Flammable Atmosphere Ignition Testing for Aircraft Certification

Issues and current status of laboratory test methods

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Potential Flammable Atmospheres

- Fuel must be mixed with air and within flammable range
- Factors
  - Fuel composition
  - Fuel temperature
  - Air temperature and pressure (altitude)
  - Air oxygen content
  - Mean flow and turbulence
- Fuel tank ullage
  - Aviation kerosene or similar HC derivative fuels (biofuels or SAF)
- Engine and APU compartments
  - Kerosene, engine oil, hydraulic fluid
- Control systems
  - Hydraulic fluid

Examples of Potential Sources of Ignition

Focus is on unpressurized locations in aircraft

- Internal arcs and sparks
  - Electrostatic discharge between isolated components
  - Tribo-charging of fuel
  - Arcing in powered and instrumentation circuits (including optical fibers)
- External lightning strike on external surfaces
  - Melting of metal components
  - Lightning-strike induced voltage arcs between internal components
  - Strike attachment to fasteners, generation of particle and hot gas jets
  - Current flow in composites, edge glow
- Hot surfaces <- Focus of today's presentation
  - Engine, APU and electrical components
  - Bleed air ducts and heat exchangers
  - Frictional heating in pumps and actuators
  - Lightning induced hot spots

Issues for Hot Spot Ignition

Currently there is no guidance regarding hot spot characteristics (size, temperature-time history) as part of the existing guidelines (FAA 24.954) covering lightning strike protection for aircraft fuel tanks. In order to develop guidance, we need to consider the following issues.

- What are the characteristics of the hot spots (temporal and spatial) that are representative of the lightning strike events of interests?

  Although there have been substantial industry programs on flammable mixture ignition due to lighting strike hazards, these have been primarily focused on ignition due to strikes on fasteners, penetration of wing skin and electromagnetic effects due to current flow on structures. Information on hot spot characteristics is apparently not yet available and will be essential for further progress.
- Are there any tests and test data available that examine the potential of hot spot ignition for appropriate flammable mixtures?

  The available test methods for thermal ignition of flammable mixtures are the ASTM E659 and comparable EU standards for Autoignition temperature (AIT). These tests lack the necessary similarity required to apply the results to the situation of lightning-strike generated hot spots.

Hot Surface Ignition Criteria

What variables control the ignition process for a given flammable atmosphere?

Autoignition Temperature (AIT) is the conventional concept for defining ignition threshold for a flammable atmosphere in contact with a hot surface. AIT is a term of art and refers to temperatures determined by a very specific test procedure (ASTM E-659, ISO/IEC 80079) with cold fuel injected into a stagnant volume of hot air atmosphere inside a hot vessel of small (200 to 500 mL) volume.

Laboratory testing with a wide range of hot surfaces and cool flammable atmospheres shows that AIT does not correctly predict ignition threshold for many common situations and many parameters are important in determining ignition thresholds, including:

- Fuel concentration and atmosphere pressure
- Configuration of hot surface
  - Shape
  - Orientation
  - Size
- Flow across surface, turbulence levels
- Effects of surroundings and lack of confinement of atmosphere in large volume
- Heating rate and elapsed time

Heating of a flammable atmosphere does not always result in fire or a propagating flame, outcomes vary from slow consumption of the fuel and oxygen with no significant transients to rapid events with significant pressure and temperature transients.

The challenge of hot surface ignition testing

“Unlike the flash point and the minimum auto ignition temperature, which are well defined combustion properties that can be measured with accepted ASTM standards, **the temperature at which hot surface ignition occurs is not a fundamental fluid property** and is strongly coupled to numerous factors, including the properties of the surface, the liquid spray or stream and the local airflow. Because of this coupling, the temperature required for ignition can vary widely. **Hot surface ignition data cannot easily be extrapolated to different conditions** and the use of general rules of thumb based on the minimum auto ignition temperature can be very inaccurate.” - Colwell and Reza, Fire Technology, 2005

“At all test conditions, the **ignition temperatures of the fluids were noticeably higher than their minimum autoignition temperatures** which are determined in uniformly heated vessels. “ – Strasser, Waters, and Kuchta, AFAPL-TR-71-86, 1971.

Gaps between testing and application

Laboratory test methods

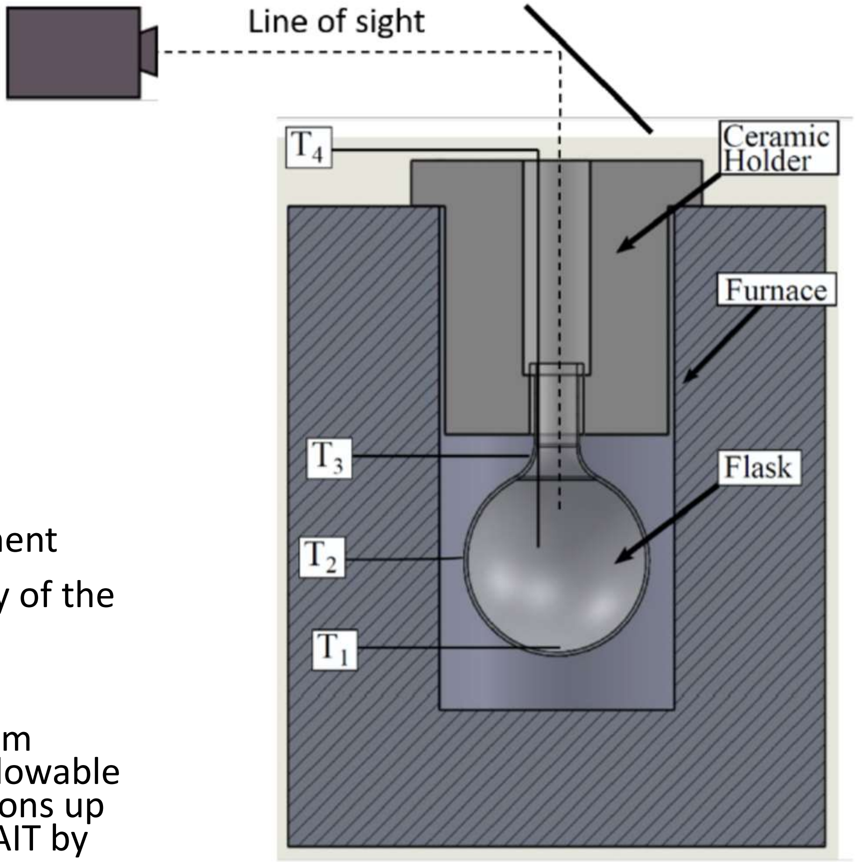
Lightning strike on upper wing surface

Some Representative Hot Surface Tests

Types of testing explored at Caltech:

- Extended hot surface confining a hot flammable atmosphere
  - Rapid injection of liquid into hot air volume - ASTM E659 test (Martin 2020)
  - Slow heating of flammable mixture in closed volume (Boettcher 2012, Mével 2017)
- Isolated hot surface within a cool flammable atmosphere
  - Diesel engine glow plug (Boettcher, Boeck, Sung)
  - Small (10 mm, 0.4 in) cylinder (Boeck)
  - Metal and ceramic spheres (6 mm, 0.25 in) (Coronel)
  - Large (25 mm dia, 250 mm, 10 in long) cylinder (Jones)
  - Wires (50 µm dia) (Smetana)
  - Hot spot embedded in cold surface (mm^2) (Schoeffler)

ASTM E-659 Autoignition Test



Procedure:

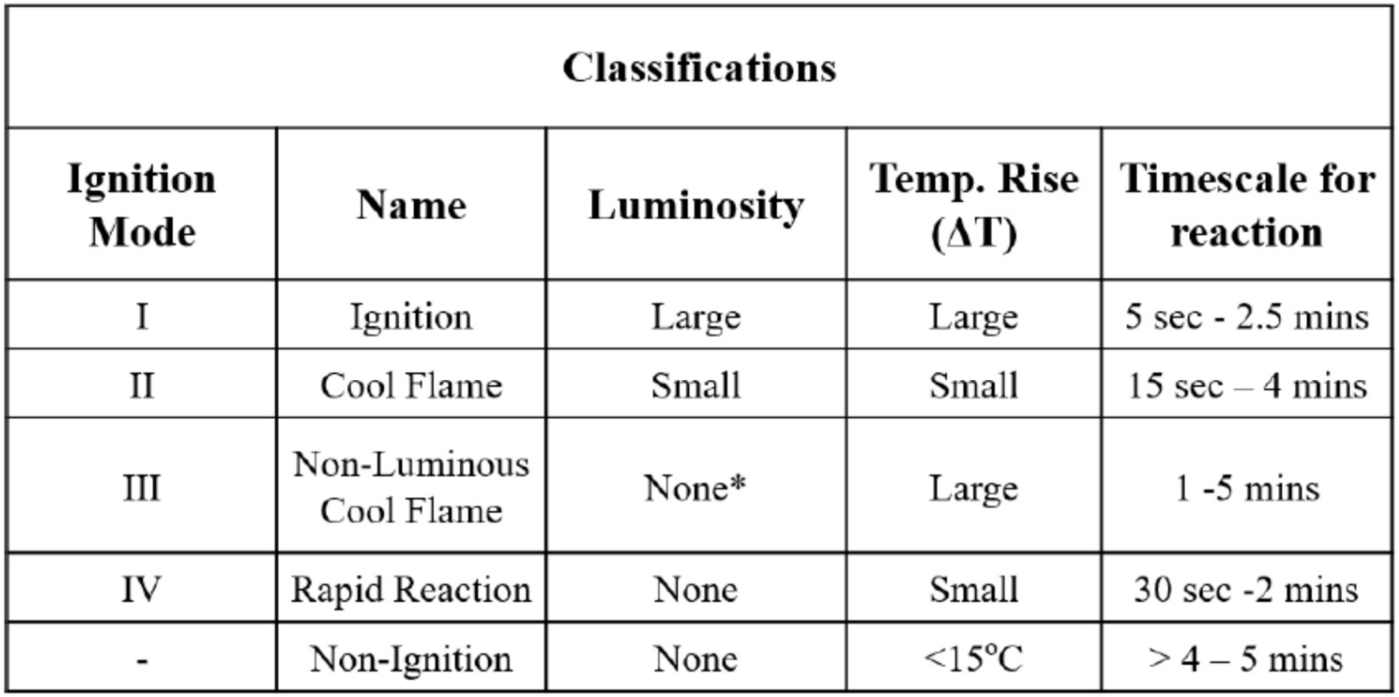
1. 500 mL spherical flask heated to specified temperature (T)
2. 0.1 mL liquid sample injected through open top
3. Wait up to 10 min for flash of light (by eye)
   - If no flash: repeat steps 1-3 at higher T
   - If flash: repeat steps 1-3 at lower T
4. Iterate until T between ignition and non-ignition reached
5. Repeat for range of sample volumes

Results:

- Subjective evaluation based on visual results and operator judgement
- Single Auto ignition temperature (AIT) reported (lowest T from any of the tested samples) based on arbitrary ignition criteria.

ASTM test results are basis of FAA guidance (AC 25.981) on maximum allowable hot surface temperature within fuel tanks of 400^{o}F with allowable transient excursions to 450^{o}F. External to fuel tank, transient excursions up to 500^{o}F are allowable. Primary data and testing used to establish AIT by FAA is not referenced.

