Statistical Analysis of Spark Ignition of Kerosene-Air Mixtures

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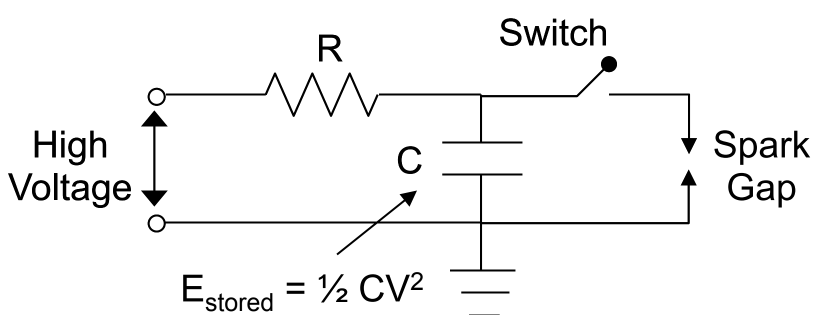
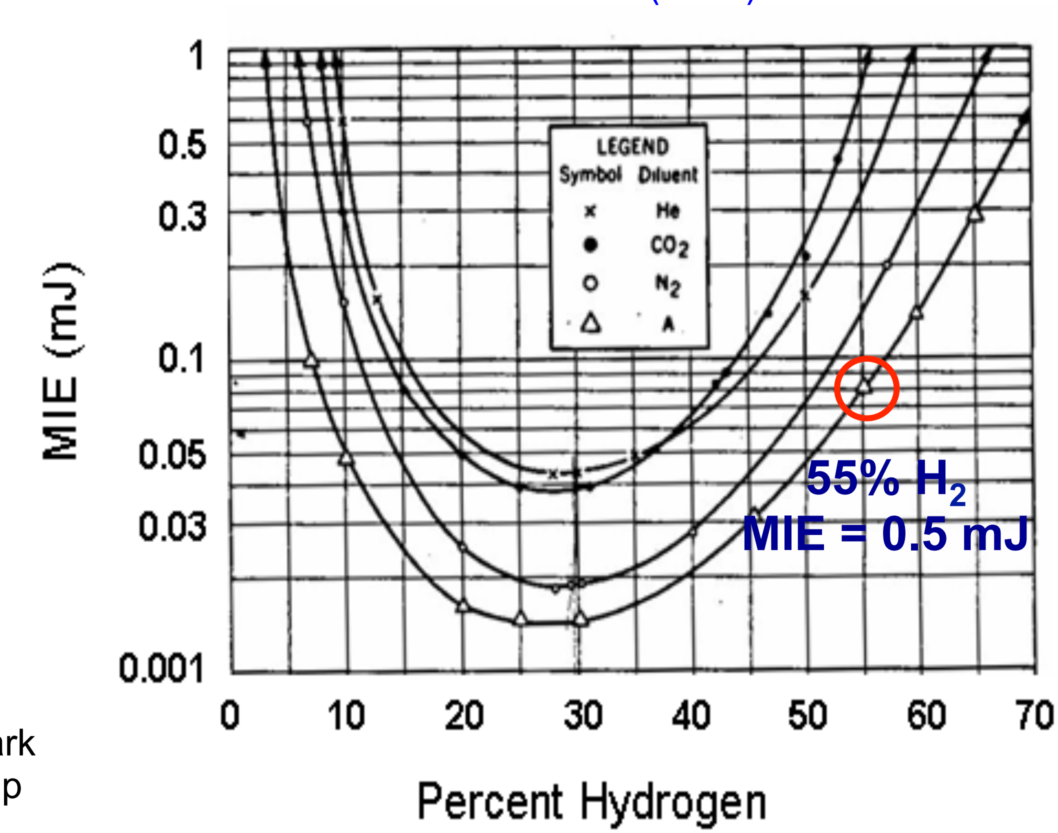
Spark Ignition and Minimum Ignition Energy

- Risk of accidental ignition in industry and aviation
- ***Minimum Ignition Energy*** (MIE): traditional basis for quantifying ignition hazards
- Capacitive spark discharge as ignition source
- Pioneering work – Blanc, Guest, Lewis & von Elbe at Bureau of Mines (1940s)



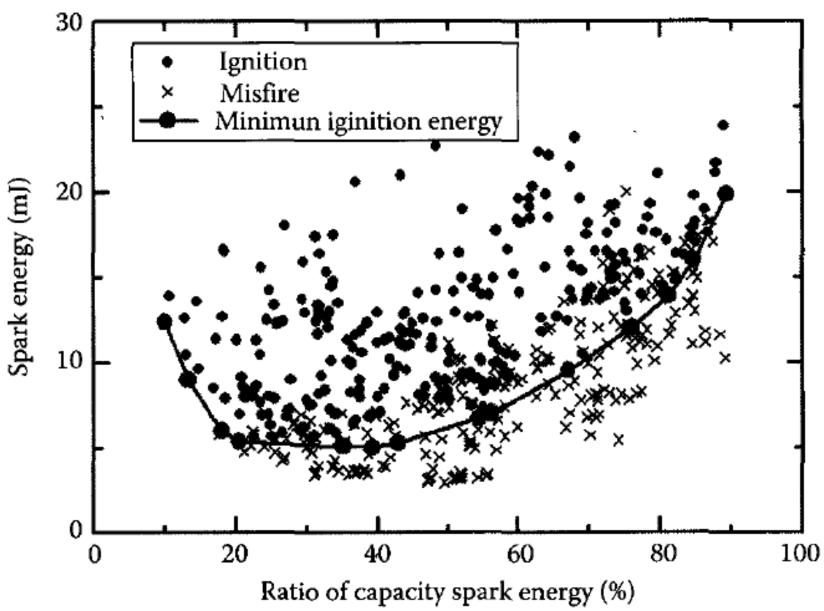
MIE curves for hydrogen mixtures, Lewis and von Elbe (1961)



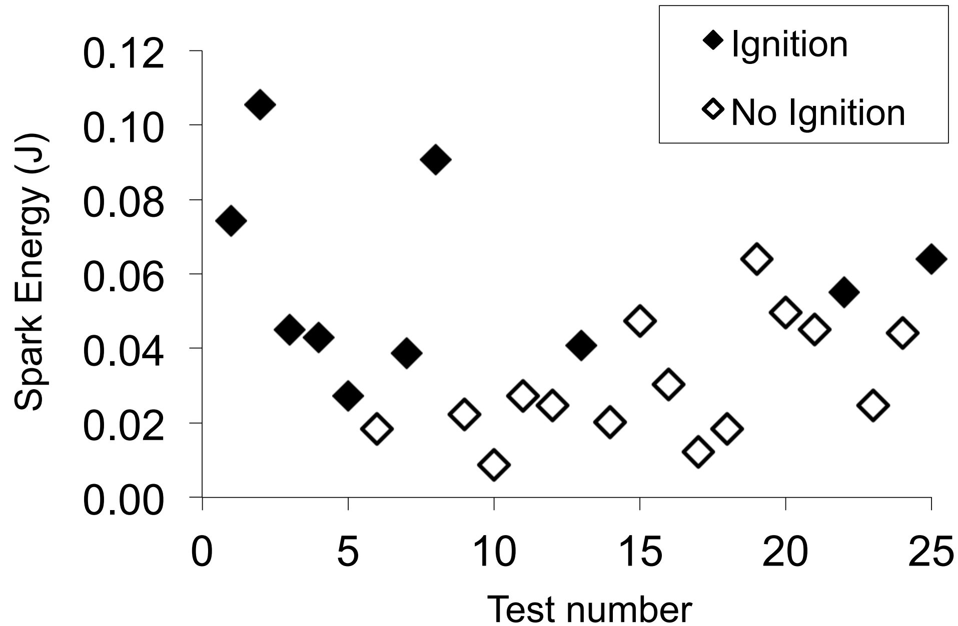
Statistical Analysis of Ignition Test Data

- ***New viewpoint*** – ignition as statistical phenomenon
- More consistent with test data
- Little work done on statistics of ignition of other flammable mixtures
- Can't assign a probability to historical MIE data

Stoichiometric Methane-Air
Kono and Tsue (2009)

