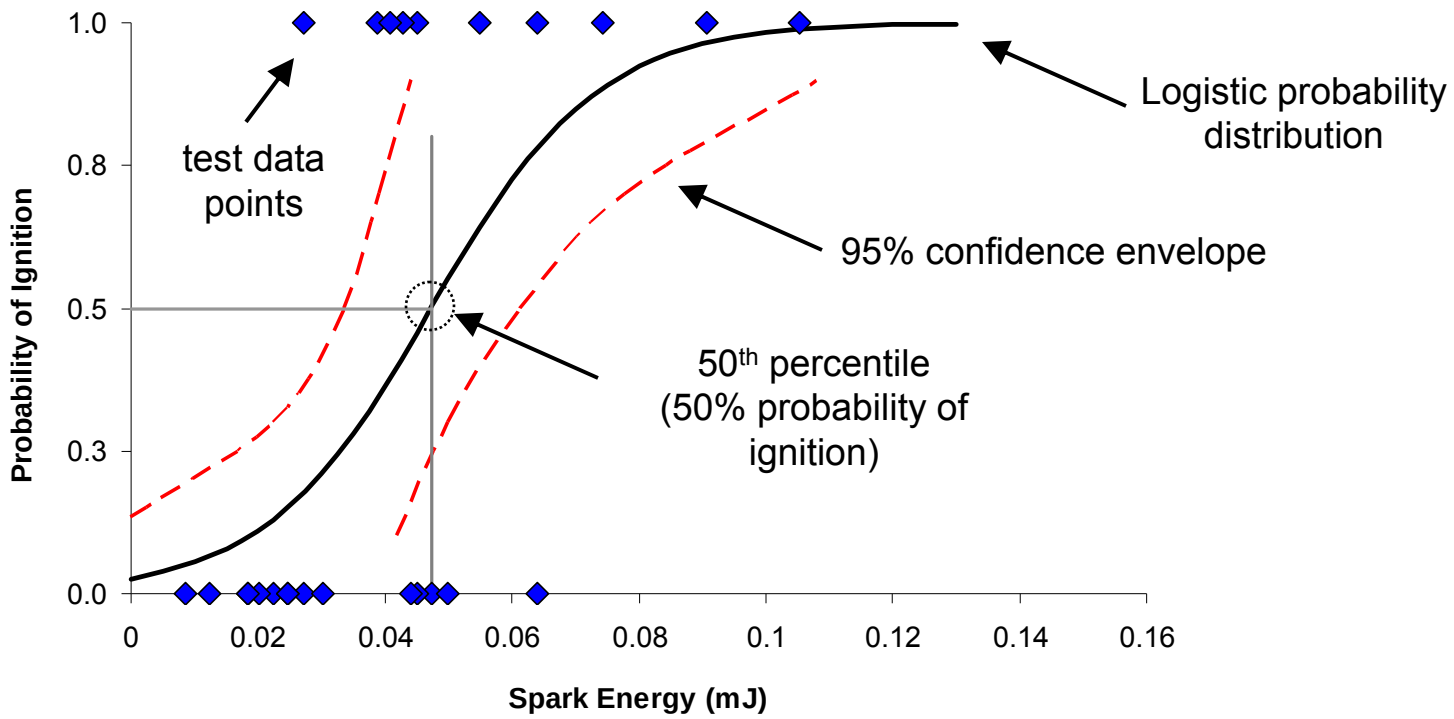
Objective: examine statistical nature of lean hydrogen aviation test mixtures

Statistical Analysis of Ignition Test Data

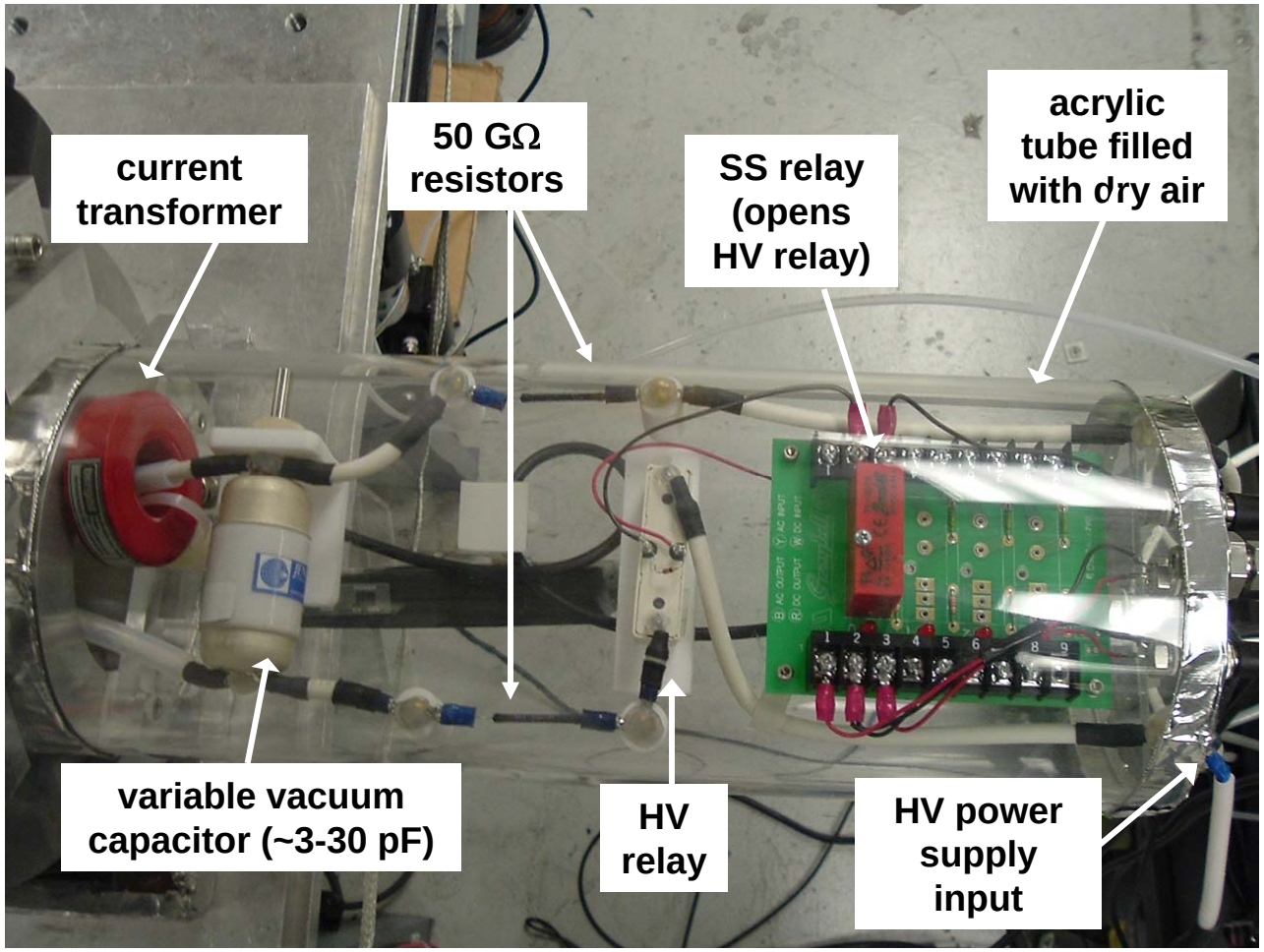
Goal: probability distribution for ignition versus stimulus level (spark energy)