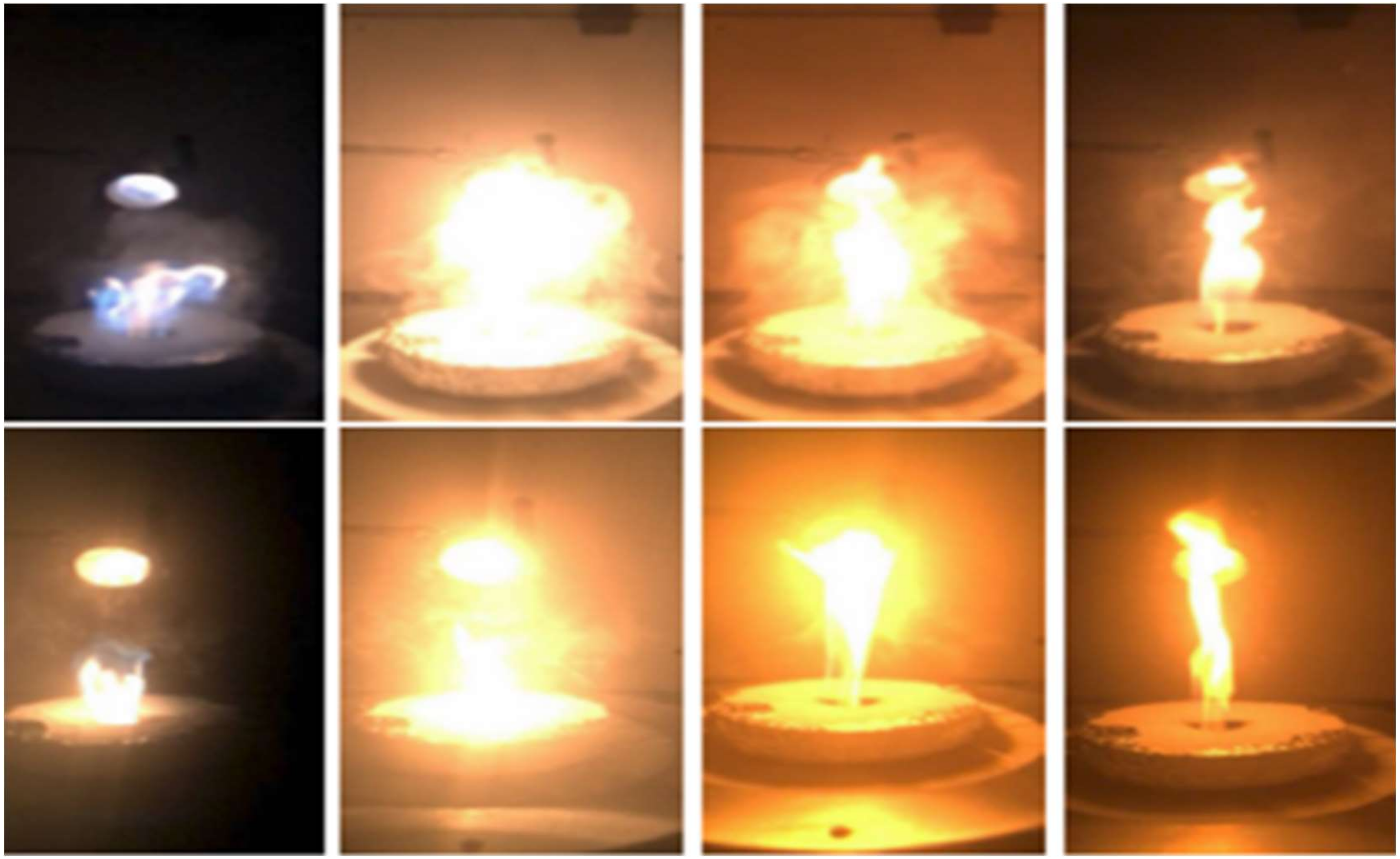
Range of outcomes from ASTM E-659 tests



Classifications				
Ignition Mode	**Name**	**Luminosity**	**Temp. Rise (ΔT)**	**Timescale for reaction**
I	Ignition	Large	Large	5 sec - 2.5 mins
II	Cool Flame	Small	Small	15 sec – 4 mins
III	Non-Luminous Cool Flame	None*	Large	1 -5 mins
IV	Rapid Reaction	None	Small	30 sec -2 mins
-	Non-Ignition	None	<15°C	> 4 – 5 mins

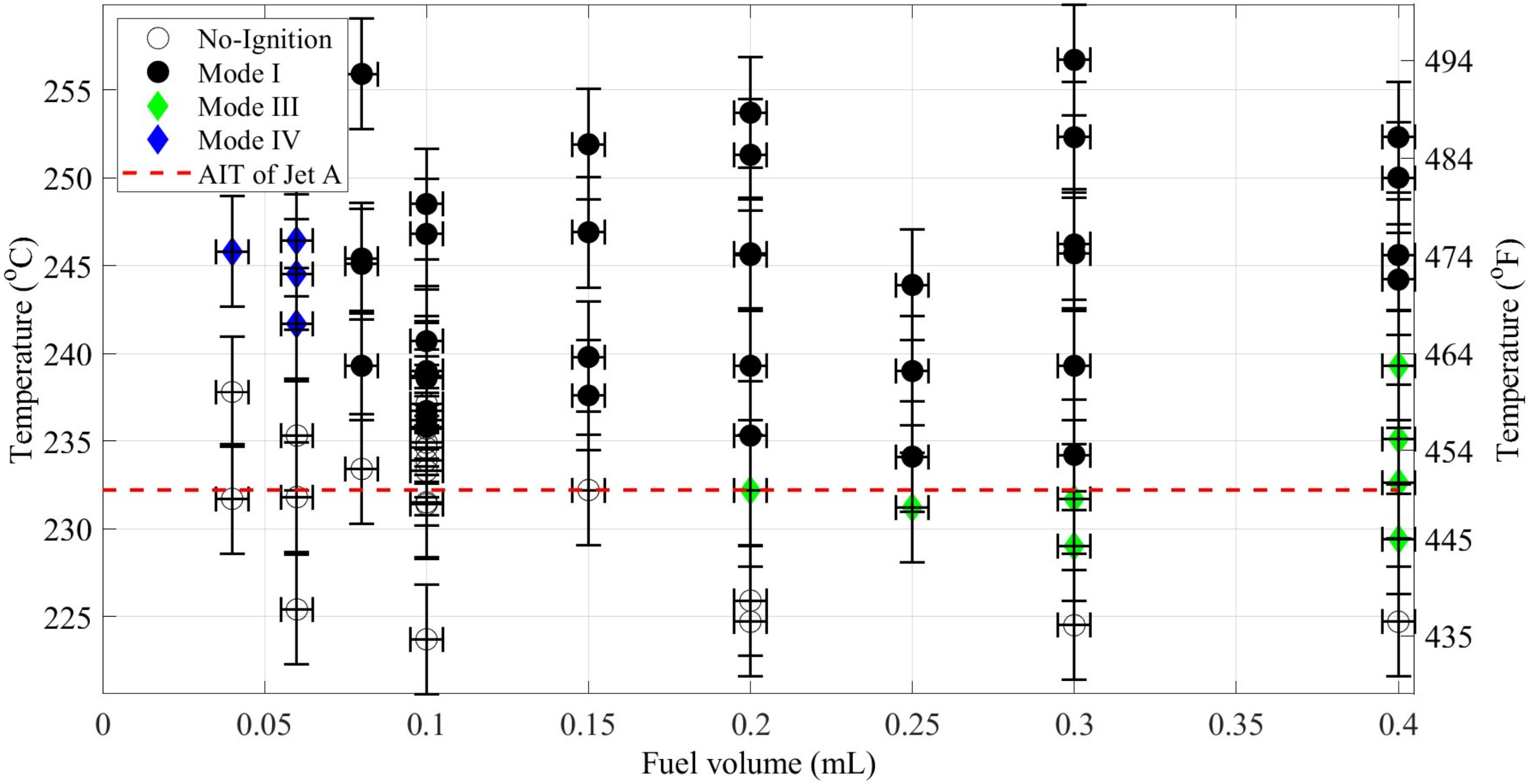
*Faint glow only visible to naked eye and small puff of smoke

Ignition in ASTM E-659 test



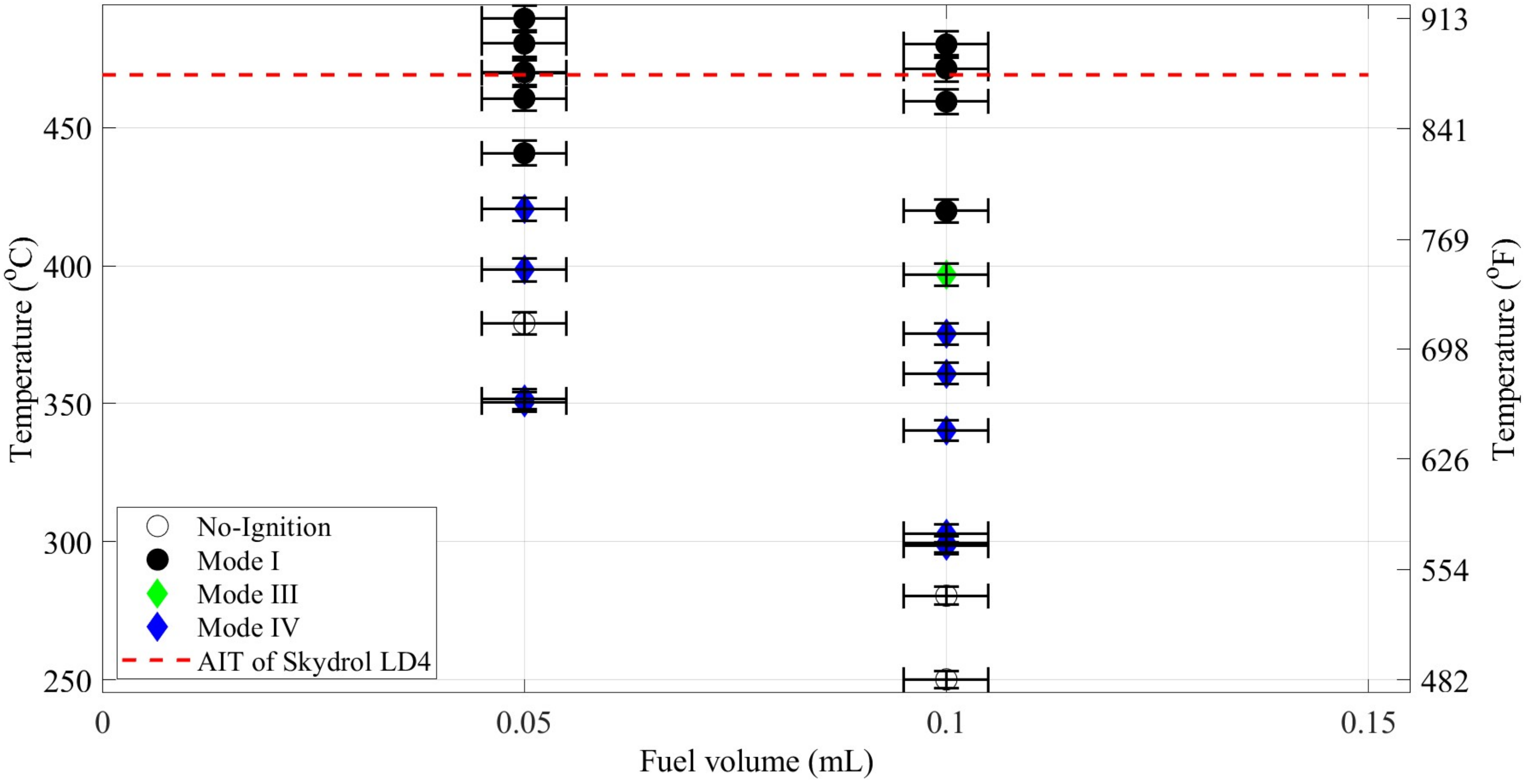
Martin 2020

ASTM E-659 test results for Aviation Kerosene



POSF4658 Martin and Shepherd 2020

ASTM E659 test results for Hydraulic Fluid (LD-4)



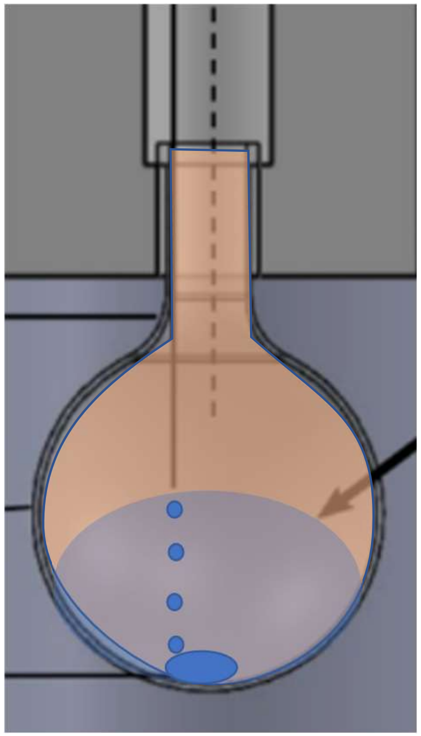
Luchsinger and Martin 2022

When is ASTM E-659 AIT relevant?

- Useful as guidance for:
  - Hot atmospheres and hot surfaces
  - Confined flammable atmosphere with recirculation
  - Long duration (minutes) for hazard conditions
- Lacks essential similarity to many potential aviation hazard situations
  - Lack of confinement, transient conditions, cold atmospheres, flow, …
- Alternative tests and ignition criteria are needed for:
  - Unconfined surfaces and cold flammable atmosphere without recirculation
  - Surfaces with transient and localized high temperatures (Lightning Strike)
  - Convective flows and turbulence in atmosphere
  - Impact of fuel droplets on hot surfaces in cold atmosphere

Inside ASTM E-659

- Not just hot surface!
- Stream of liquid droplets
- Impingement of liquid on bottom
  - Splashing, coalescence
  - Liedenfrost effect, bouncing
  - Vaporization from surface heat transfer
  - Breakdown (pyrolysis) of fuel
- Hot air atmosphere
  - Droplets evaporate from atmosphere heat transfer
  - Fuel vapor mixes with atmosphere
  - Ignition of droplet by hot atmosphere
- Hot fuel-air mixture

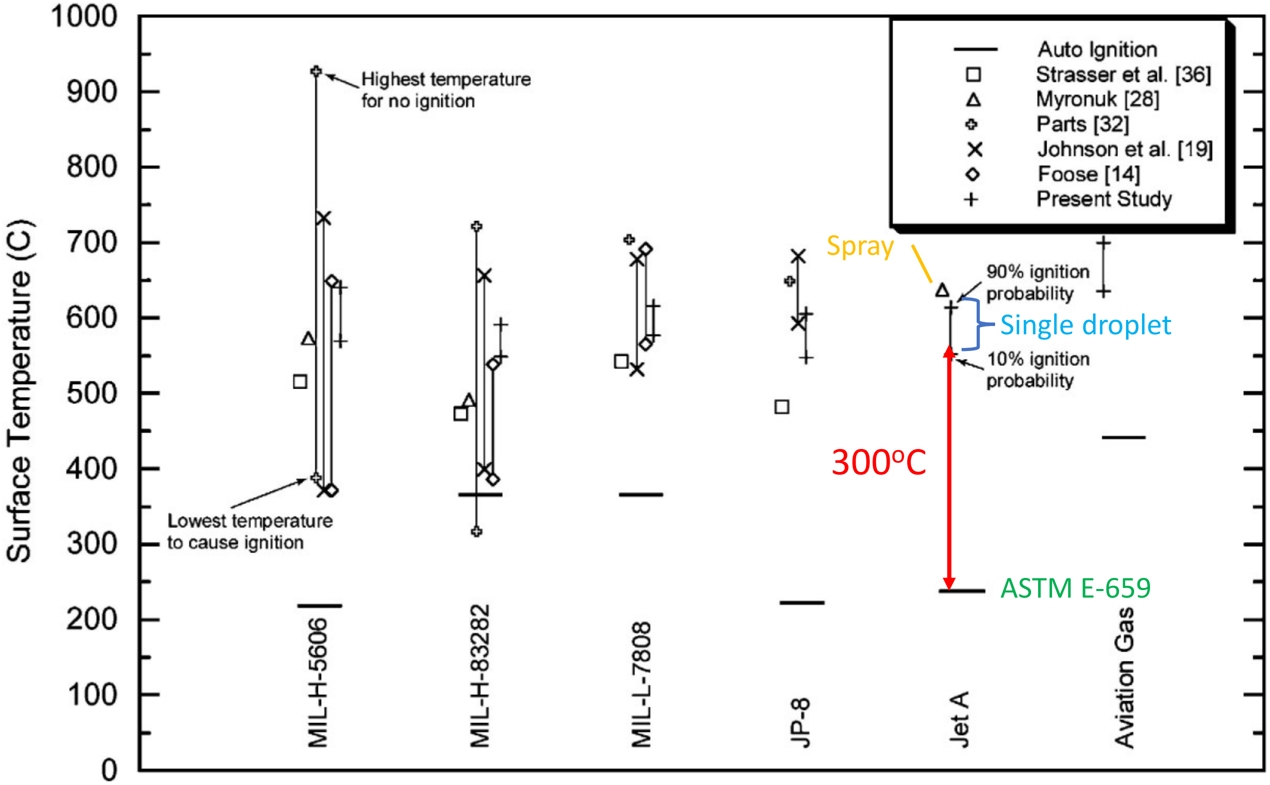


What is actually responsible for ignition?