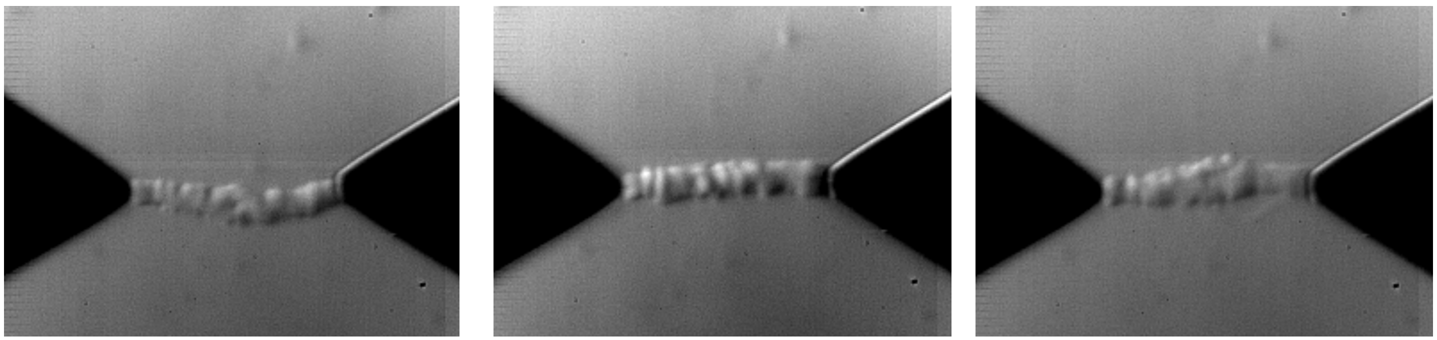


Jet A, Lee and Shepherd (1999)

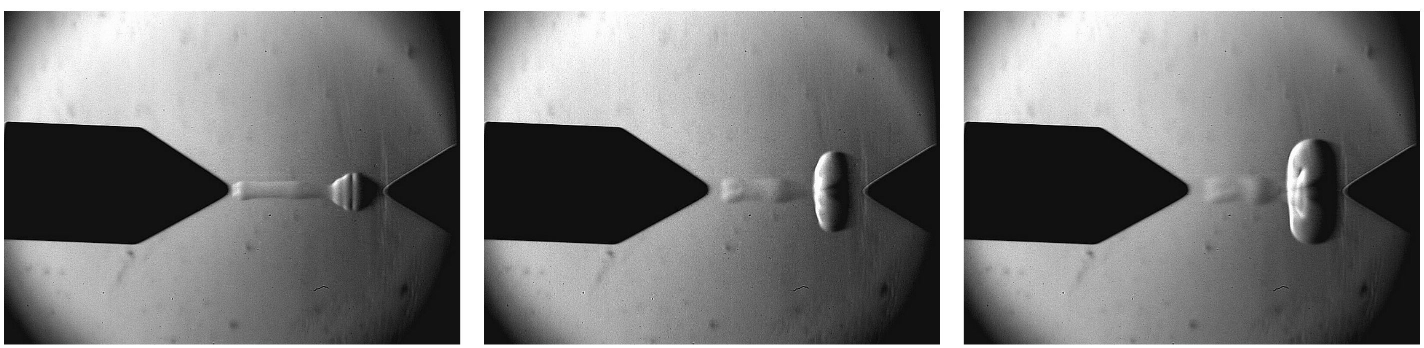


Spark Breakdown and Spark Channel Formation

Unpredictable Plasma Instabilities



Localized Ignition

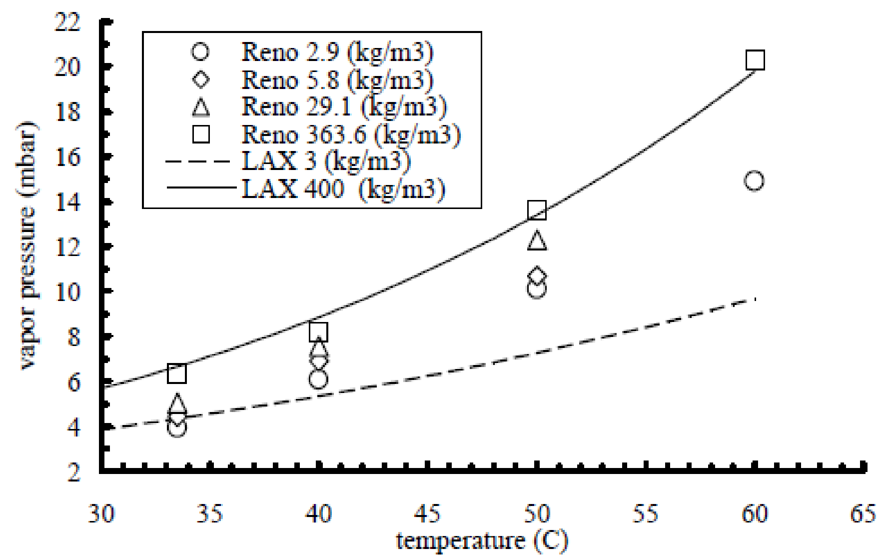


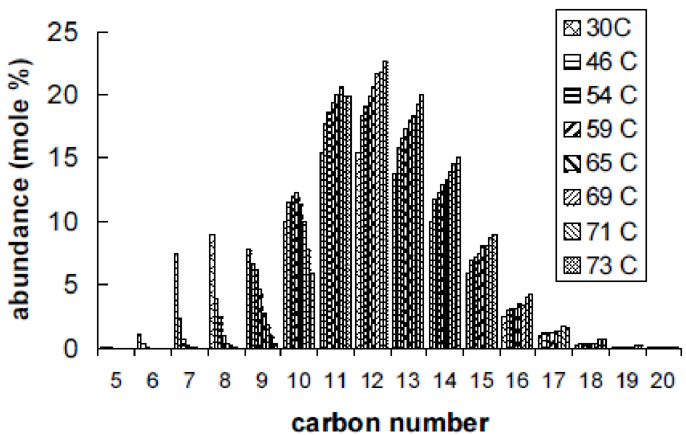
Kerosene Tests: Experimental Considerations

Ignition hazard in aircraft is due to much more complex fuels, that is a kerosene-based fuel

- Ignition testing: low vapor pressure must heat significantly or decrease pressure
- vapor pressure depends on many variables

Fuel vapor pressure vs. temperature and fuel mass loading (Lee and Shepherd, 1999)

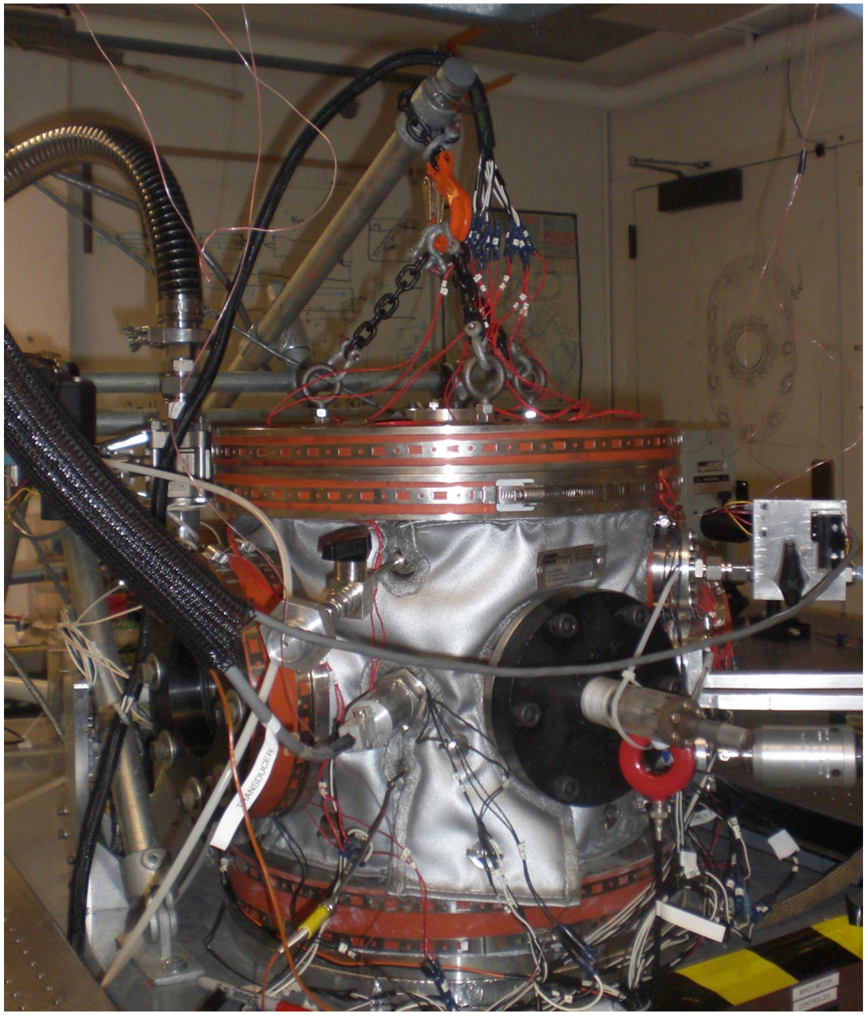




Gas chromatograph (Woodrow, 2000)