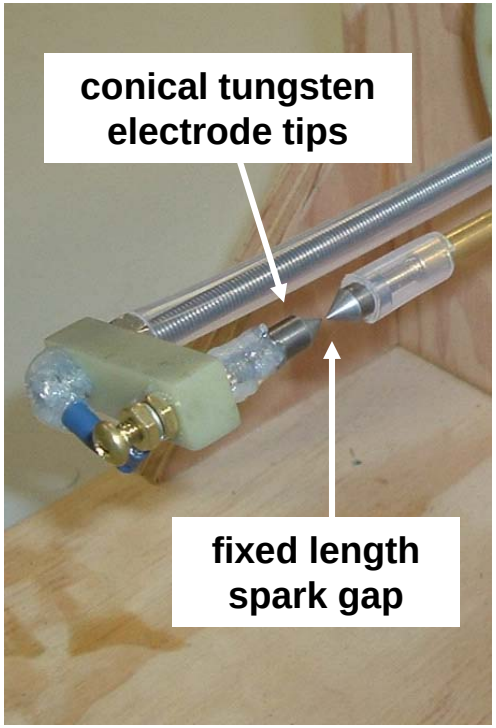
- logistic distribution – often used to analyze binary "failure" data

Example: Jet A spark ignition (Lee and Shepherd, 1999)



Short, Fixed Spark Ignition Testing: Spark Ignition System





Short, Fixed Spark Ignition Testing: Estimating Spark Energy

$$E_{stored} = \frac{1}{2}CV^2 = E_{thermal} + E_{residual} + E_{shock} + E_{EMR} + E_{i^2R} + \ldots$$

$\approx E_{spark}$ estimate neglect

$$E_{spark} \approx E_{stored} - E_{residual}$$

$$E_{stored} = \frac{1}{2}CV_{breakdown}^2$$

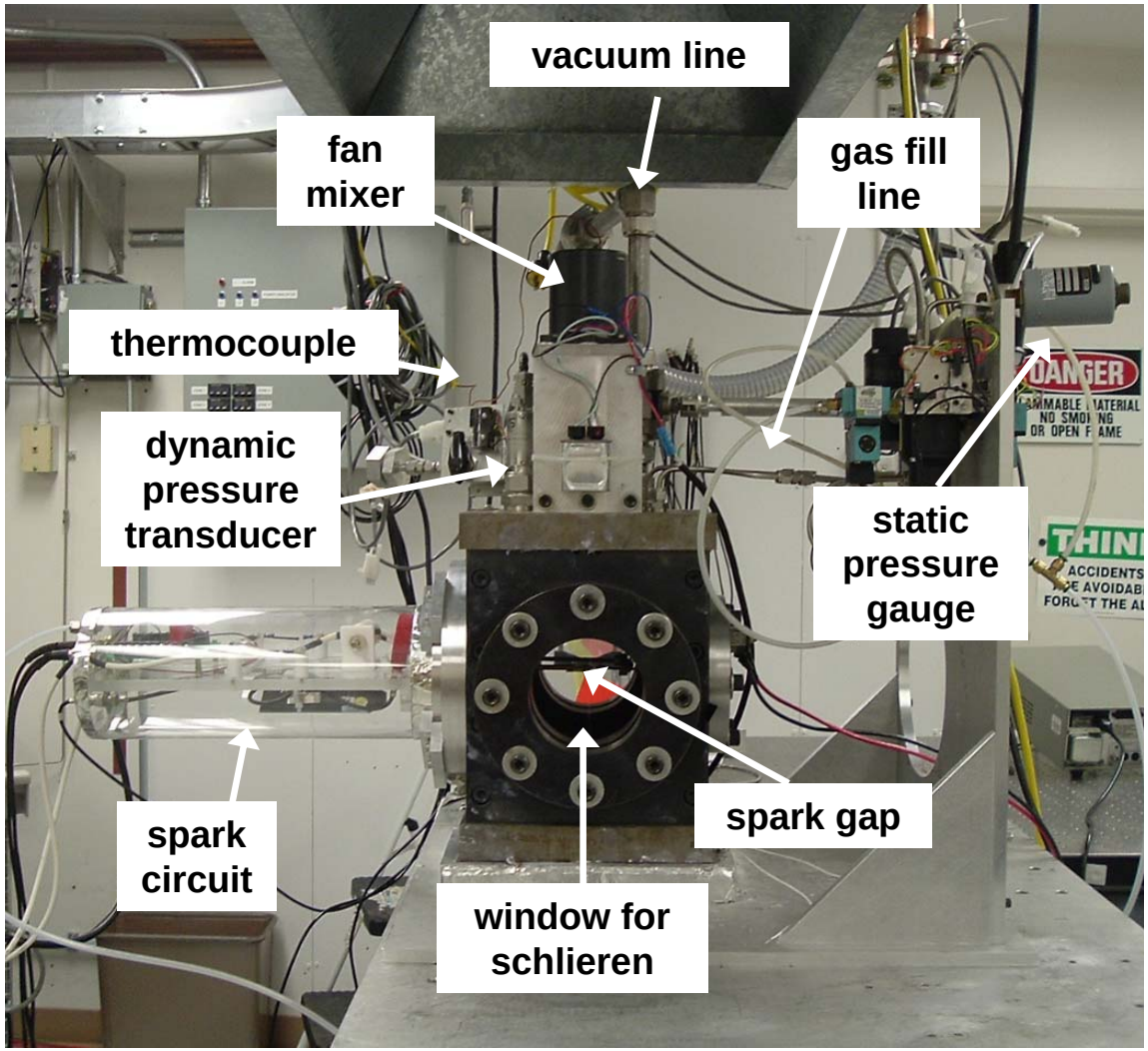
$$E_{residual} = \frac{1}{2}\frac{Q_{residual}^2}{C}$$