Conclusions

- Multiple competing processes
  ASTM E-659 is not just a Hot Surface!
- To interpret and apply results we need to “get inside” of test vessel and understand individual and synergistic effects:
  - Impingement of fuel droplet stream on hot surface
  - Ignition of droplets on hot surface with air atmosphere (hot and cold)
  - Mixing and ignition of fuel vapor-air mixture
  - Role of hot surface vs hot atmosphere
  - Liquid vs vapor fuel
- Combination of applying past research and doing new work – in progress at Caltech (Fouchier) and Stanford (Ihme and Simitz)

Example: Single cold fuel drop on hot surface



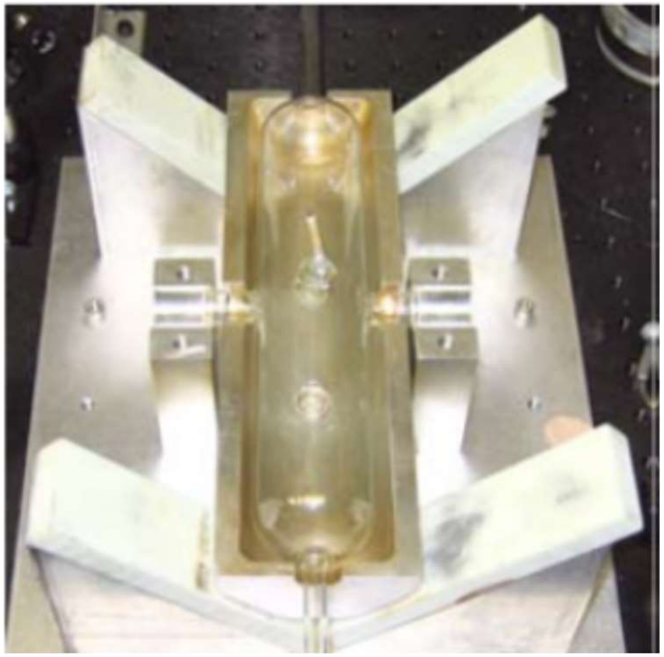
A single 25 μL droplet of Jet A impacting a heated surface ignites at > 550°C, nearly 300°C higher than the ASTM E-659 AIT!

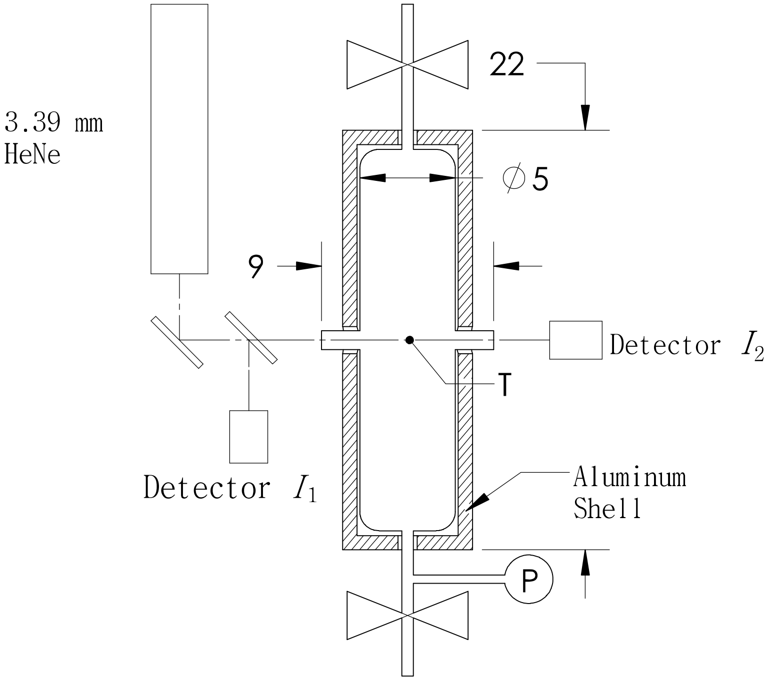
Similar results were obtained for fuel sprays on hot surfaces (Strasser, Waters ,and Kuchta 1971)

Conclusion: The amount of fuel, hot atmosphere, and confinement in the ASTM test play a key role in determining the threshold temperature for ignition.

Colwell and Reza 2005

Example: Slowly heating fuel-air atmosphere

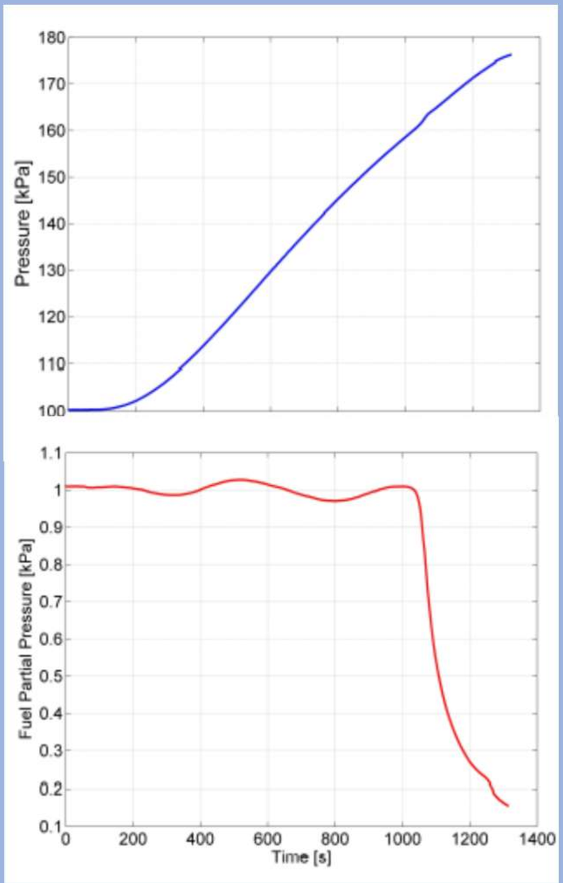




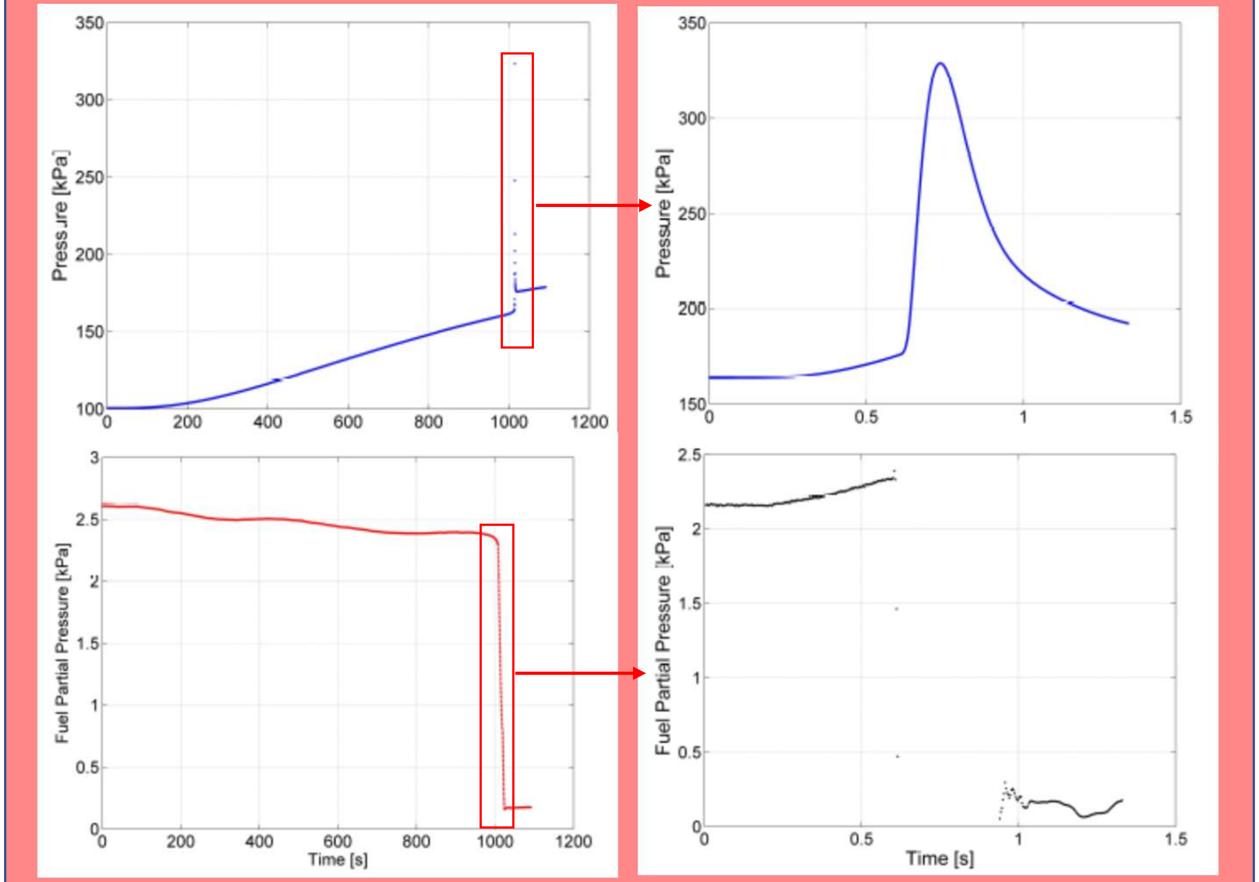
Boettcher 2012

Effect of Fuel Concentration

Fuel lean – 1 atm – no explosion



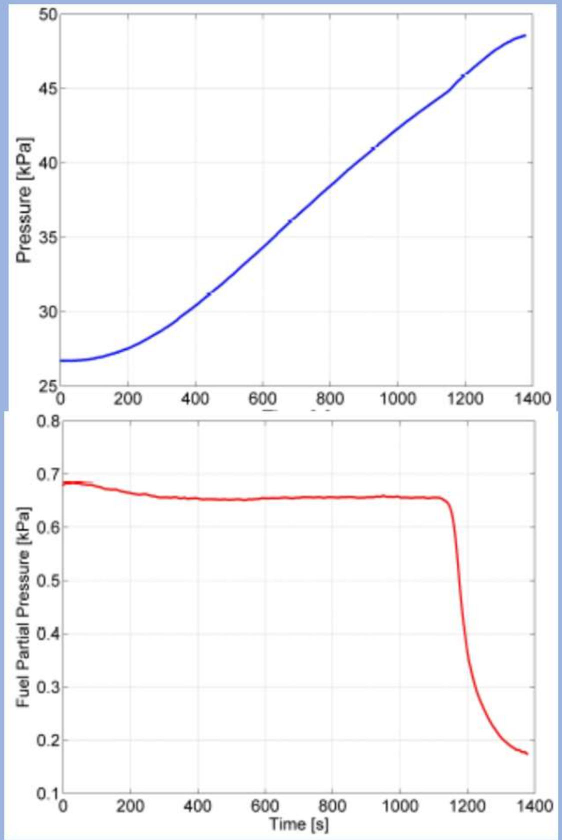
Fuel rich – 1 atm – explosion



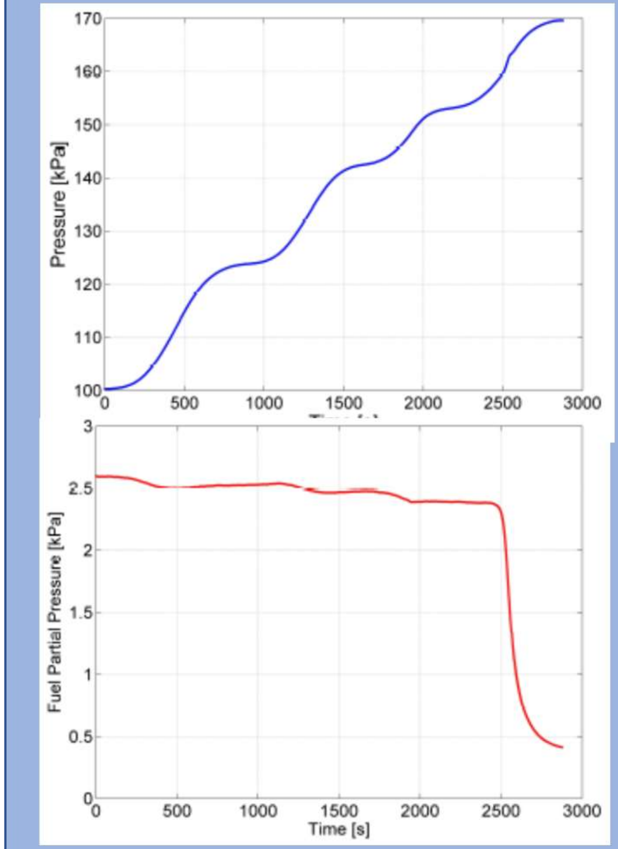
Boettcher 2012 – 20°F/min (11°C/min)