- Liquid fuel composition usually not known for commercial fuels → several 100 components
- composition changes from batch to batch, can be affected by history, transport, etc.
- composition of liquid not the same as fuel vapor

Experimental Setup



22 L, stainless steel, cylindrical combustion vessel

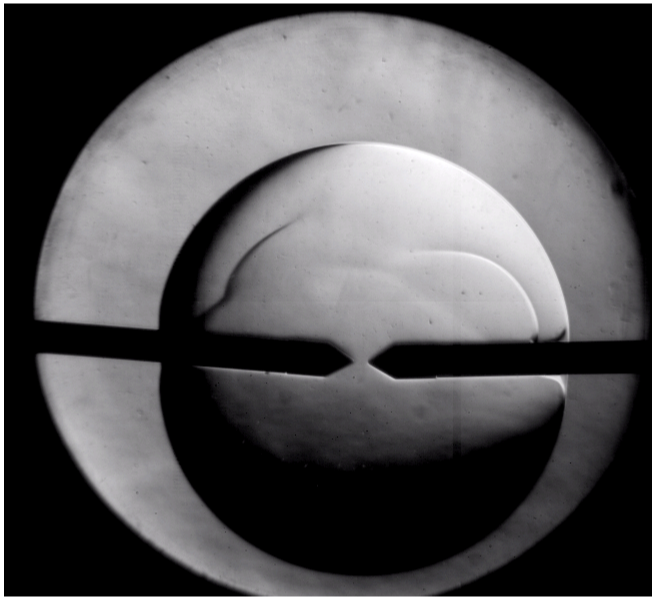
✧ **Ignition Detection**
- flame visualization
- pressure transducer
- thermocouple

✧ **Schlieren visualization**
- high-speed camera (10,000+ frames per second)

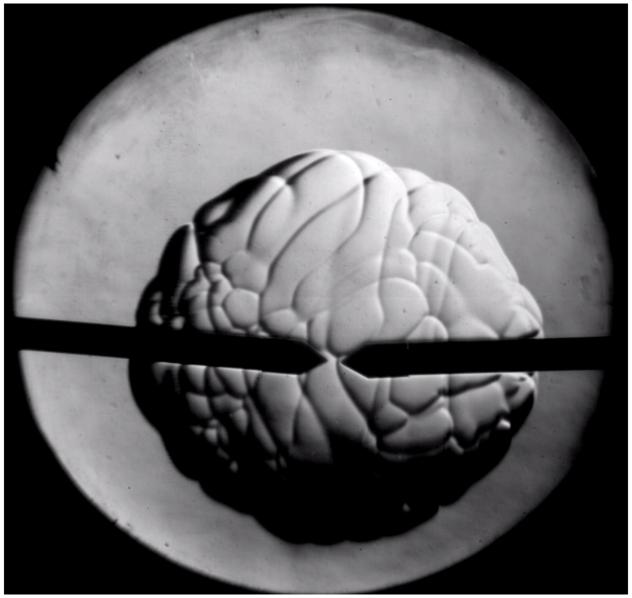
✧ **Vessel Heating System**
- silicone heaters, 4 zones
- high-current heater control unit
- up to ~ 150°C

Results: Kerosene Ignition

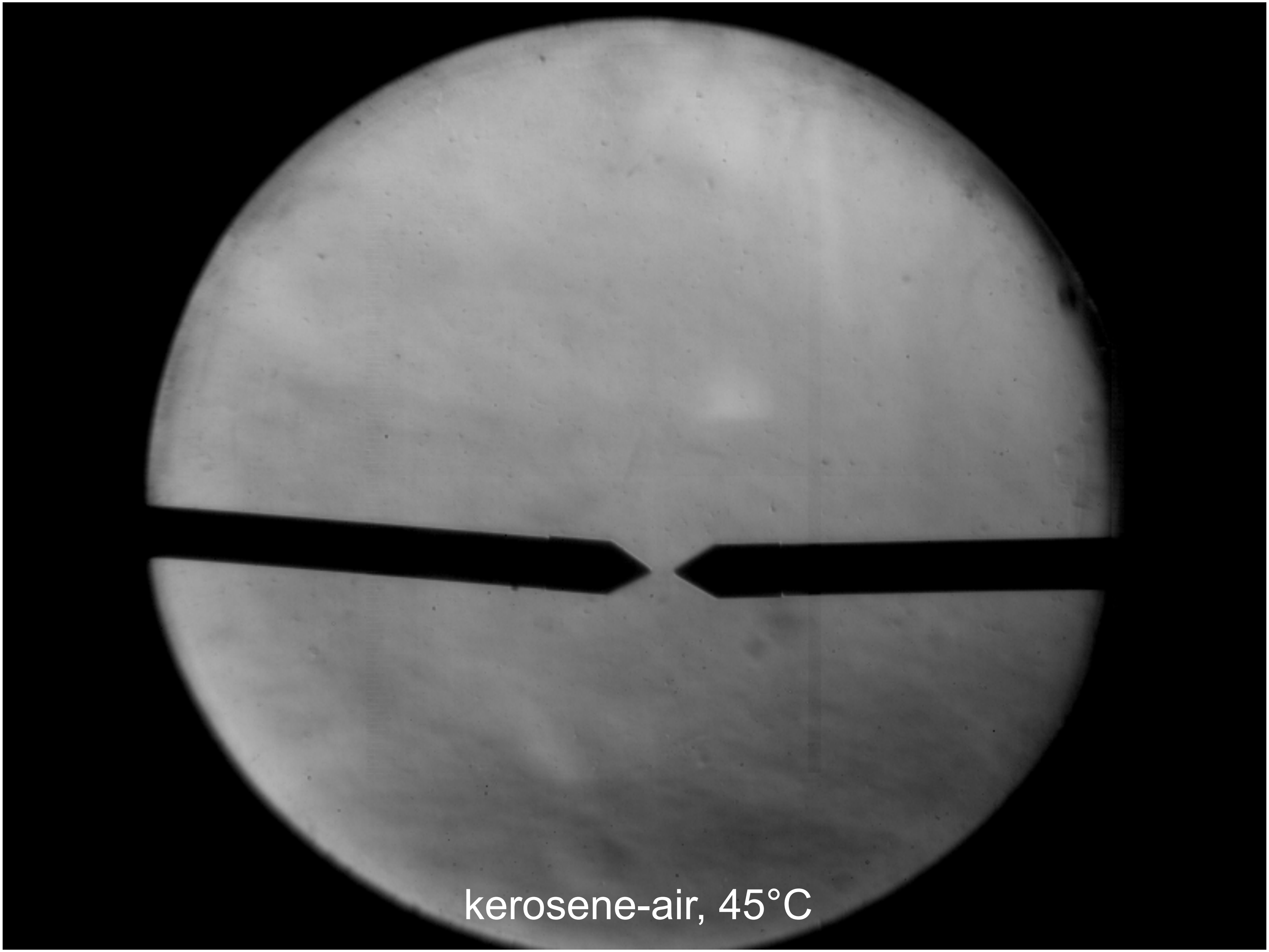
- 1-K kerosene at 45-62°C, 100 kPa
- fixed 3.3 mm spark gap
- 50 kg/m^3 fuel mass loading
- C ~ 11 – 68 pF, V ~ 6.4 – 11.4 kV → E_{spark} ~ 0.3 – 2.3 mJ