Calculate the charge left in the capacitor using the spark current

$$Q_{residual} = Q_{stored} - Q_{spark} = CV_{breakdown} - \int i_{spark}(t)dt$$

high-speed current transformer

Experimental Setup

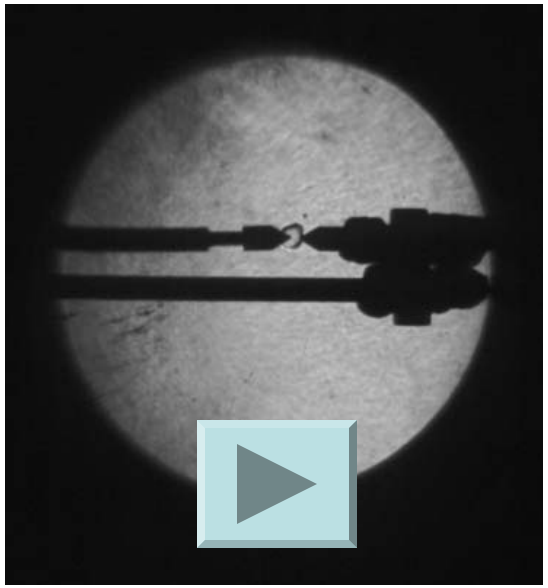


- **Composition control**
  - vacuum chamber
  - fill by partial pressures
  - static pressure measurement with 0.01 kPa precision
- **Reliable ignition detection**
  - pressure transducer
  - thermocouple
  - high-speed schlieren visualization
- **Turbulence**
  - fan mixer
  - wait time after turn-off

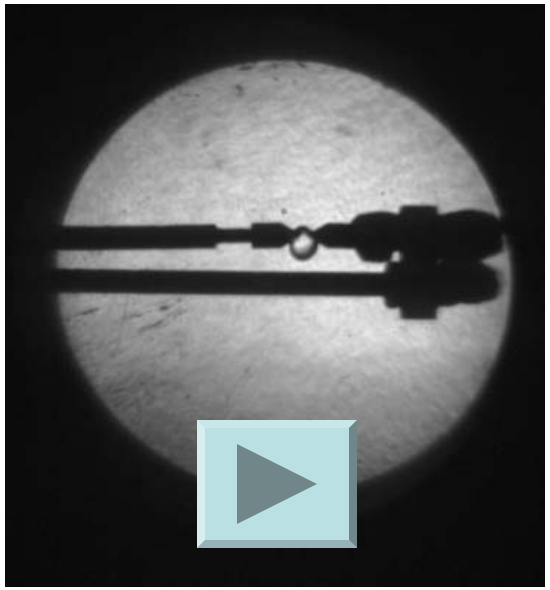
Flame Visualization

- high-speed flame visualization using schlieren optics
- high-speed camera (1000 fps)
- 5% hydrogen test mixture (ARP), 2 other mixtures with 1% more H_2

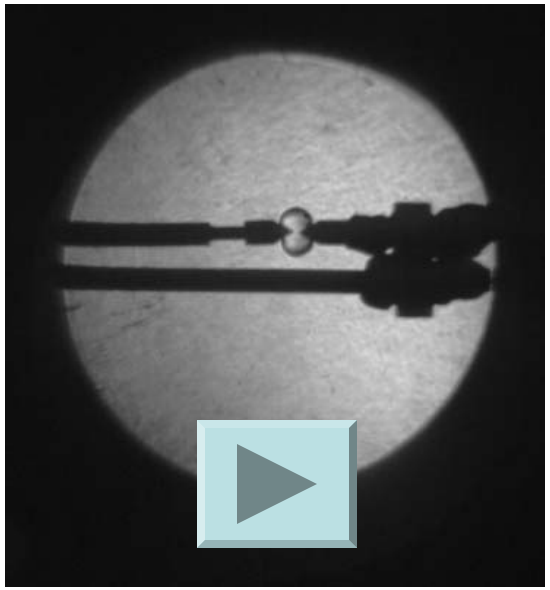
  → 5% H_2–12% O_2–83% Ar, 6% H_2–12% O_2–82% Ar, 7% H_2–12% O_2–81% Ar