Reducing Pressure and Heating Rate

0.25 atm (20°F/min, 11°C/min)



1 atm (9°F/min, 5°C/min)

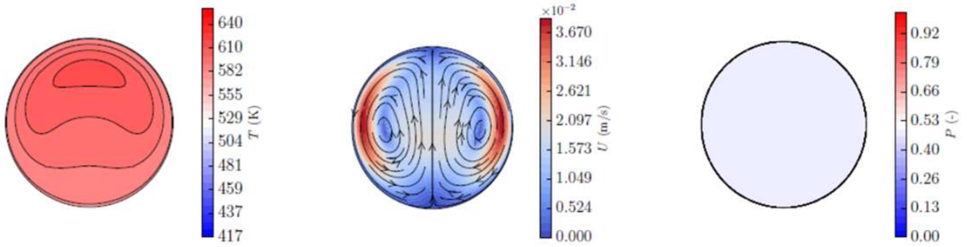


- Slow heating tests
  - Surrogate for Jet fuel (hexane)
  - Well-mixed vaporized fuel in air
  - Vessel of 0.4 L
  - Heating for 15-40 min
  - Temperature at ignition: 190-270°C, 374-518°F
- Two types of events
  - Fast or explosive
    - Rapid & high pressure rise
  - Slow or non-explosive
    - No pressure rise
  - Fuel consumed in both cases
- Dependent on
  - Fuel concentration
  - Atmospheric pressure
  - Heating rate

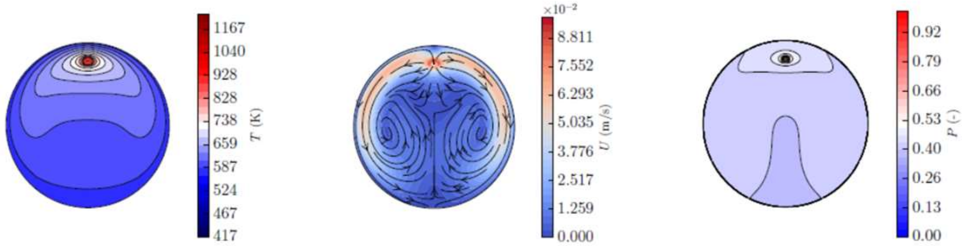
Boettcher 2012

Interpretation with numerical simulation

- Slow reaction

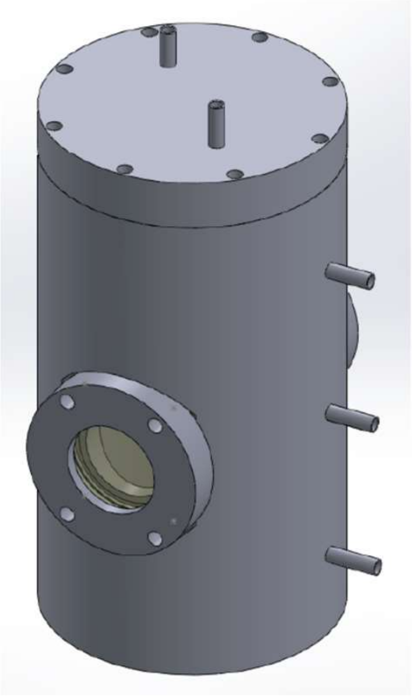


- Fast reaction

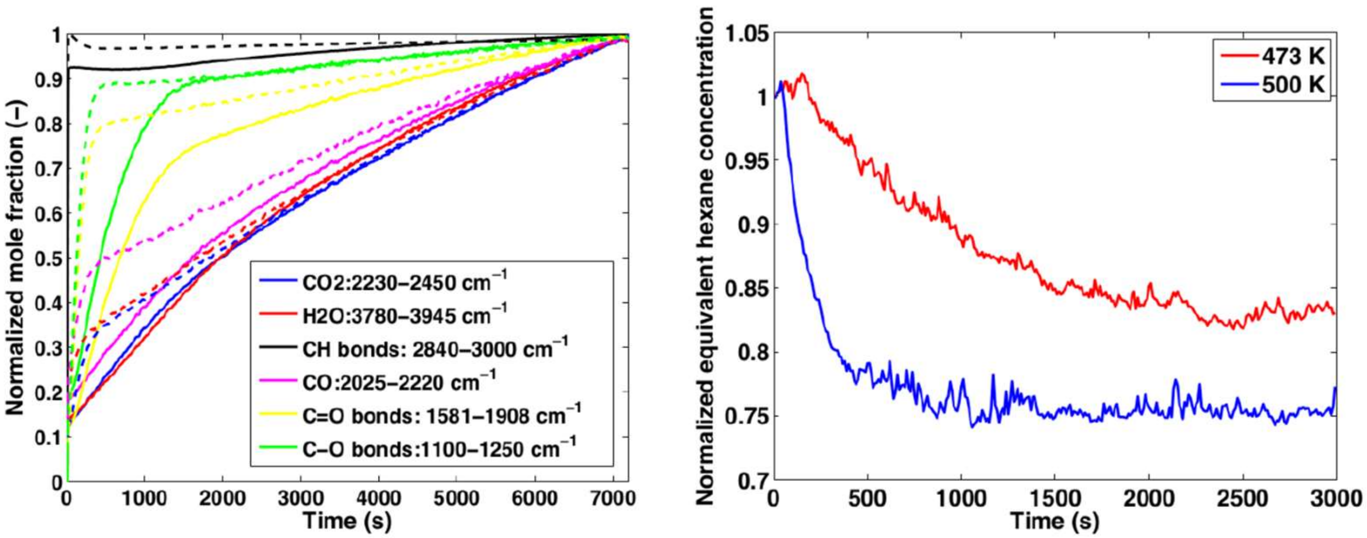


Melguizo-Gavilanes 2019

What is happening to fuel?



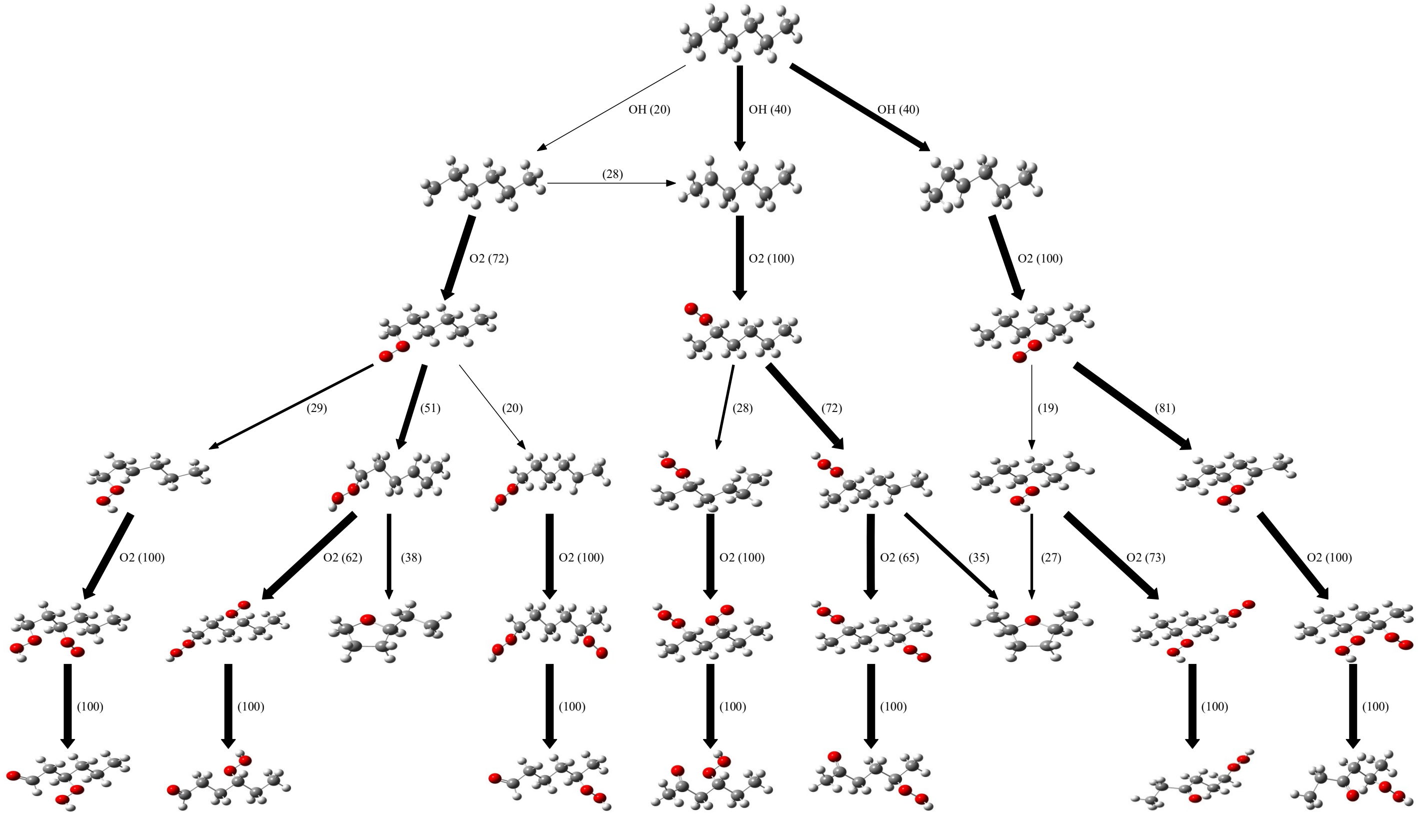
Slow conversion to products (CO, CO2, H2O and fuel fragments)



Significant amount of fuel can remain after extended heating period.
No explosive reaction but can be ignited with isolated hot surface!

Mével 2019

Low temperature Fuel Oxidation

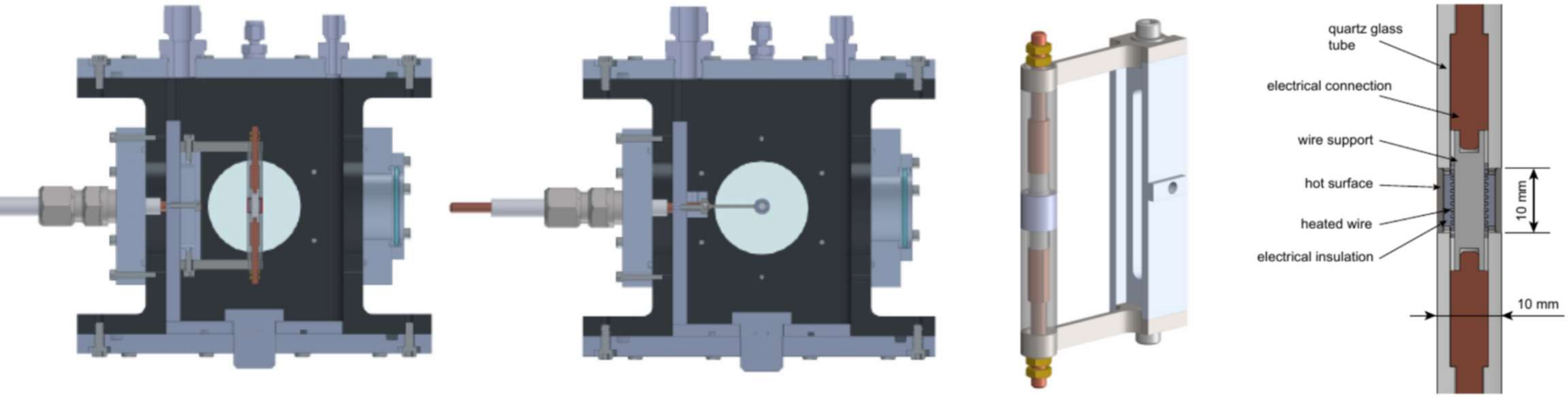


Mével 2019

What about hot surfaces alone?