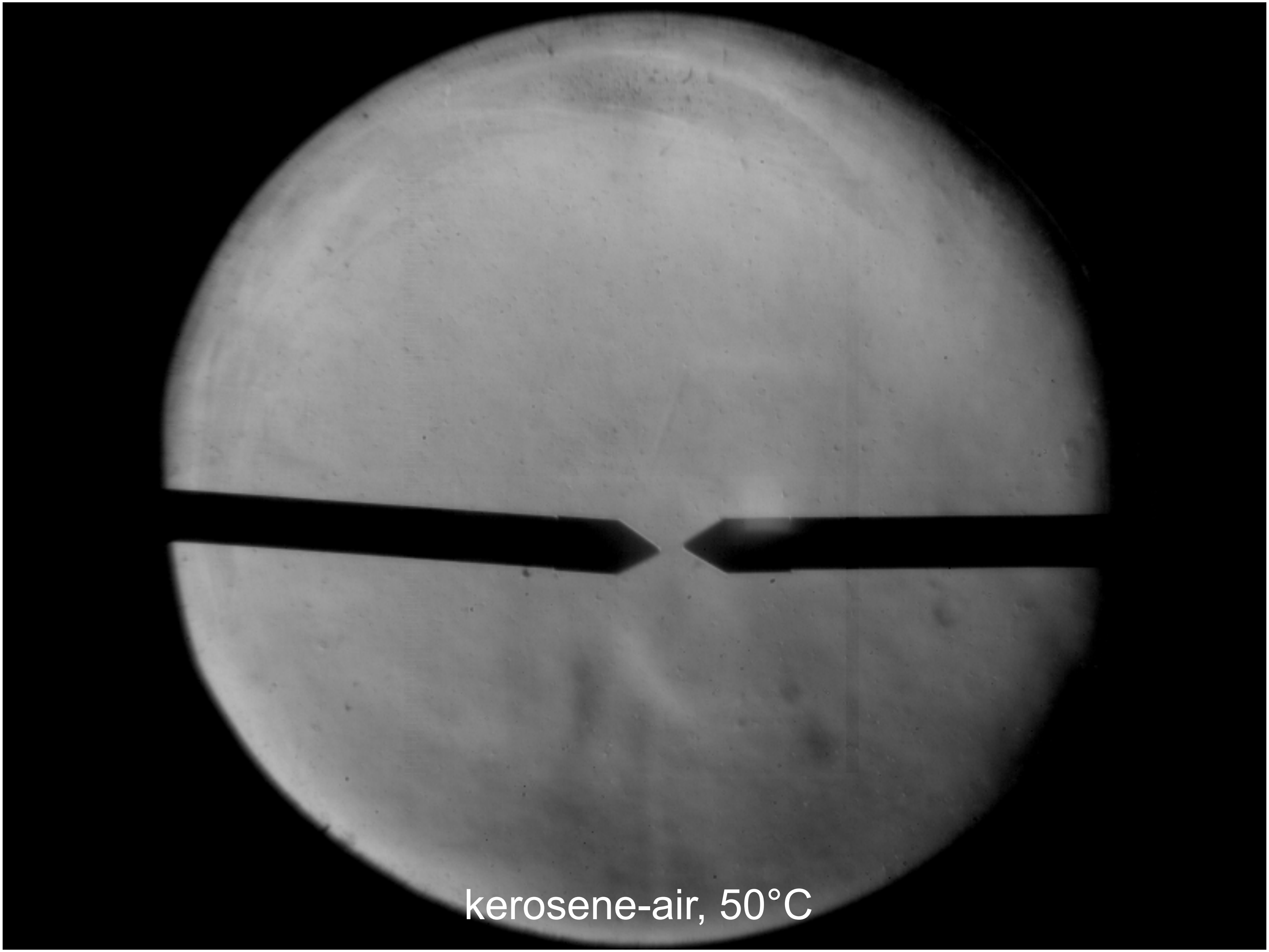


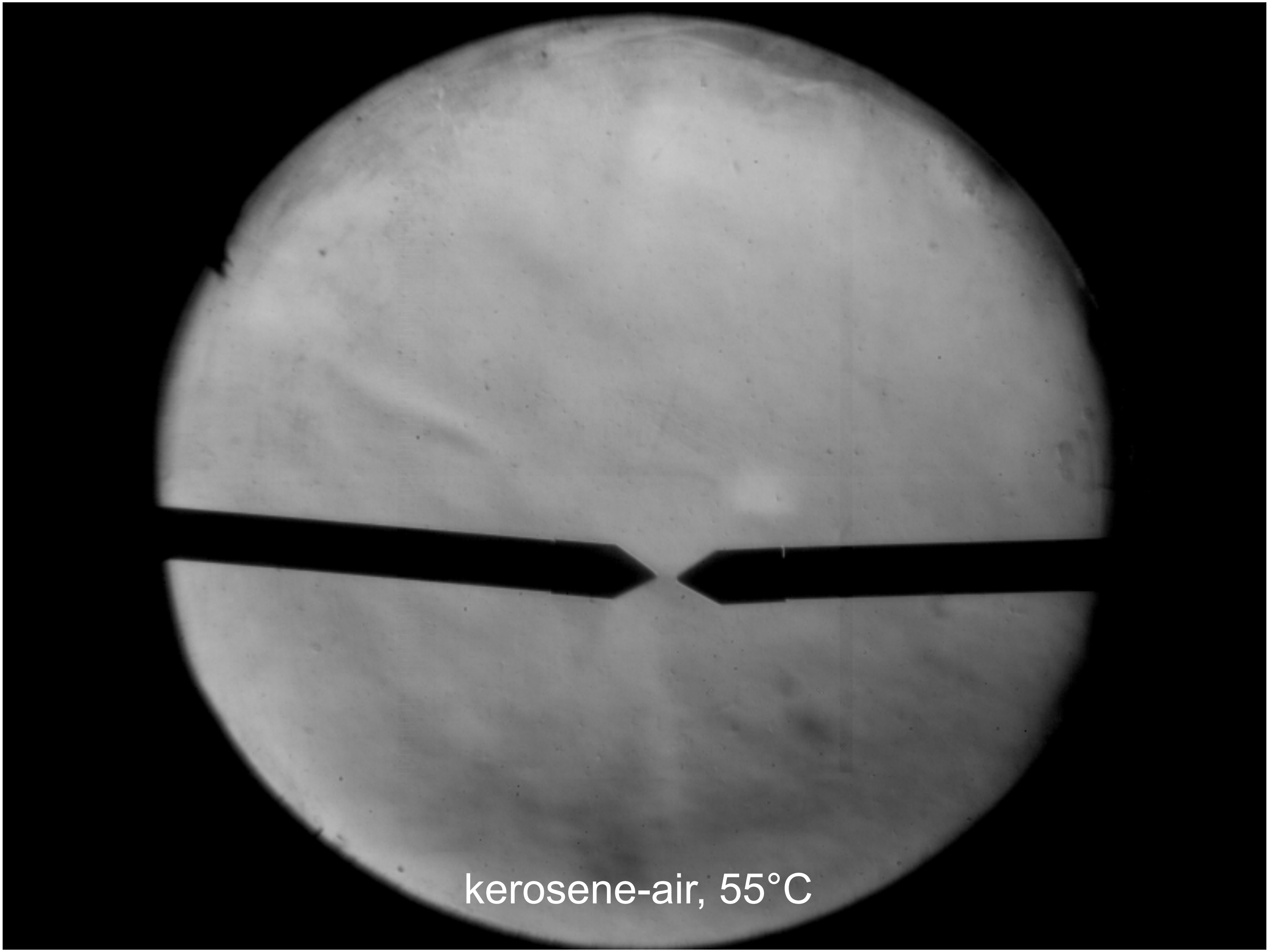
kerosene-air, 45°C



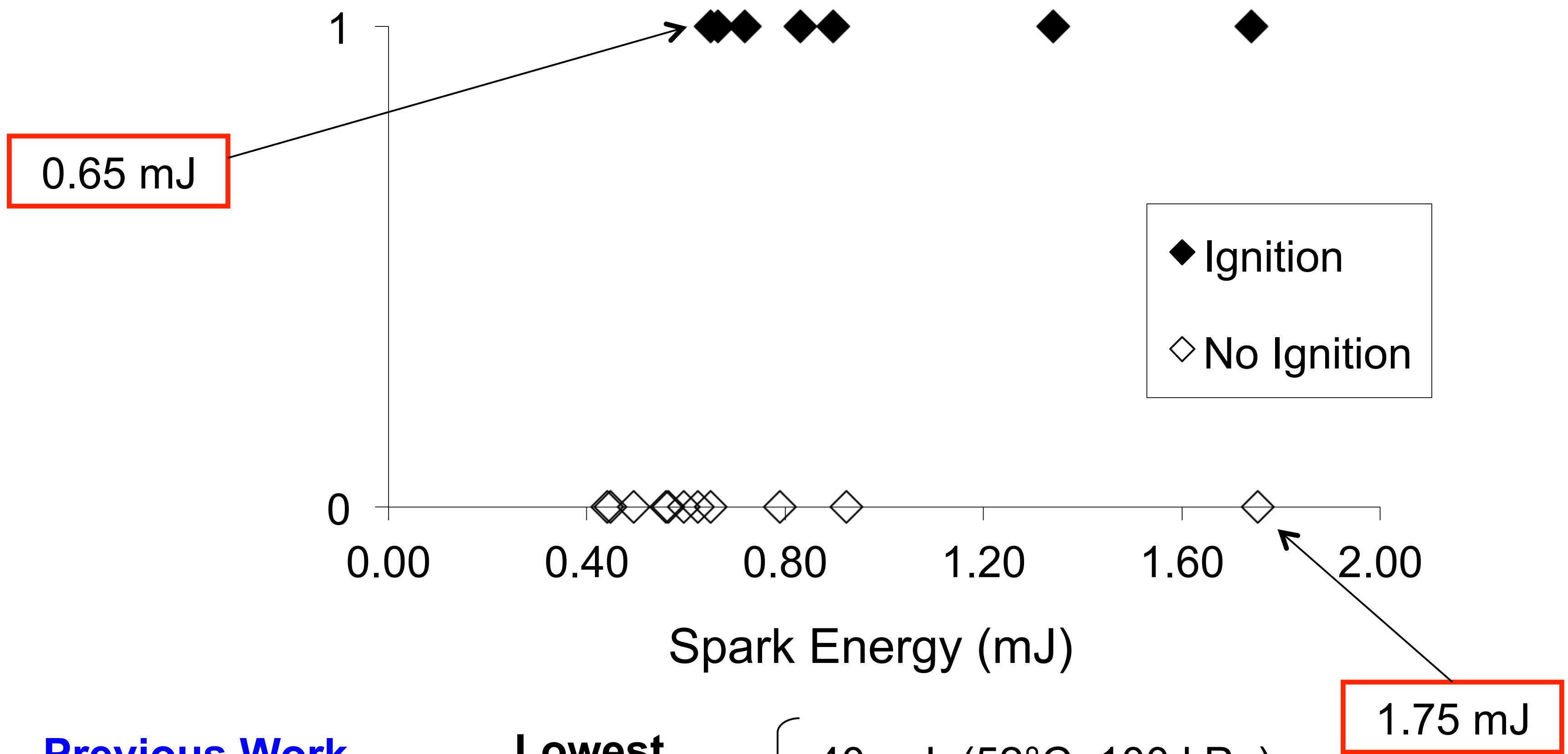