5% H2

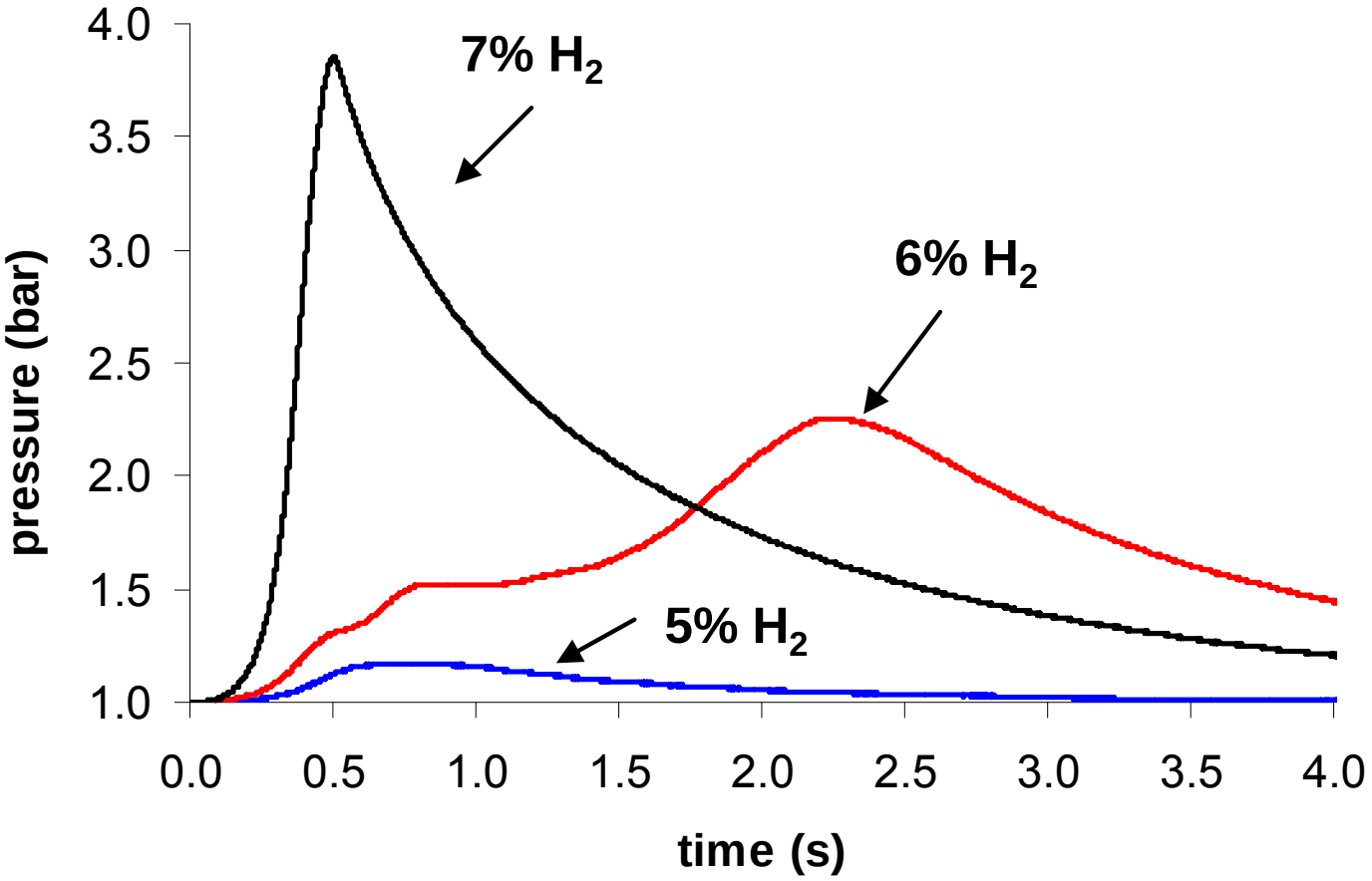


6% H2



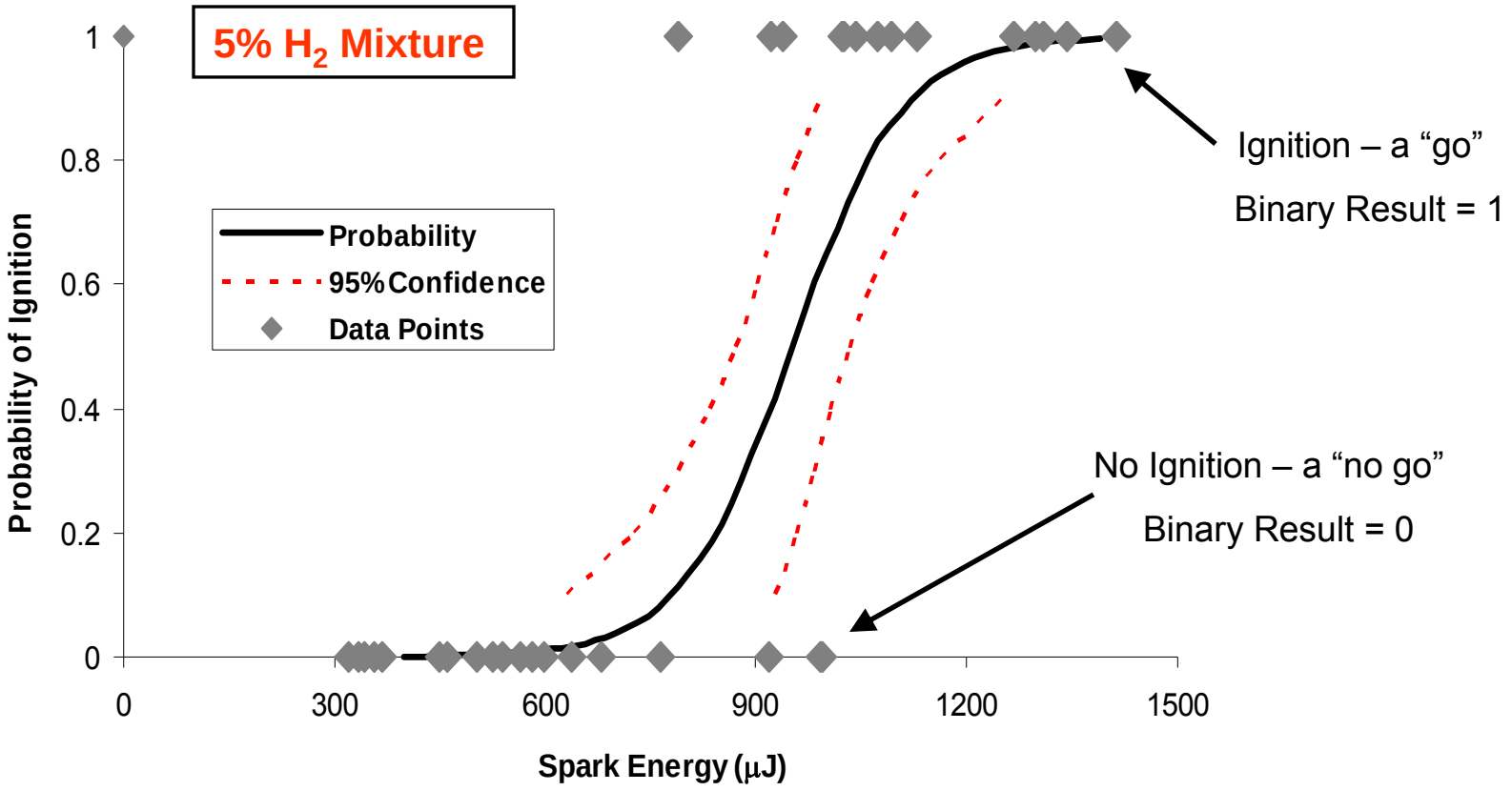
7% H2

Pressure Measurement

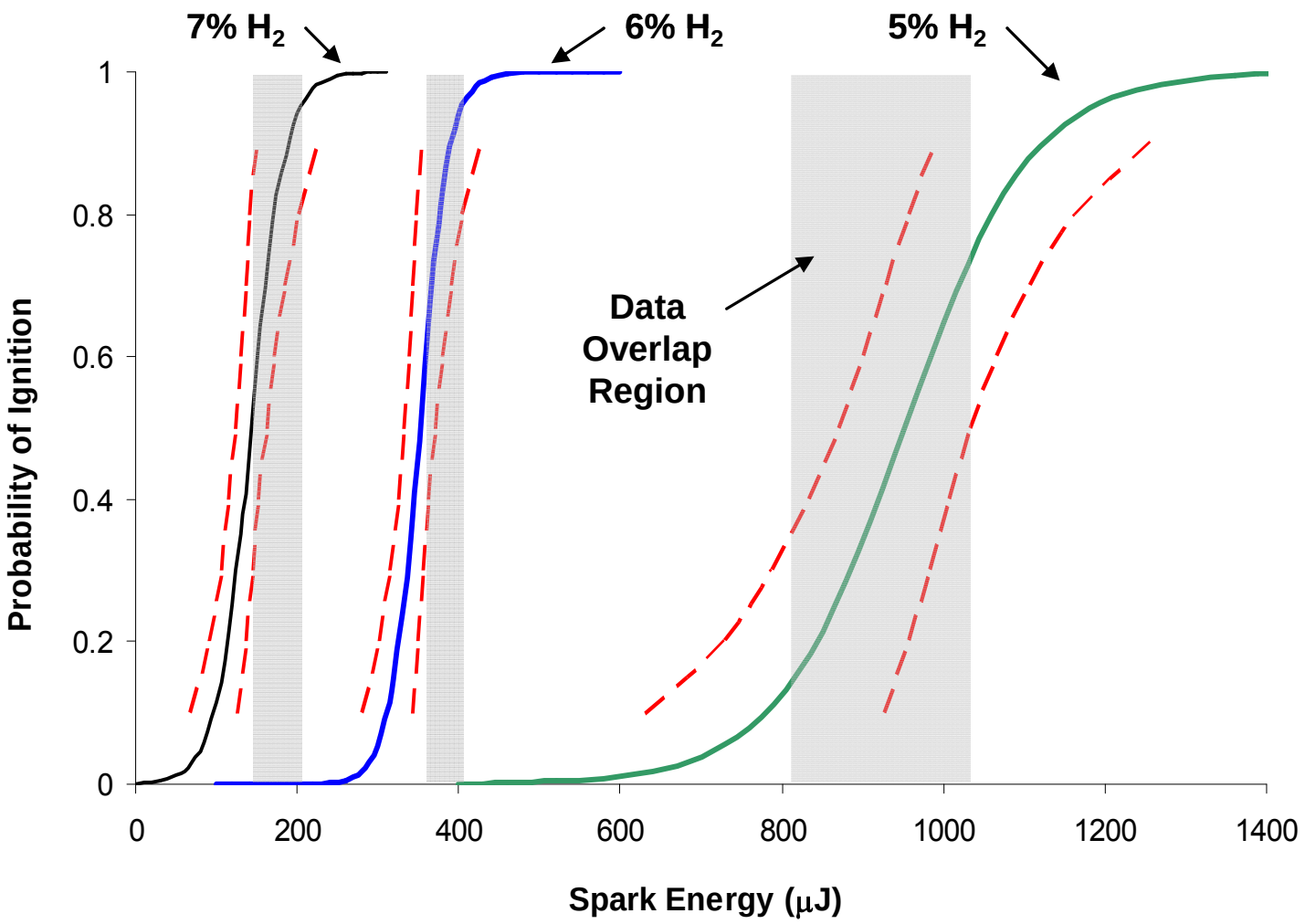


Short, Fixed Spark Ignition Testing: Ignition Probability

- ignition tests in three H_2 test mixtures
- fixed spark gap length (1-2 mm), range of spark energies (vary capacitance)