- Isolated hot surface with cool flammable atmosphere, no recirculation or significant heating of atmosphere outside thermal layer near surface
- Examples from our studies:
  - Diesel engine glow plugs
  - Stainless steel cylinders
    - Small 10 mm
    - Large 100-1000 mm
  - Titanium and ceramic spheres (2-6 mm)
  - Heated wires
  - Hot spots – laser and electrical heating

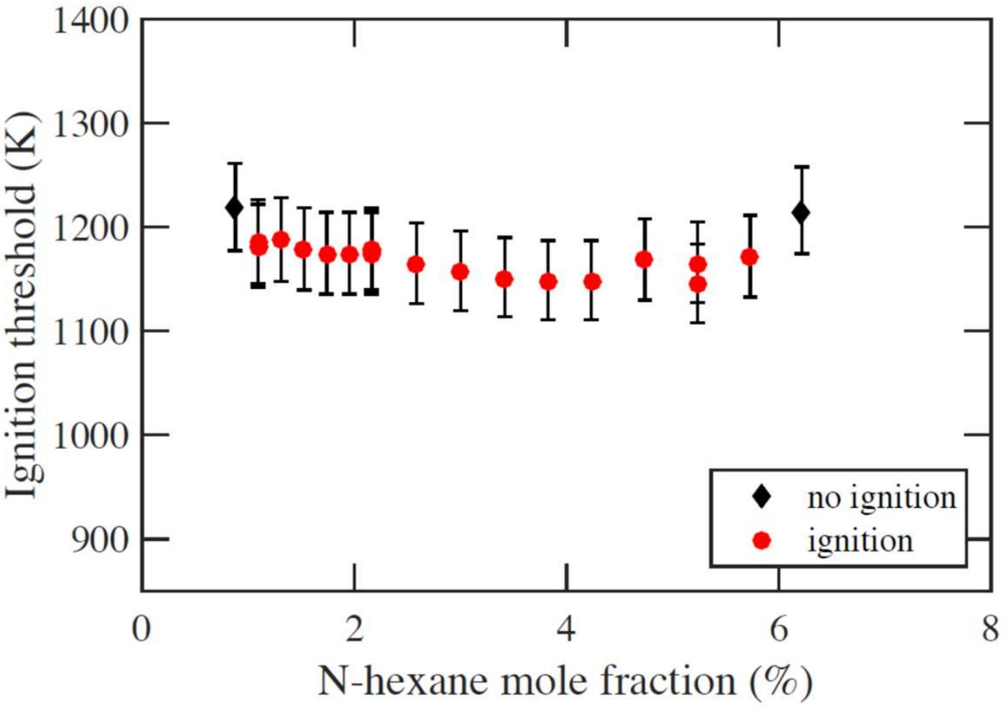
Small hot cylinders



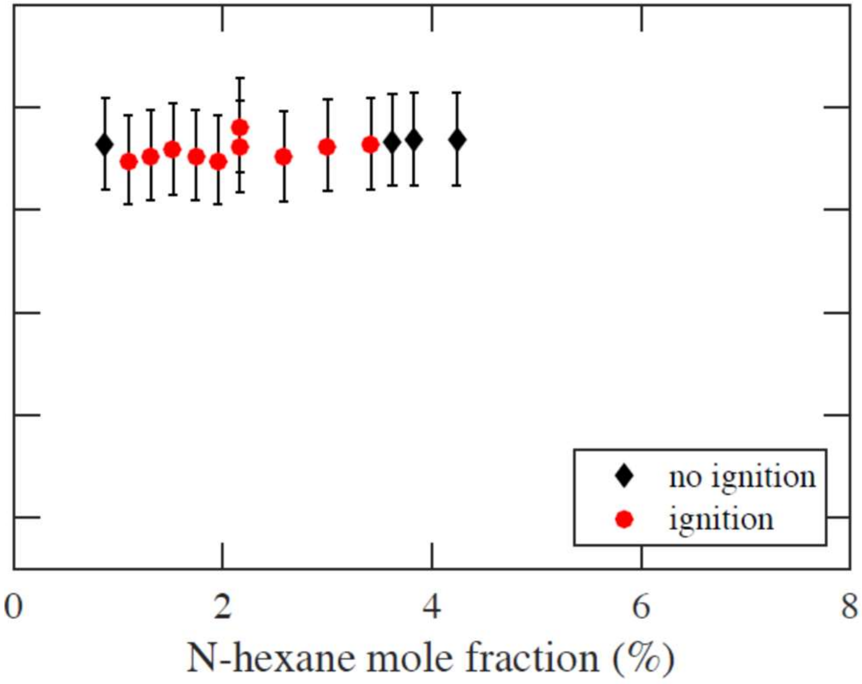
Boeck 2017

Results for Jet A surrogate (hexane)

Vertical

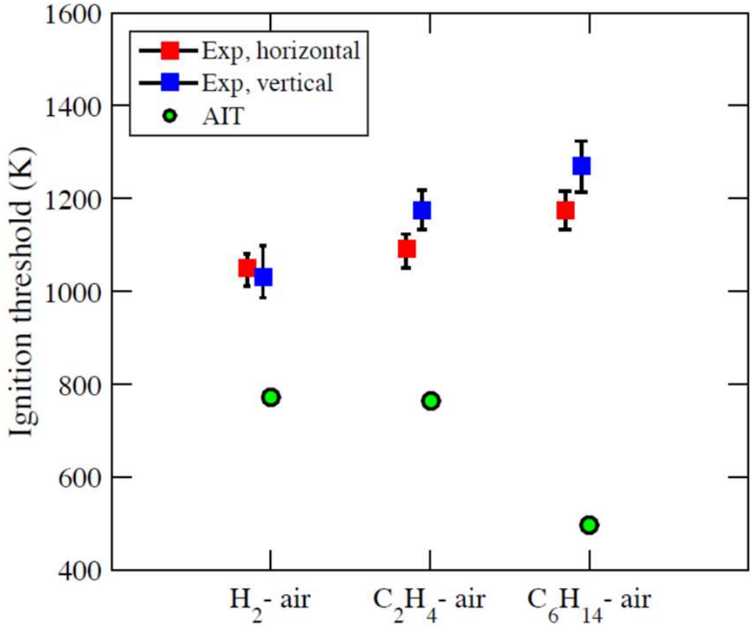


Horizontal



Boeck 2017

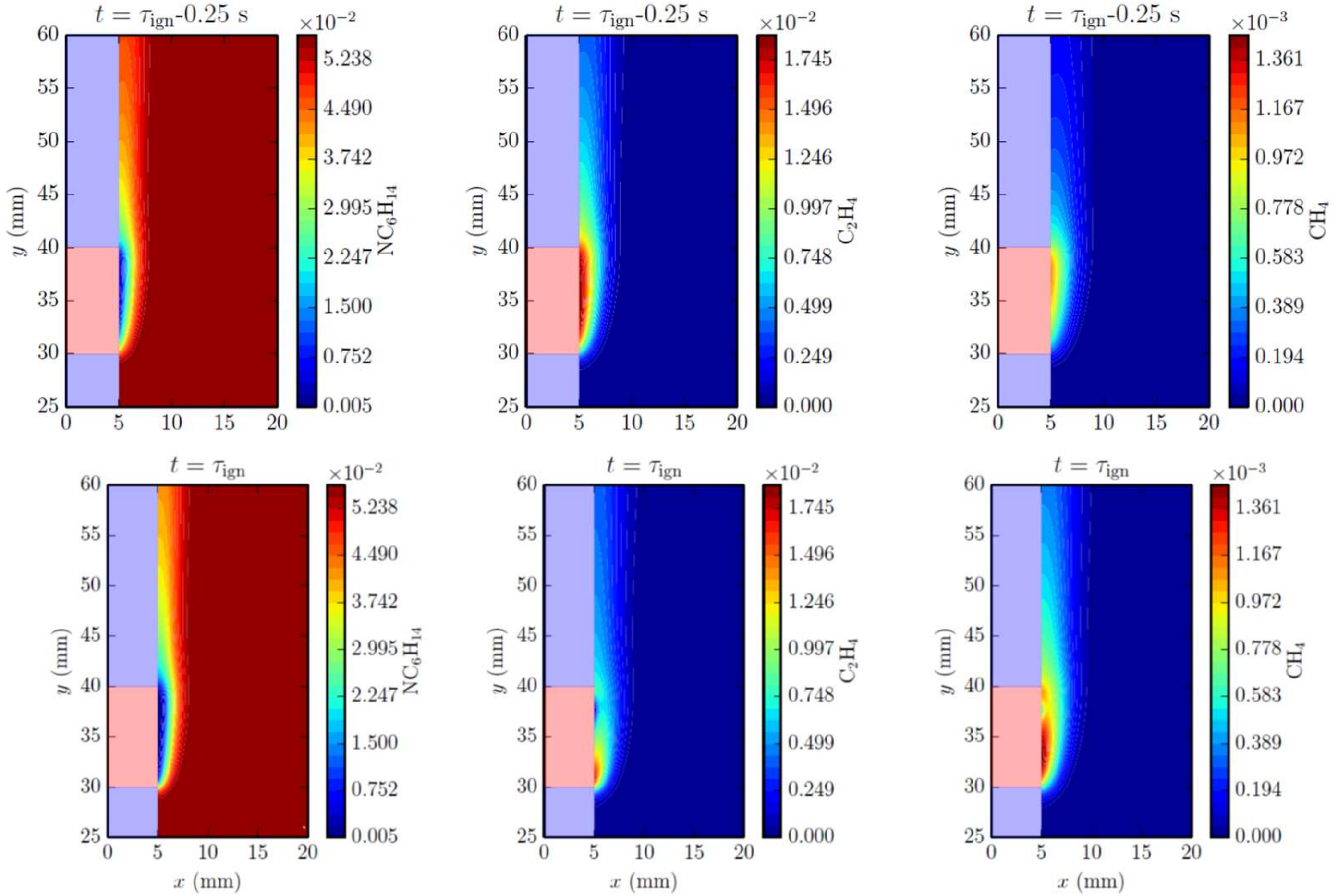
Summary of small cylinder testing



Boeck 2017

- Threshold temperature much higher than ASTM E-659 AIT
- Orientation plays minor role
- Flammable atmosphere composition dependence (rich vs lean) minor
- Consistent trends for H_2, C_2H_4 and C_6H_{14} fuels

Interpretation with Numerical Simulations

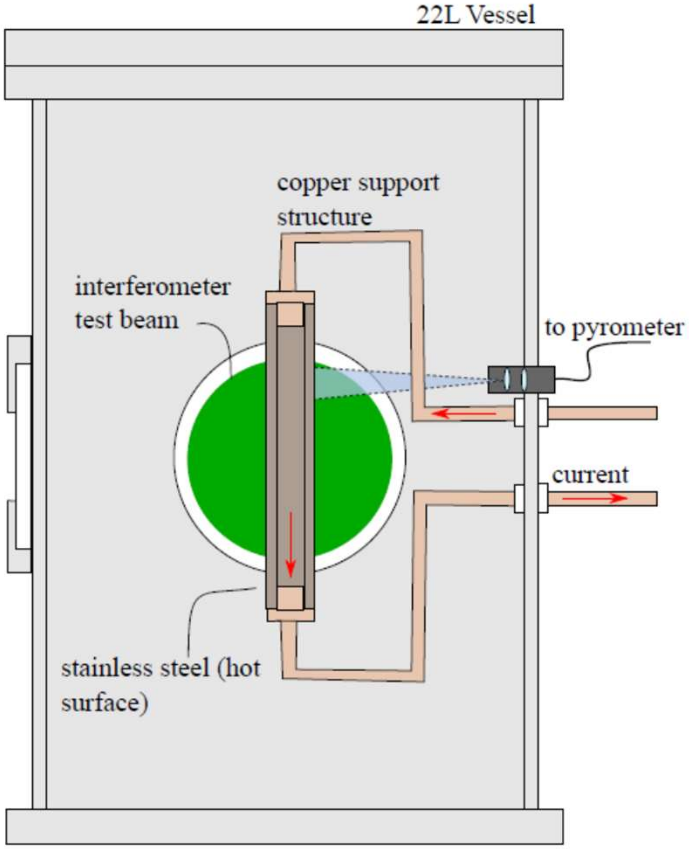


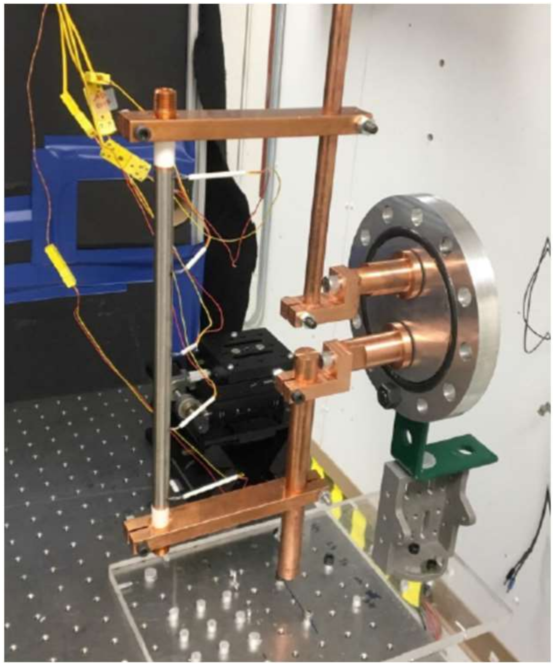
Breakdown of flammable mixture near surface into smaller fuel fragments