kerosene-air, 55°C


kerosene-air, 45°C


kerosene-air, 50°C


kerosene-air, 55°C

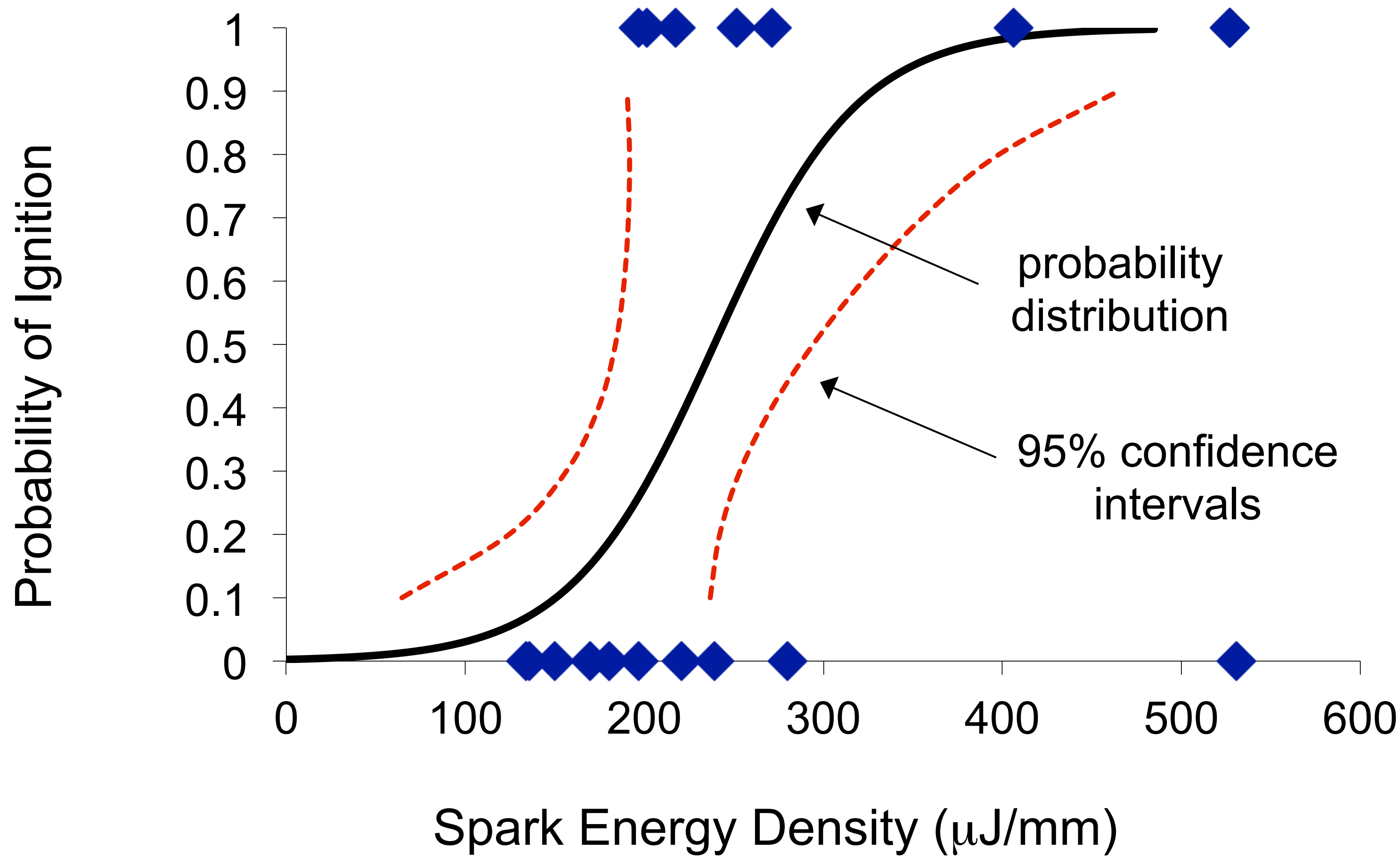
Results: Kerosene-Air at 60°C