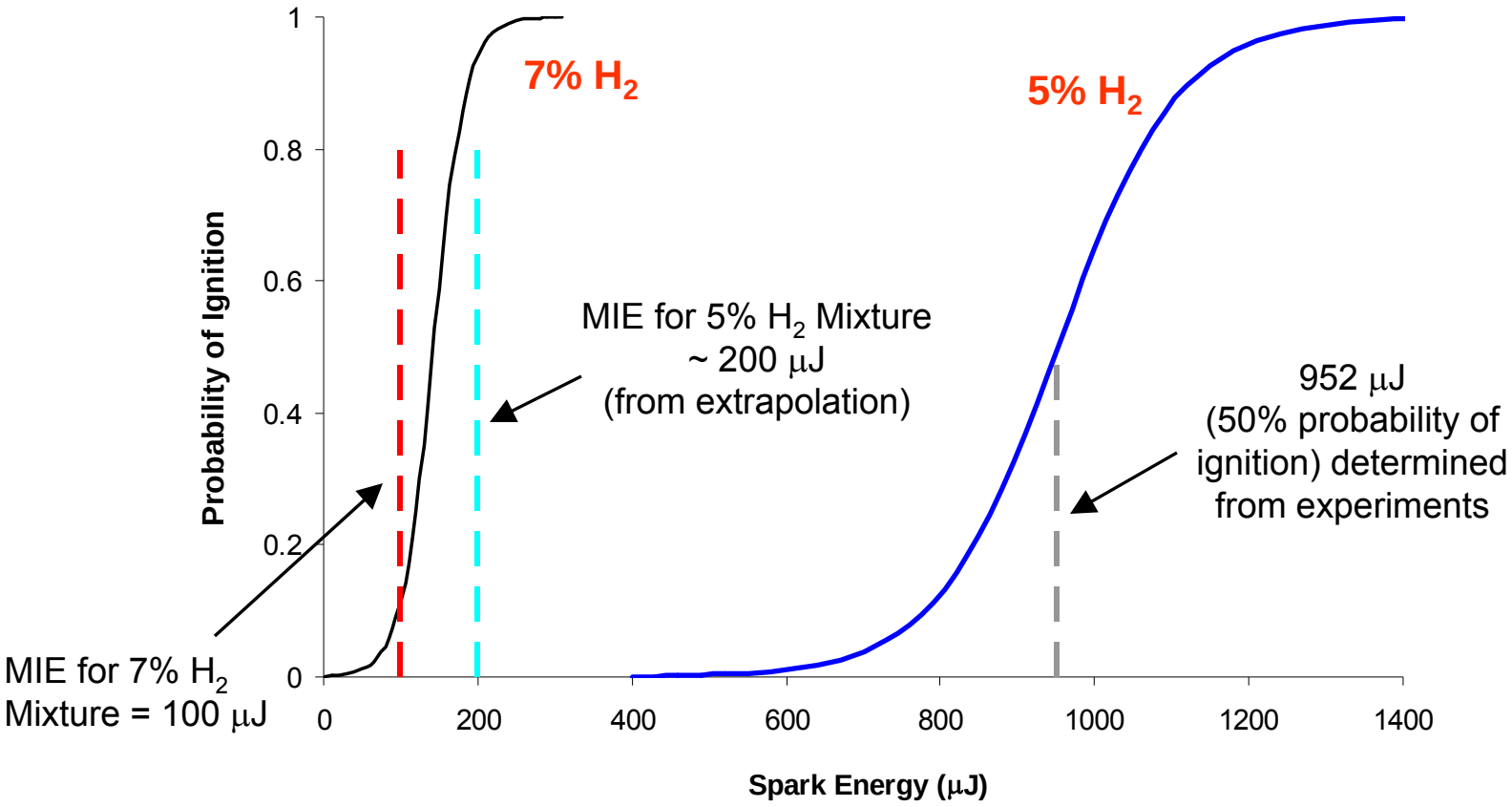


Short, Fixed Spark Ignition Testing: Ignition Probability (cont.)



Short, Fixed Spark Ignition Testing: Ignition Probability (cont.)

Comparison with original MIE data (Lewis & von Elbe 1961):