Ignition of smaller fuel fragments in thin layer next to surface

Melguizo-Gavilanes 2017

Larger Hot Cylinders

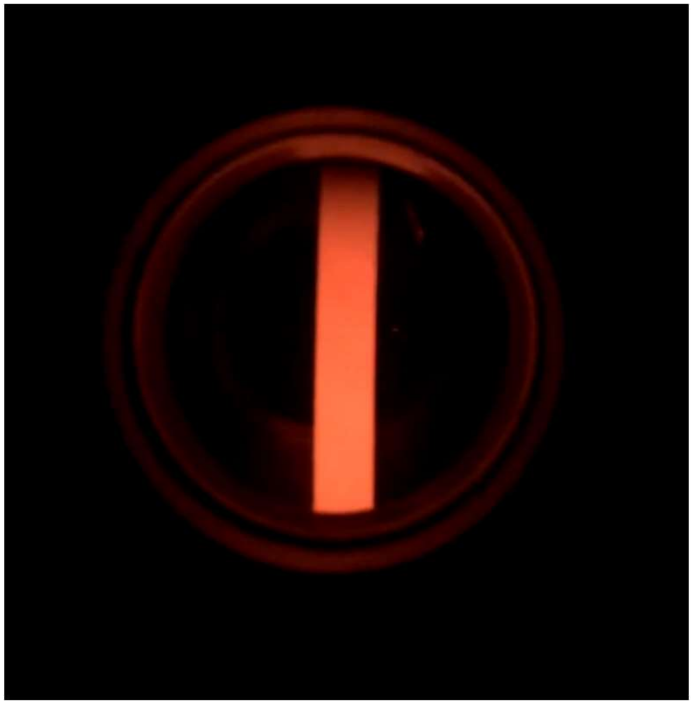


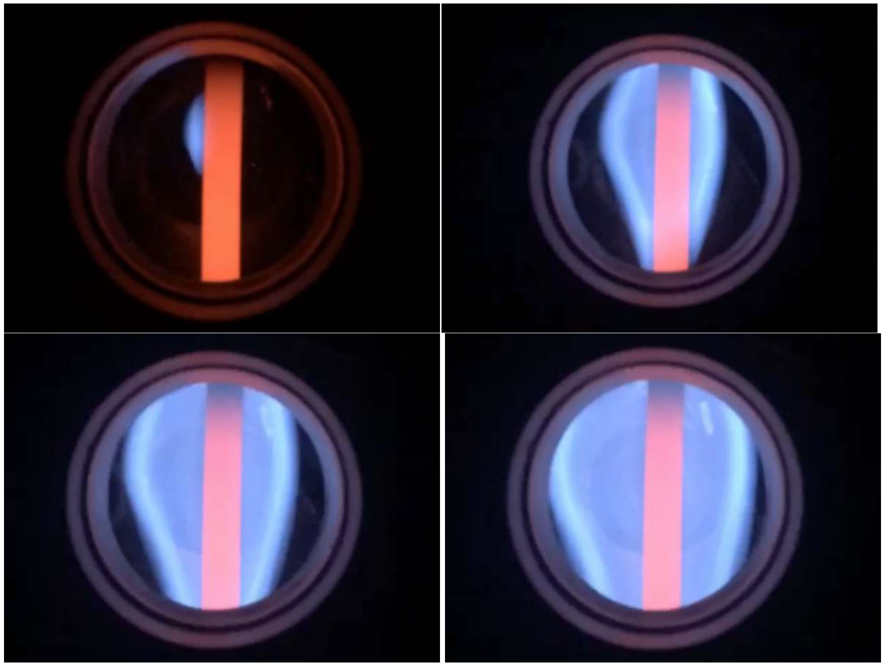


Jones 2021

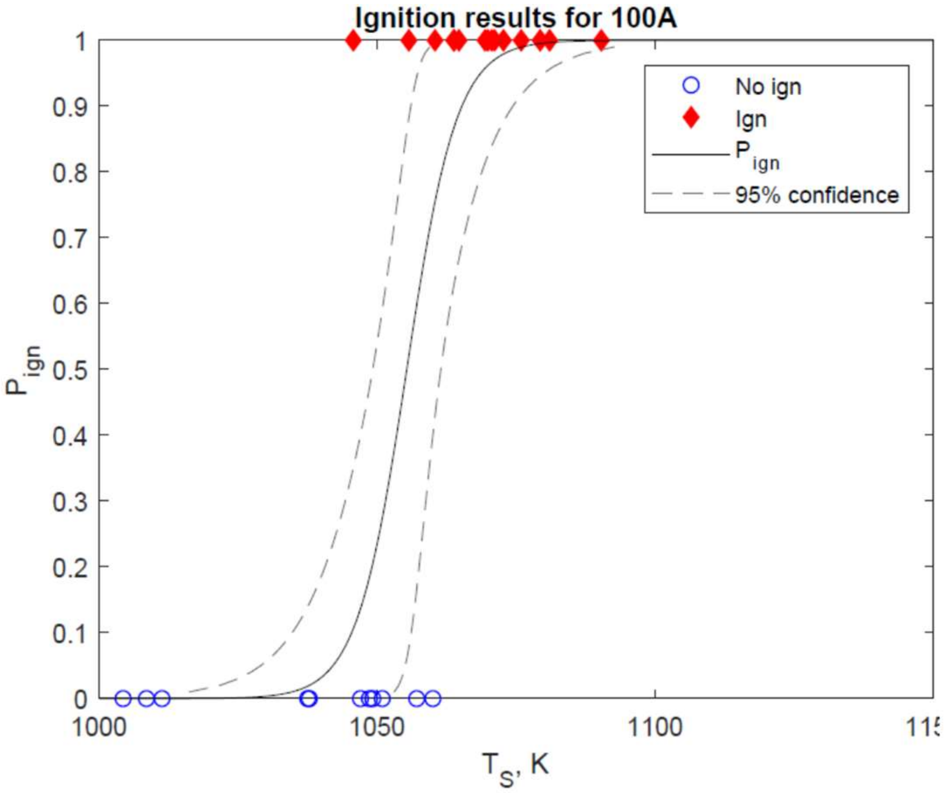
Larger Hot Cylinders

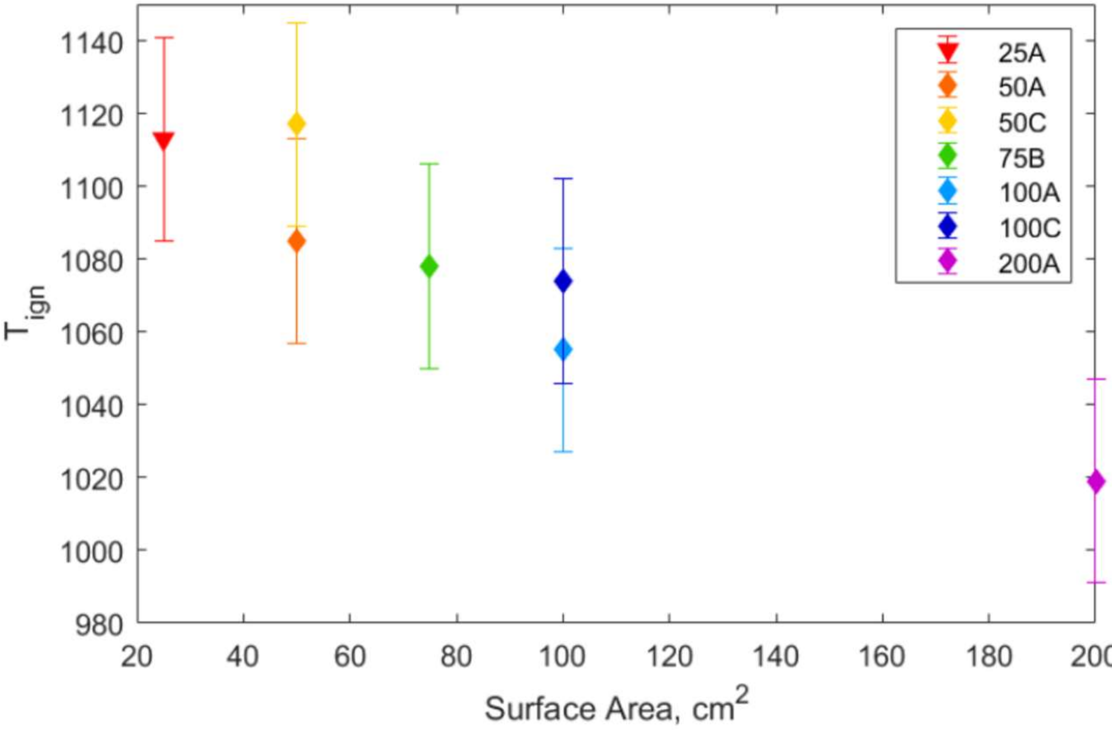
250 mm (10 in) tall, 25 mm diameter (1 in) stainless steel cylinder electrically heated within 1 min to $T=752^{o}$C (1385^{o}F). Flammable atmosphere: cold n-hexane/air (1 atm, stoichiometric) - Martin 2022, Jones 2021