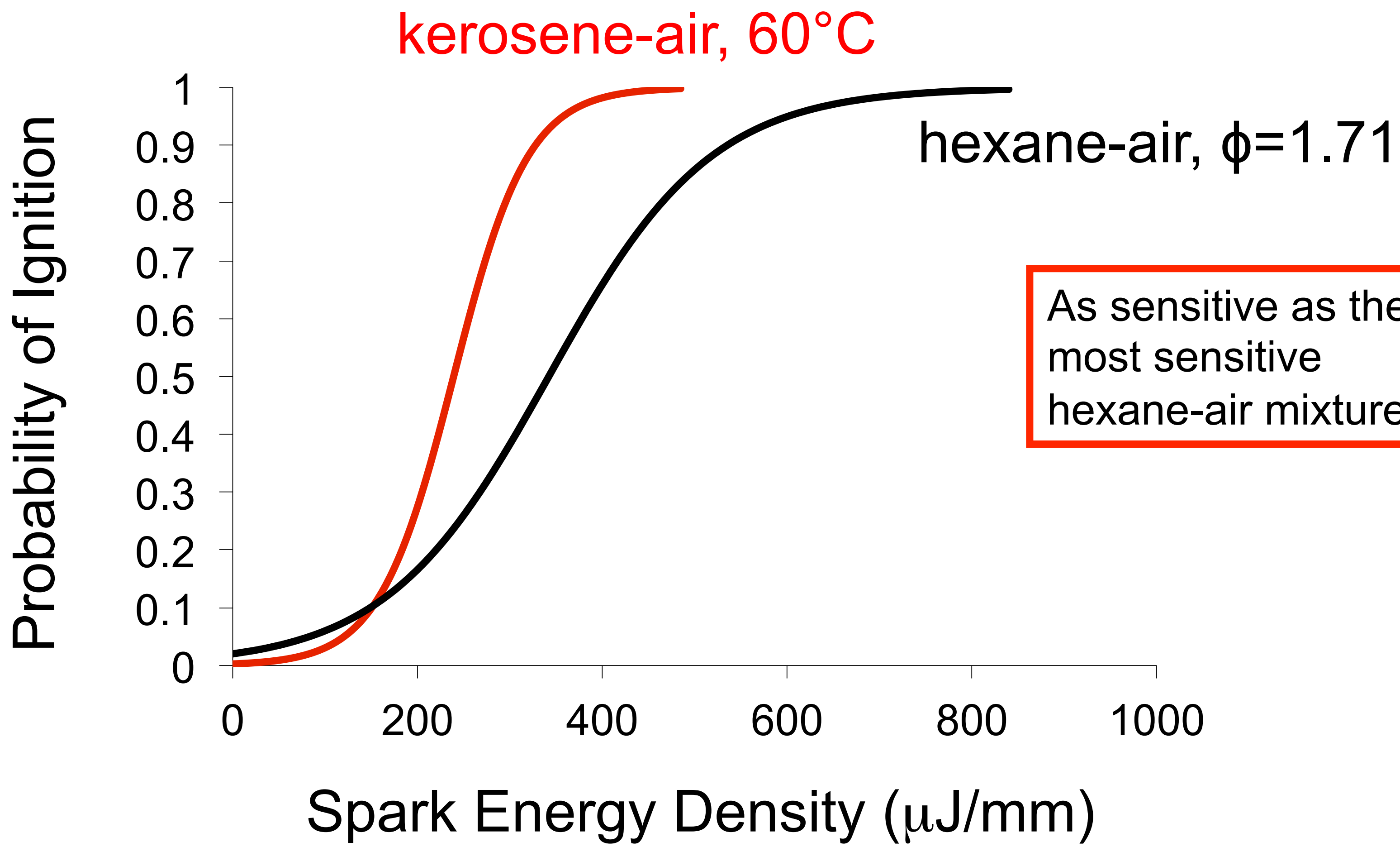
Previous Work (Lee and Shepherd): **Lowest ignition energy** =

- 40 mJ (52°C, 100 kPa)
- 2 mJ (56.1°C, 58.5 kPa)