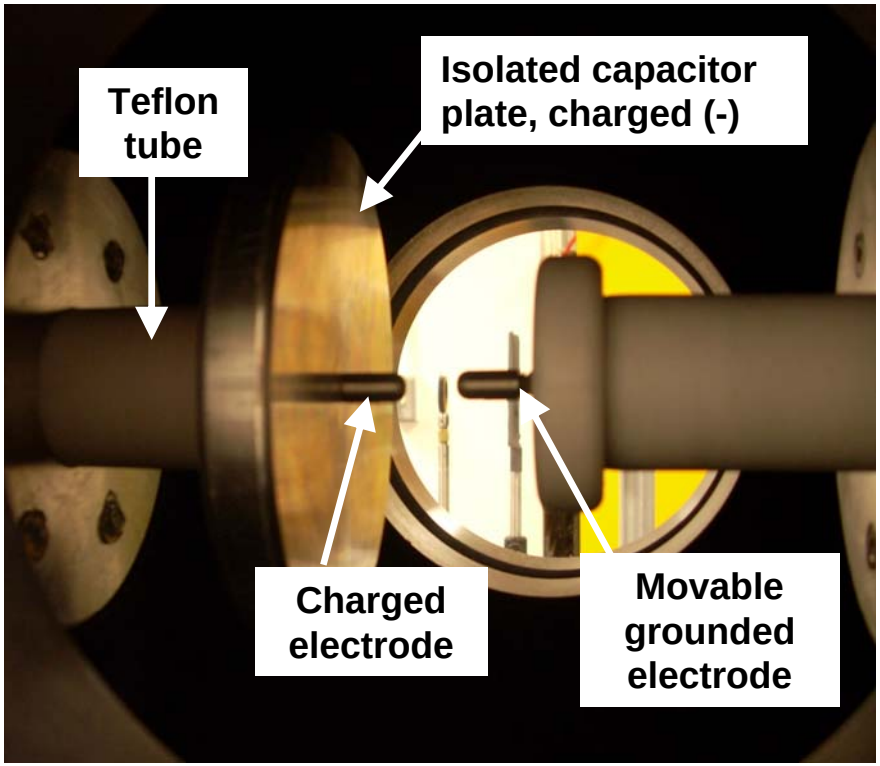


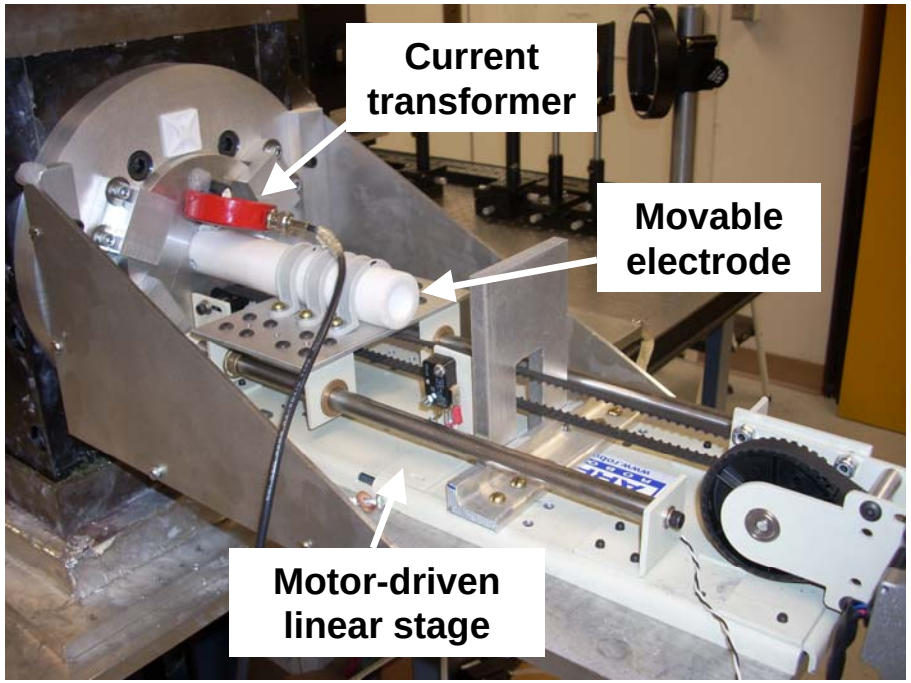
Long, Variable Spark Ignition Testing

QUESTION: In addition to the spark energy, is the *spark length* important too?

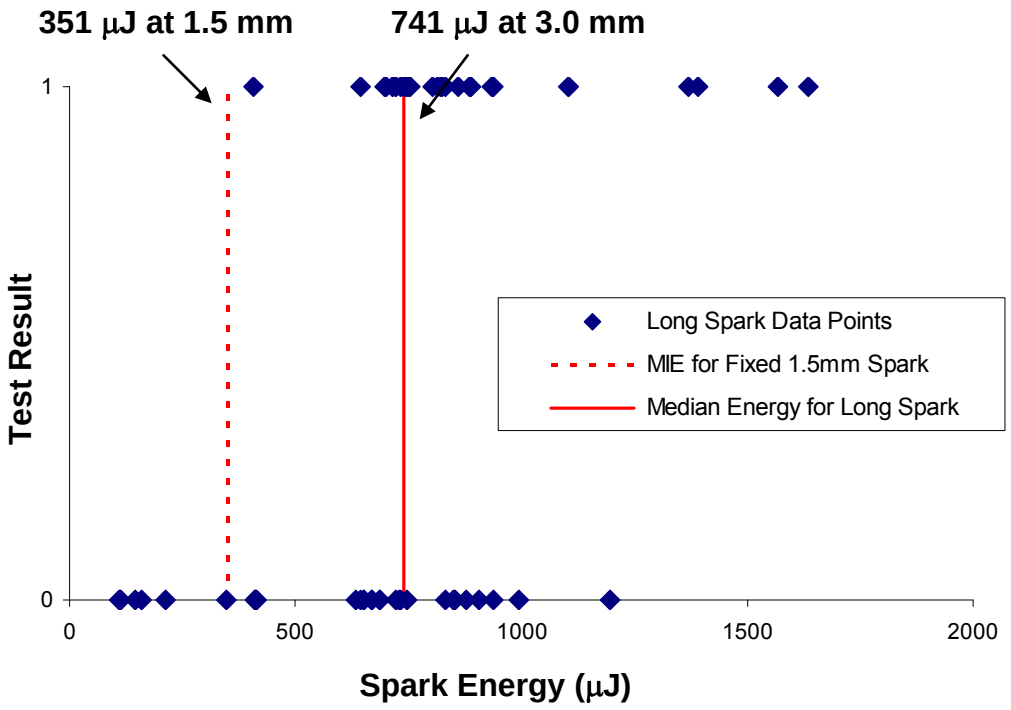
Is ***spark energy density*** (spark energy/spark length) a more appropriate parameter?