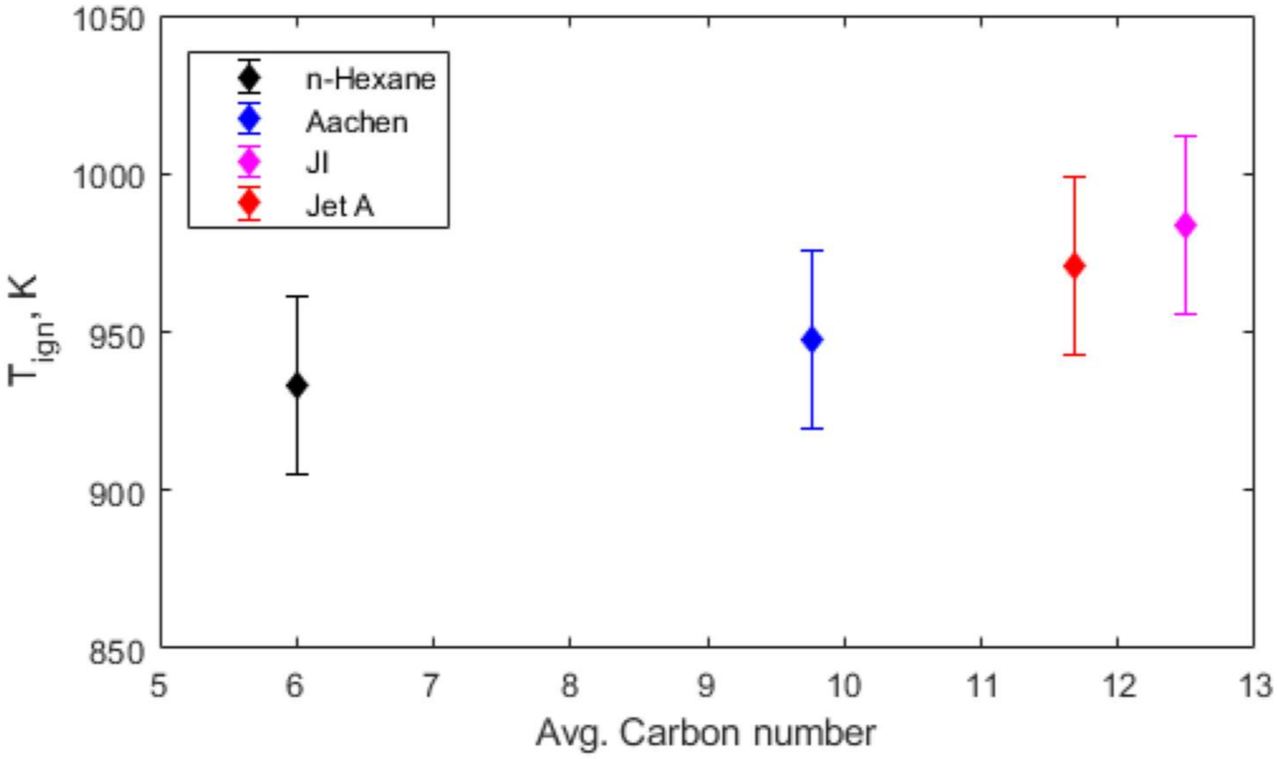
Results





Jones 2021

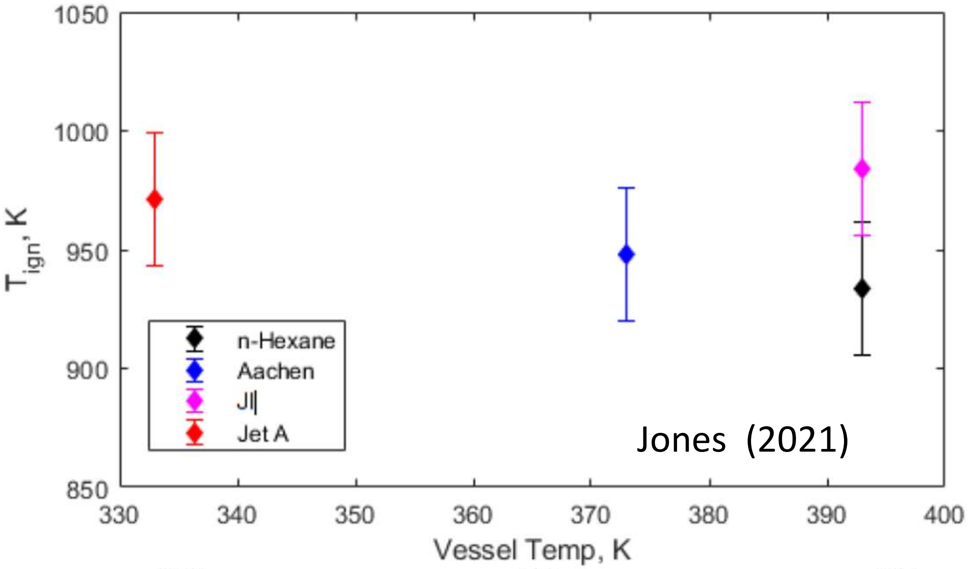
Effect of fuel or surrogate composition

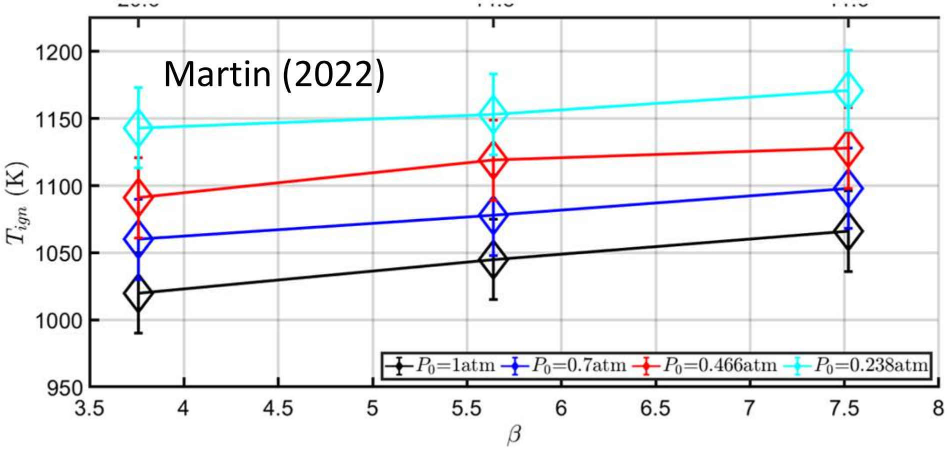


Jones 2021

Further Observations

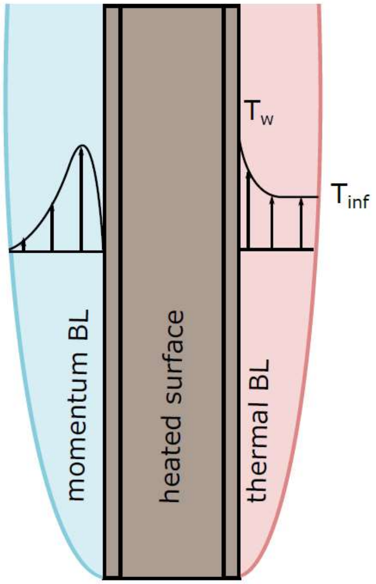
- Parametric study of
  - Fuel type
  - Atmosphere temperature
  - Atmosphere O2 concentration
  - Atmosphere pressure
- All have modest (+/- 100^{o}C) effect on ignition threshold temperature compared to difference from AIT



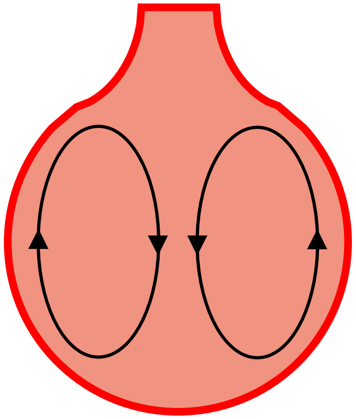


Cylinders vs ASTM E-659 AIT

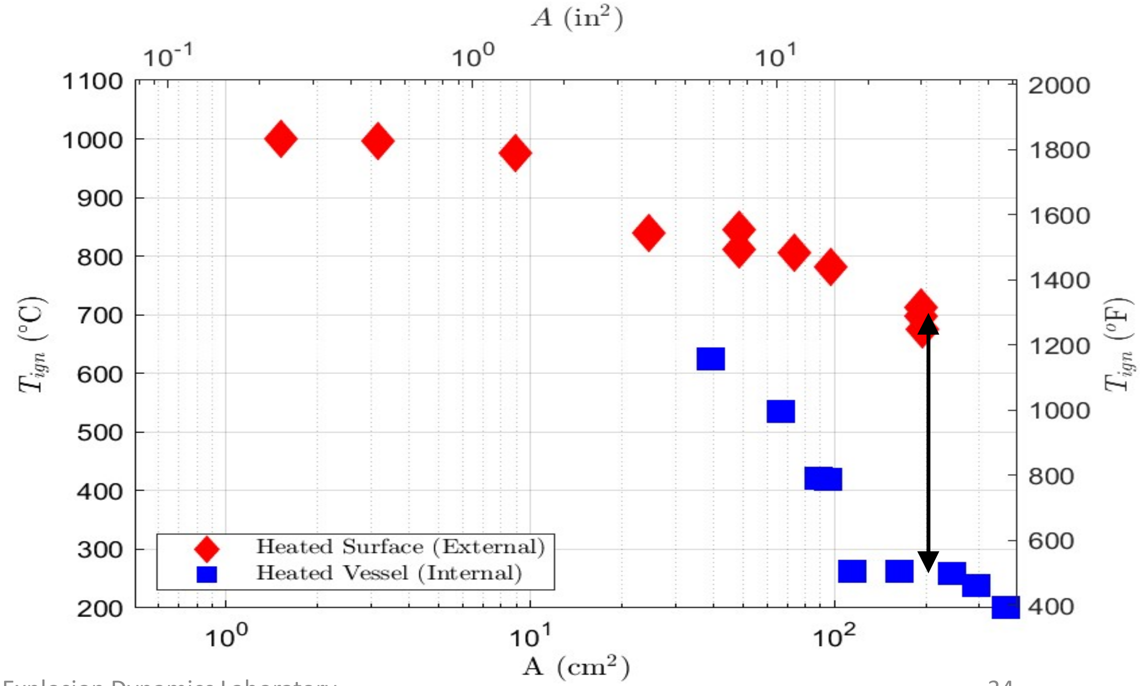
Unconfined flow, cold atmosphere external to heated surface



Confined flow, hot atmosphere internal to heated surface



Ignition threshold temperature 700°F higher for unconfined vs confined flammable atmospheres at largest sizes. Ignition threshold temperature increases significantly with decreasing size.



Back to Lightning Strike

Laboratory test methods

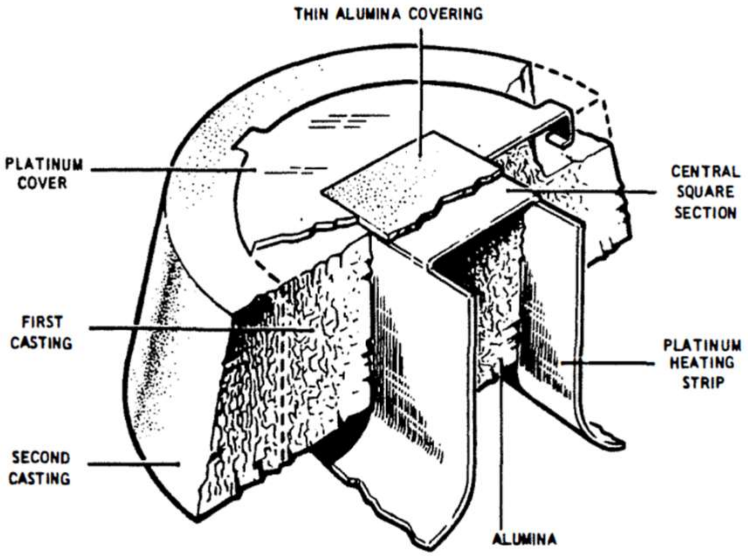
Lightning strike on upper wing surface

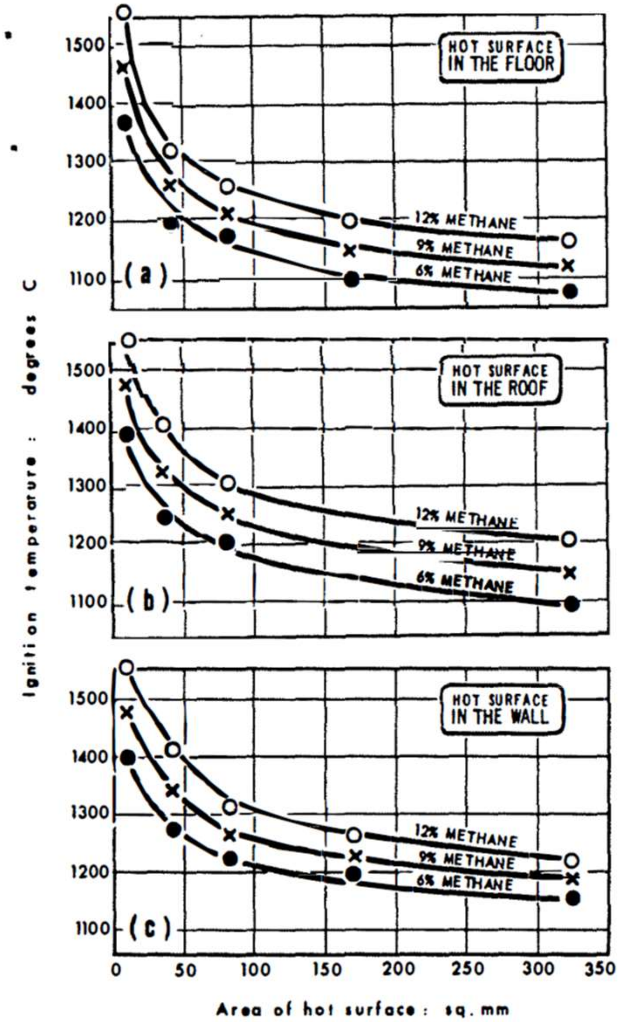
How to close the gap: design tests appropriate for lightning strike

- Consider strikes on "acreage" that do not penetrate skin
- Parameters to consider
  - Wing skin material
    - CFRC
    - Aluminum
  - Hot spot parameters
    - Peak temperature
    - Spatial extent of heated region
    - Time history of surface temperature
    - Location of hot spot
  - Flammable atmosphere
    - Fuel type
    - Pressure (altitude), temperature (hot vs cold day)
    - Oxygen and fuel concentration
    - Flow and turbulence conditions.

Ignition by hot spots on surfaces?

- Few systematic studies on cold flammable gas atmospheres
- Rae 1964 – methane-air

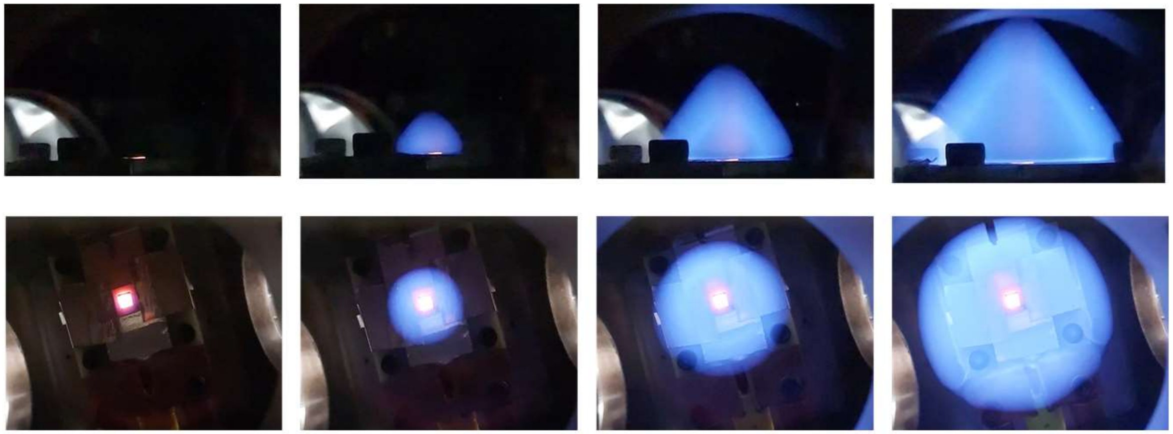


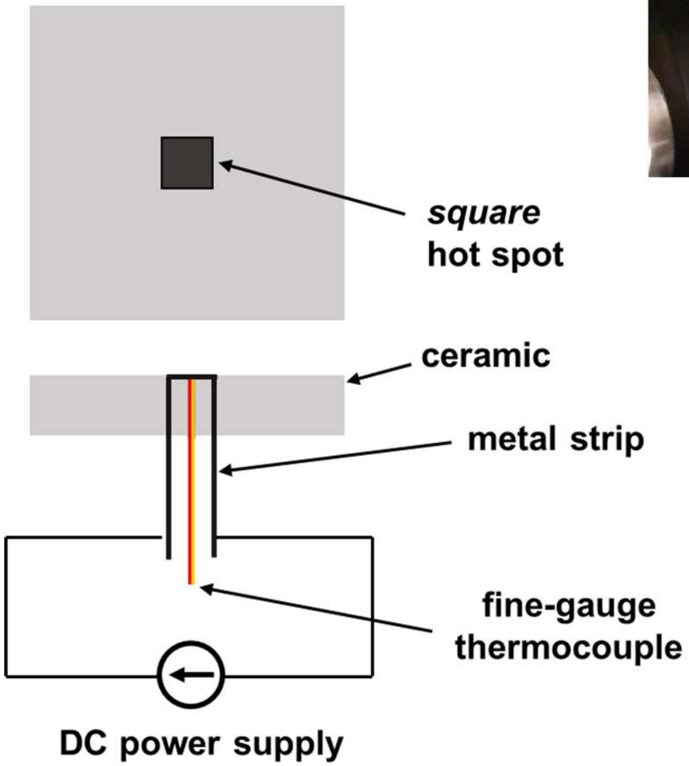


Observations On Rae Results

- Fuel is methane, not representative of aviation commodity fuels like Jet A, JP8, SAF
  - Tests with aviation fuels and surrogates are needed
- Ignition thresholds all > 1000^{o}C (AIT for methane is 537^{o}C)
  - Trend consistent with isolated, unconfined hot surface tests using aviation fuel surrogates but threshold needs to be determined in future tests with more aviation relevant fuels or surrogates.
- Ignition temperature threshold relatively independent of surface location and orientation, less than 100 ^{o}C variation observed.
- Ignition temperature threshold increases with decreasing spot size.