Results: Kerosene-Air at 60°C

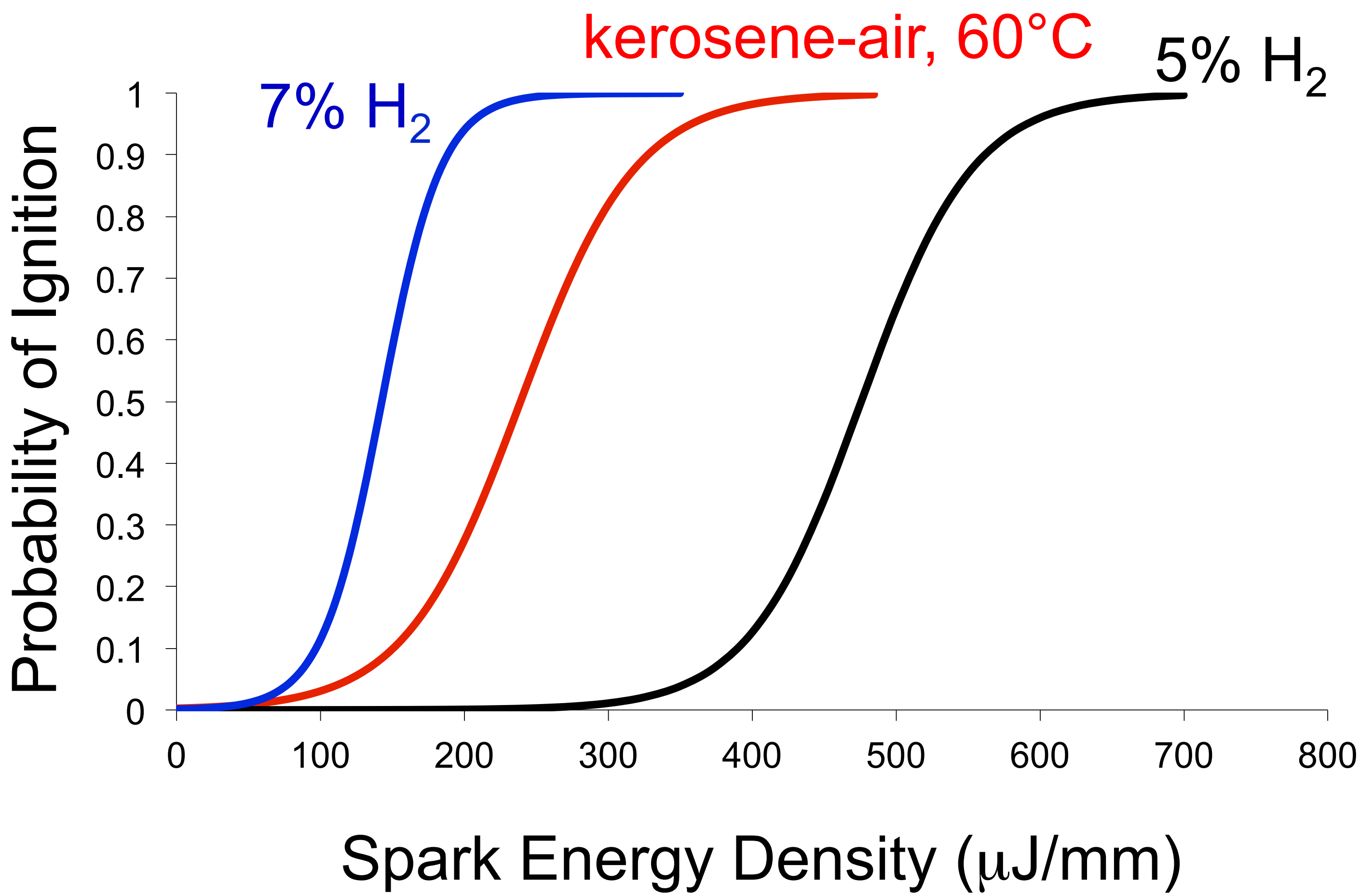


Results: Comparison with Hexane



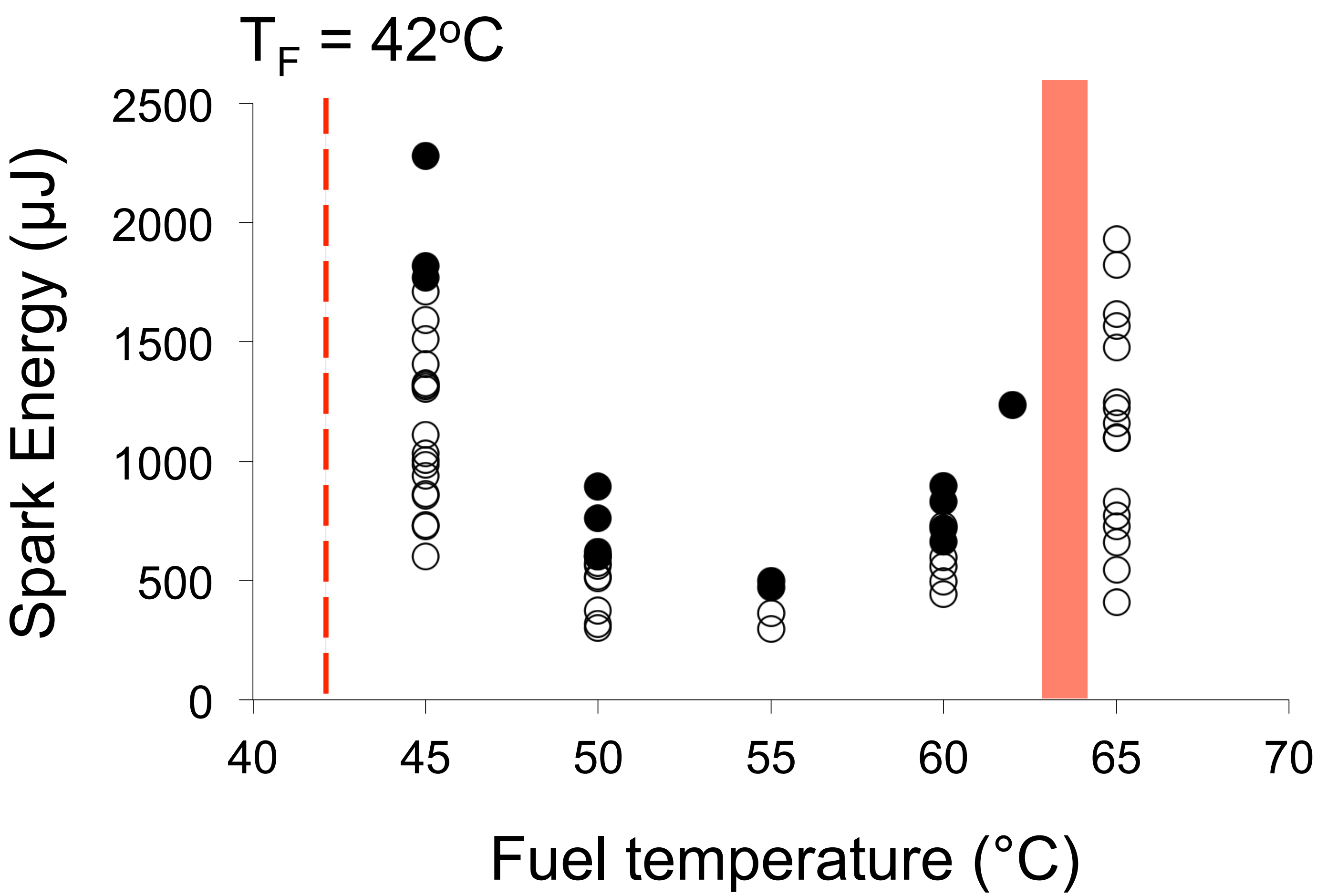
As sensitive as the most sensitive hexane-air mixture

Results: Comparison with H_2



- Energy/length used to account for different length sparks
- Normalize spark energies from 5% and 7% H_2 tests by spark gap widths used (2 and 1 mm)
- Normalize spark energies from kerosene tests by 3.3 mm

Results: Varying Kerosene Fuel Temperature



Parametric Study

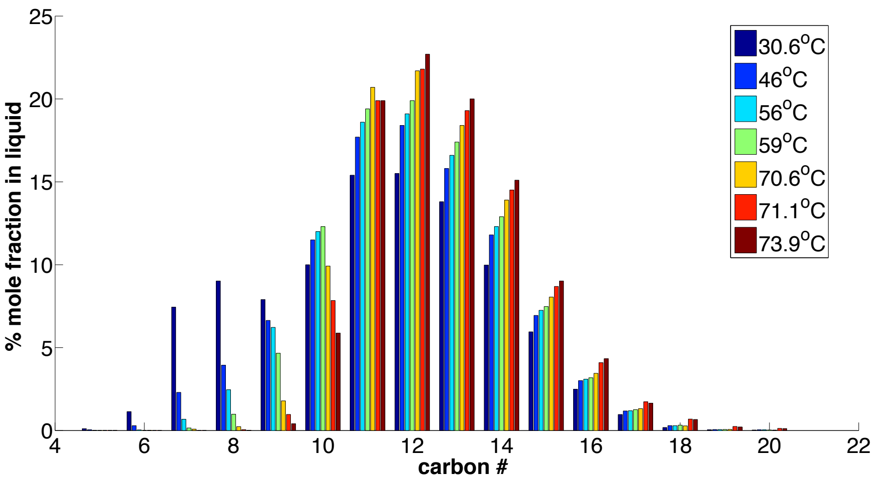
- Ignition energy model
- Mixture composition is required
- Raoult's Law

saturation pressure

$$P_i = X_i P_{vp,i} \text{ for } i = 5, 6, ..., 20$$

liquid composition

- Obtain X_i through a distillation curve or gas chromatography



Gas chromatograph (Woodrow, 2000)

Parametric Study

- Raoult's law does not take into consideration the fuel mass loading
- "headspace equation" → conservation of moles
- *K* is the hydrocarbon liquid-vapor distribution coefficient