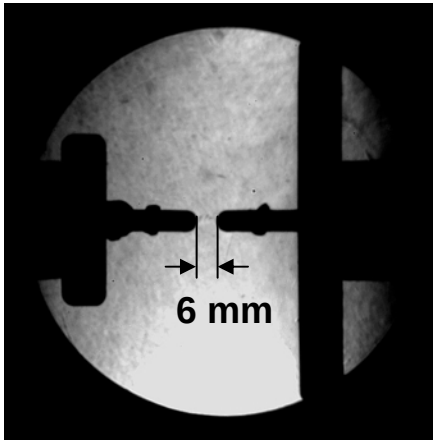
⇨ developed ignition system to vary both spark energy and spark length





Long Spark Ignition Testing: Results (cont.)



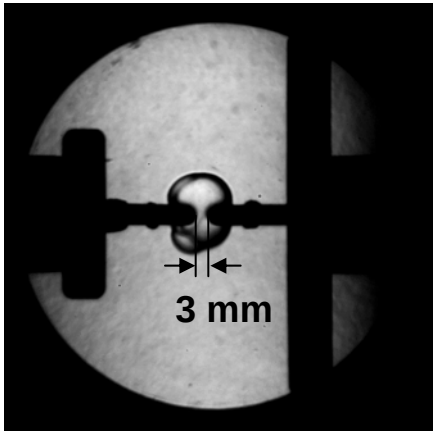


NO IGNITION

Spark Energy: 1000 μJ

Spark Length: 6 mm

Energy Density = 167 μJ/mm



IGNITION

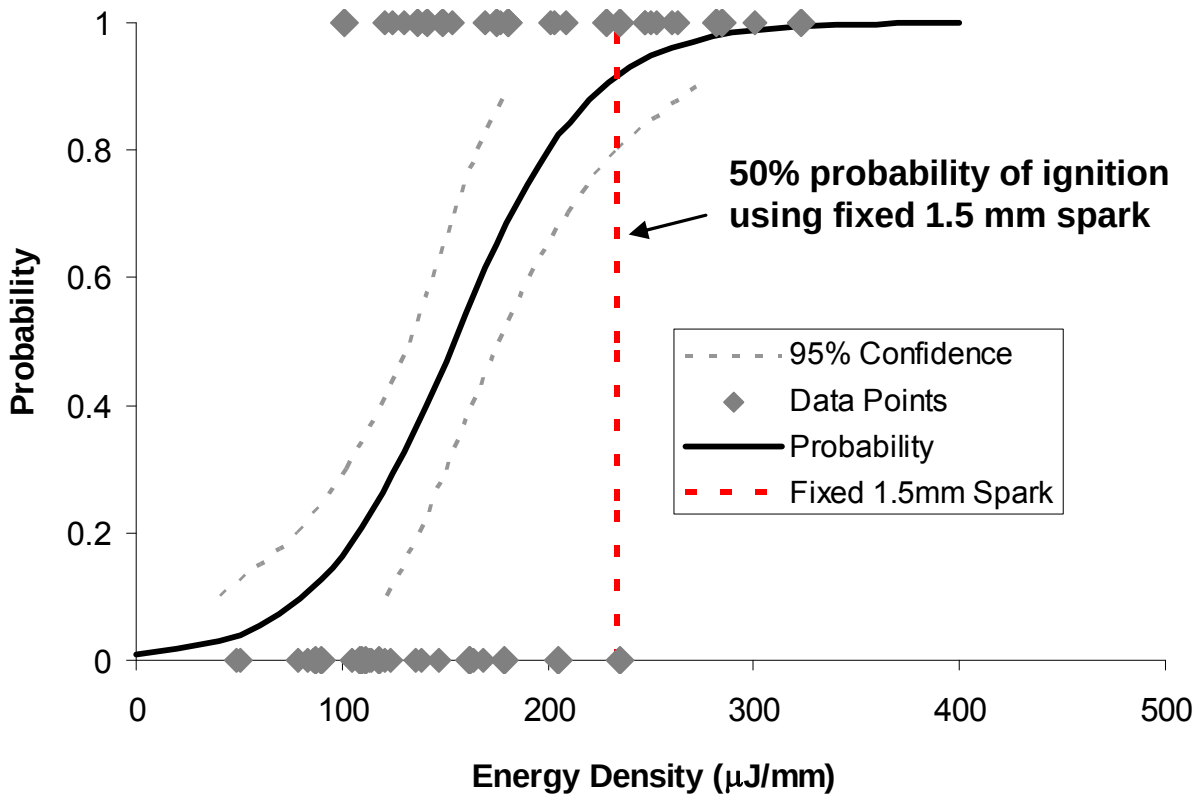
Spark Energy: 740 μJ

Spark Length: 3 mm

Energy Density = 247 μJ/mm

Long Spark Ignition Testing: Results

- second set of tests in 6% H_2 mixture
- vary both spark energy and length → range of energy densities



50% Probability of Ignition:

Short, Fixed Length Sparks:

351 μJ at 1.5 mm

➡ **234 μJ/mm**

Longer, Variable Length Sparks:

➡ **154 μJ/mm**

- reduced effect of quenching
- instability of spark channel

Conclusions

- developed low-energy capacitive spark system to produce short, fixed length sparks
- used to perform ignition tests in 3 hydrogen-based aviation test mixtures
- analyzed statistically – probability distributions for ignition vs. spark energy
  - results statistical in nature – contradict traditional MIE view
  - small change in composition → large change in flame propagation, MIE

- second spark ignition system – sparks of variable energy and lengths
- ignition tests in 6% H_2 mixture, varying spark energy density
- probability distributions for ignition vs. spark energy density
  - longer sparks = more energy to ignite
  - spark length must be considered, NOT just energy
  - spark energy density is more appropriate parameter