New Studies at Caltech





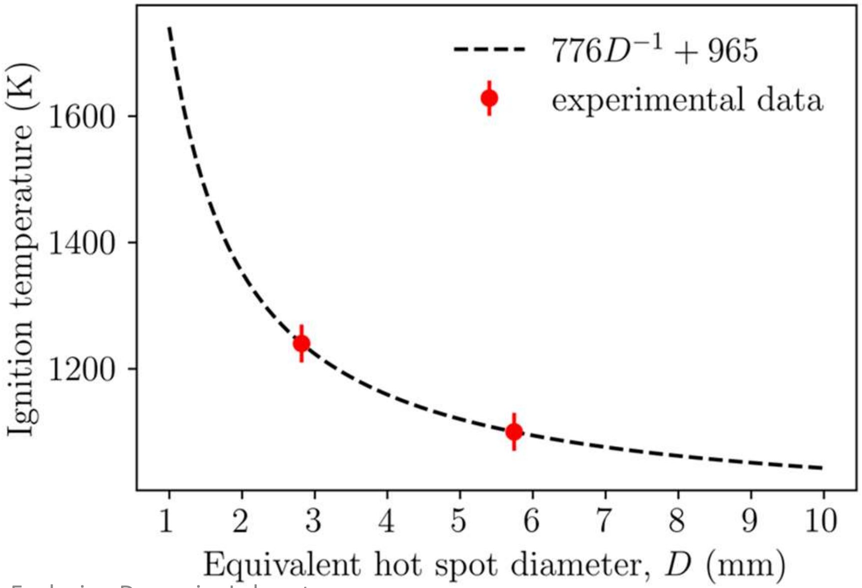
square hot spot

ceramic

metal strip

fine-gauge thermocouple

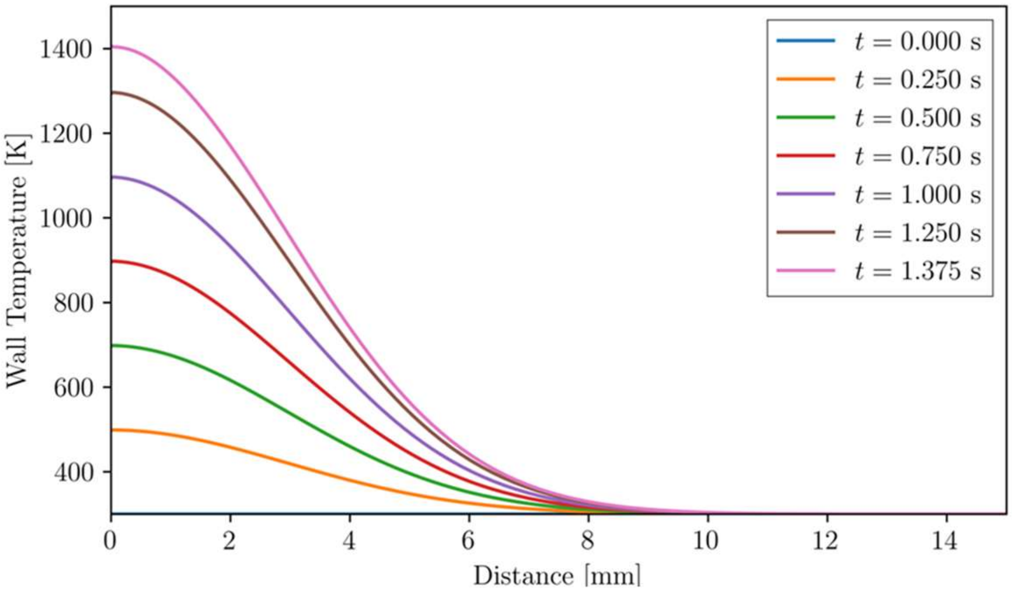
DC power supply

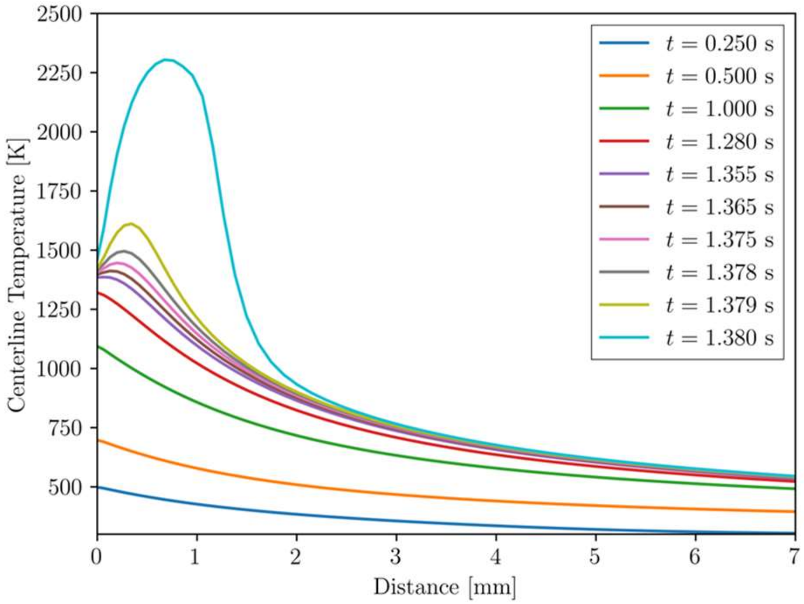


Schoeffler 2022

Ignition Predicted to Occur Near Surface

- Simulations with simplified chemical model and axi-symmetric hot spot in cold flammable atmosphere
- Ignition occurs in heated layer of gas very close (<1 mm) to surface
- Ignition kernel is small (< 1 mm) so only peak temperature in a small region is relevant to ignition
- Threshold temperature comparable to or greater than measured isolated hot surface temperatures





Schoeffler 2022

What have we learned?

- Thermal ignition is highly configuration dependent
  - Confinement effect (hot, recirculating atmosphere) more important that surface size, location or orientation
- ASTM E-659 AIT temperatures result of multiple competing processes
  - liquid droplet-hot surface-hot atmosphere interactions significant
- AIT temperatures determined by ASTM E-659 are not isolated hot surface ignition threshold temperatures for cool flammable atmospheres
- Isolated hot surfaces in cool flammable atmospheres have hot surface ignition thresholds 300^{o}C (700^{o}F) higher than AIT
- Ignition by hot surfaces in cool, unconfined flammable atmospheres occurs in a thin layer close to surface
- Ignition in confined hot, recirculating flammable atmospheres can be occur in a distributed fashion throughout the volume and may not result in a propagating flame.
- Observed in testing and simulation with simplified and detailed chemistry

Alternative Testing Configurations at Caltech

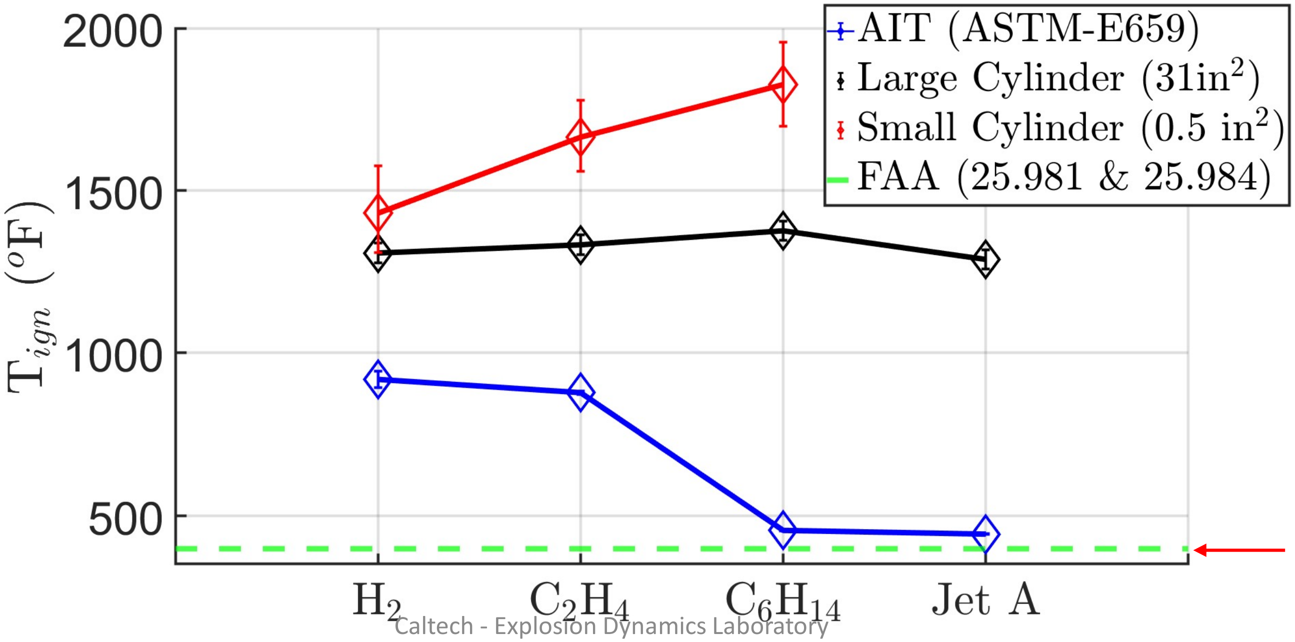
- Cold atmosphere
- No recirculation
- Isolated hot surfaces
    - Particles (Coronel)
    - Wires (Smetana)
    - Glow plugs (Boettcher, Kink)
    - Cylinders (Jones, Boeck, Martin)
- Lessons learned for unconfined hot surfaces
    - T_{ign} ~ 1000 - 1250 K (1300 - 1800°F) for aviation kerosene and surrogates
    - Relatively independent of configuration
    - Small variation with equivalence ratio
    - Modest dependence on initial pressure, oxygen concentration, fuel composition, atmosphere temperature
    - Weak dependence on surface area
    - Measuring hot surface temperature accurately can be challenging
- Small hot spots embedded in cold surfaces (in progress)
    - Resistance heating of small elements (Schoeffler)
- Effect of confinement and turbulence (in progress)
    - Unstable natural convection in confined flows (Martin, Davis)
    - Forced convection (Martin, Fouchier)
    - Droplets in hot atmospheres impinging on hot surfaces (Fouchier)

Key Role of Confinement

- For a given flammable atmosphere, the key factor is the confinement of the heated atmosphere.
- **Confined flows** continuously heat and recirculate the flammable atmosphere resulting in a hot atmosphere and reaction throughout volume. Reaction can be slow (no propagating flames or pressure rise) or fast (propagating flames and rapid pressure rise) depending on heating history and extent of recirculation.
- **Unconfined flows** only heat a cool flammable atmosphere very close to a hot surface and do not recirculate flammable atmosphere. Ignition occurs within the hot thermal layer near the surface and creates a propagating flame in surrounding flammable atmosphere. Pressure rise will depend on size of volume and amount of venting.
- Ignition threshold temperatures much higher in unconfined than confined flows.
- Secondary factors:
  - Fuel-air ratio (stoichiometry)
  - Initial pressure and temperature
  - Size of hot surface
  - Geometry of surface
- Unknown factors
  - Mean flow and turbulence in atmosphere
  - Generation of flammable atmosphere by fuel sprays

Traditional AIT (ASTM E-659) vs Hot Surface Tests

- Key distinctions:
  - **Unconfined:** Isolated hot surface in cool fuel vapor-air atmosphere, no recirculation
  - **Confined:** Hot surface enclosing hot atmosphere, cold liquid or vapor fuel, recirculation



Unconfined

Confined

FAA accepted value of AIT for aviation kerosene.

Application to Lightning Strike Hot Spots

- AIT is not relevant to hot spot ignition in unconfined, cool flammable atmospheres
- Space-time characteristics of lightning strike hot spots need to be measured with appropriate temperature instrumentation
- Ignition threshold temperatures will be closer to measured isolated hot surface conditions of 750 to 1000°C NOT 240°C
- Test Fuel
  - hexane is best surrogate for kerosene BUT ethylene could be used
  - Composition is largely irrelevant if you avoid limits
  - Threshold ignition temperature relatively insensitive to ambient pressure and oxygen concentration.
  - $H_2/O_2/Ar$ mixture used in previous lightning strike testing (ARP 5416) is NOT appropriate

Proposal

- Develop standard surface temperature-time distribution for lightning strike
  - Validate with thermal measurements
- Develop isolated hot surface ignition test standard relevant to lightning strike and other isolated hot surfaces in cold, flammable atmospheres
  - Use electrical heating of an embedded conductive foil to create hot surface
- Use aviation relevant surrogate like hexane as test fuel
  - Validation against aviation fuel standard using warm atmospheres
  - Statistical analysis of test results to establish ignition thresholds

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Resources

- Caltech Explosion Dynamics Website: https://shepherd.caltech.edu/EDL/
- Publications available for public download from website or from:

  CaltechAUTHORS: https://library.caltech.edu/caltechauthors