initial liquid composition

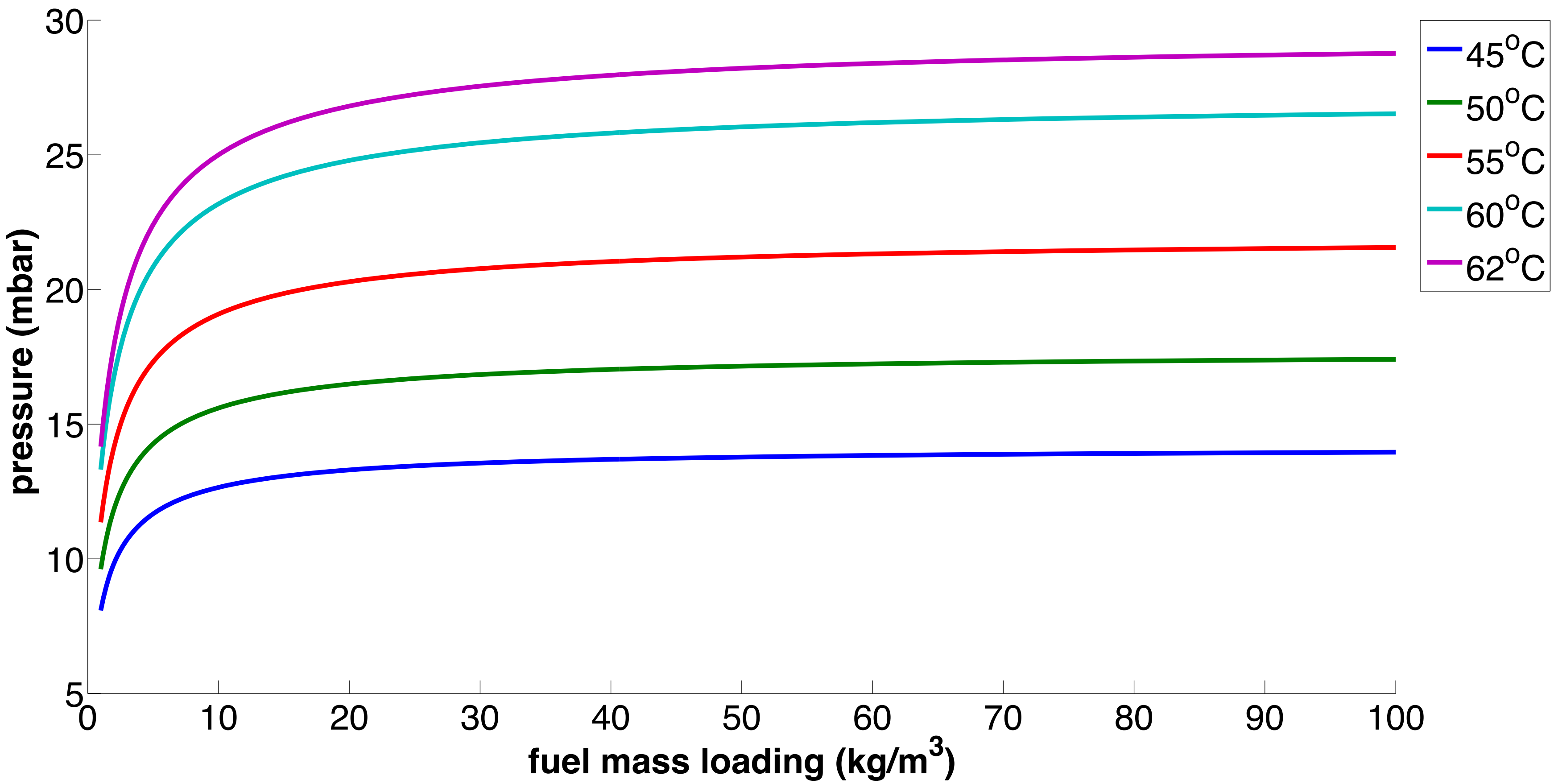
$$C_G = \frac{C_L^o}{K + V_V/V_L}$$

fuel vapor composition

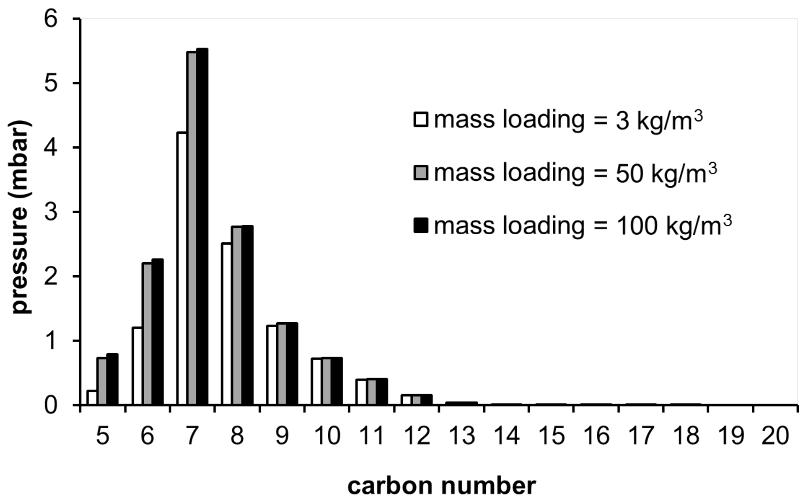
$$K_i = \frac{N}{W_L}\frac{RT}{P_{vp,i}}$$

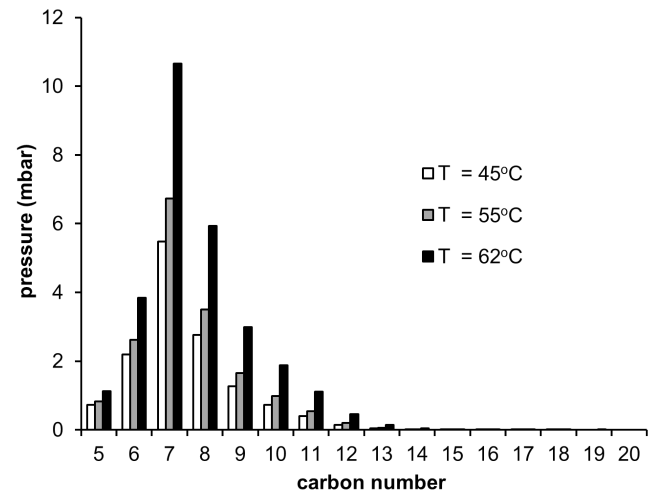
Parametric Study Results

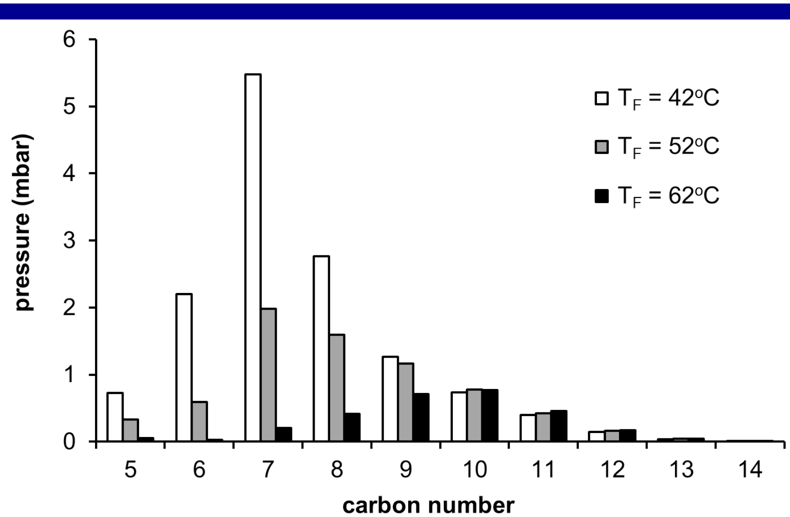
- Effect of fuel mass loading on pressure for a kerosene-based fuel



Parametric Study Results



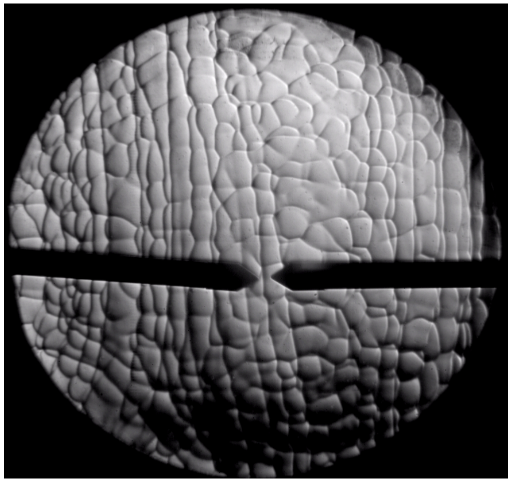


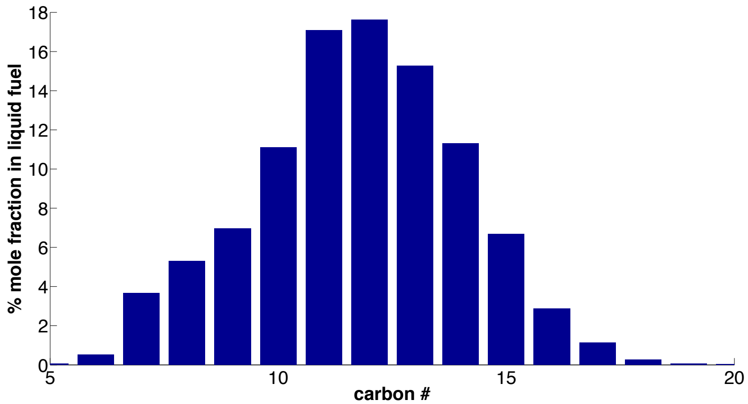


- for low fuel mass loadings, the lighter hydrocarbons become depleted
- fuel vapor pressure is always an increasing function of fuel temperature
- As the flash point increases, the lighter hydrocarbons are fewer

Conclusions

- Electrostatic spark ignition tests using kerosene over a range of temperatures at atmospheric pressure.
- Statistical analysis of probability of ignition vs. spark energy density at 60°C
- Kerosene-air mixture has a lower ignition energy at 60°C than H_2-O_2-Ar mixture previously used in aircraft certification (5% H_2)
- Model to obtain fuel vapor composition given changes in flash point, temperature, pressure and fuel mass loading
- From vapor composition predictions, lighter mass hydrocarbons are more appropriate for low temperature fuel vapor surrogates.





❖ The experimental work was carried out in the Explosion Dynamics Laboratory of the California Institute of Technology and was supported by the Boeing Company through a Strategic Research and Development Relationship Agreement CT-BA-GTA-1

Questions