NASA/CP—2004-213205/VOL1

FLEX - *Flammability and Extinction Investigations*

Michael C. Hicks

NASA Glenn Research Center

June 23, 2004

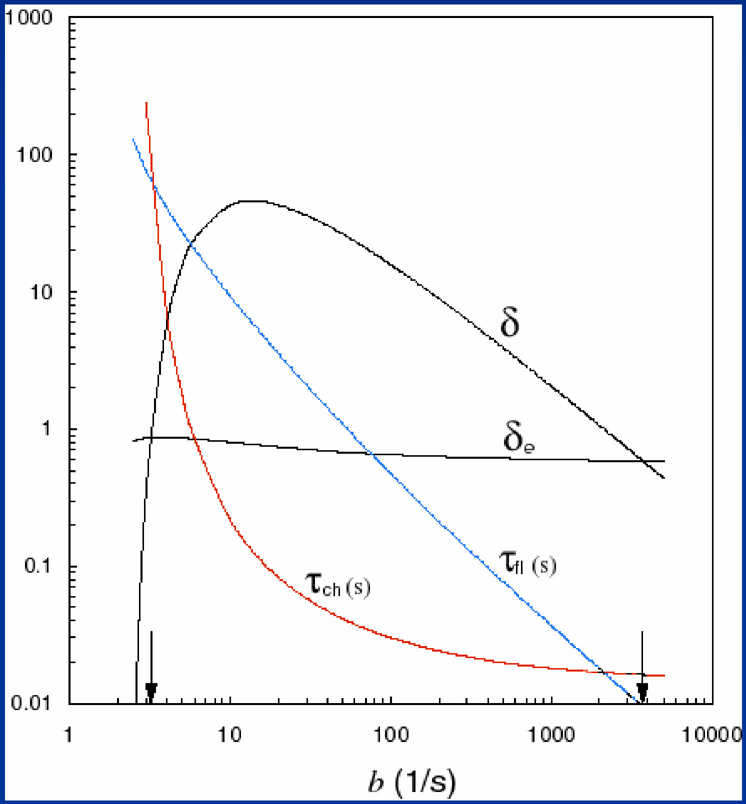
FLEX - *Flammability and Extinction Investigations*

Acknowledgements:

- Malissa Ackerman, NCMR
- Thomas Avedisian, Cornell
- Mun Choi, Drexel
- Daniel Dietrich, NASA GRC
- Frederick Dryer, Princeton
- Vedha Nayagam, NCMR
- Benjamin Shaw, UCD
- Forman Williams, UCSD
- Craig Myhre & NASA Engineering Team

FLEX - *Flammability and Extinction Investigations*

Diffusive and Radiative Extinction of Diffusion Flames



$$\delta = \frac{\text{Flow time}}{\text{Reaction time}} = \frac{\tau_{fl}}{\tau_{ch}}$$

Similar extinction scenarios for different flow configurations:

* Counter-flow
* Cup-burners
* Droplet combustion

Nayagam and Williams, 28th Combustion Symposium 2000

FLEX - *Flammability and Extinction Investigations*

What role can "droplet combustion" investigations play in spacecraft and/or extra-terrestrial Fire Safety Research?

Droplet combustion is a well-characterized fundamental experimental configuration where extinction conditions can be precisely measured ...

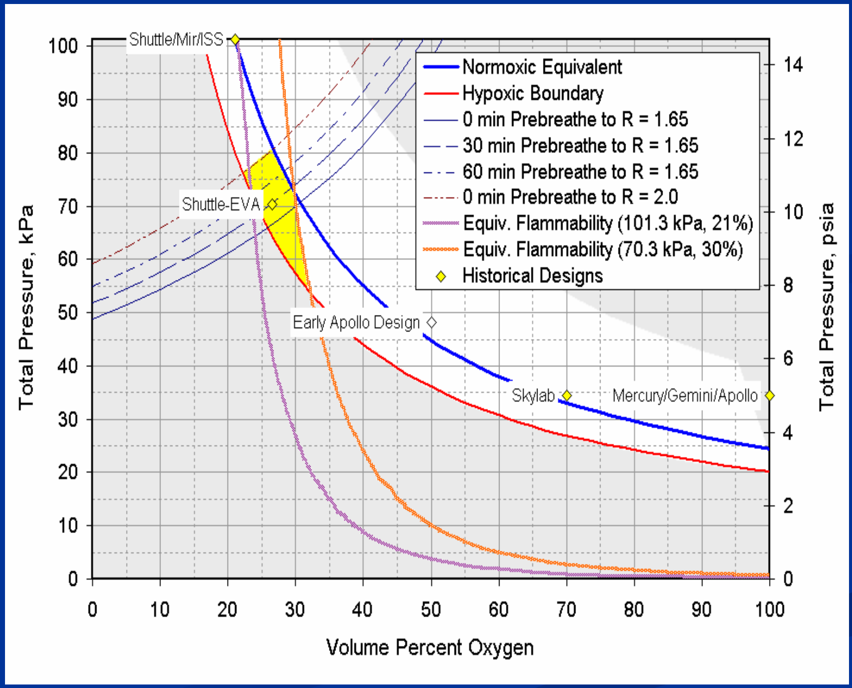
- the results obtained can be generalized
- chemistry is well characterized
- numerical scheme is well in hand
- many runs can be made
- coupling of condensed fuel is present

FLEX - *Flammability and Extinction Investigations*

Organizing questions where "droplet combustion" may play a ***significant*** *role:*

1. What is the O_2 mole fraction and total pressure below which a fire cannot exist ?

- flammability assessments in terms of the environment's propensity to support fire ... not a "material flammability" assessment
- droplet testing allows for a greater range of environmental conditions ... the entire range of atmospheres could be assessed with "precursor droplet tests"
- use results obtained from FLEX tests to identify test boundaries for follow-on material flammability studies using the FEANICS insert



FLEX - *Flammability and Extinction Investigations*

*Organizing questions where "droplet combustion" may play a **significant** role:*

2. **What is the relative effectiveness of candidate suppressants to extinguish a fire in reduced gravity, including high O_2 mole fraction low pressure environments?**

    - compare performance of suppressants in microgravity using a droplet flame configuration ... spherical (quiescent) and axisymmetric (flow) geometries.
    - results will extend modeling capabilities to practical fire configurations in both microgravity and partial gravity environments.

3. **What effect does gas-phase radiative absorption play in the overall fire and post-fire environments ... particularly when a radiatively participating suppressant is employed?**

    - extend scope of existing ground-based investigations currently using droplet configuration to assess gas phase radiation effects in post-fire CO_2 enriched environments.

FLEX - *Flammability and Extinction Investigations*

1. Limiting Oxygen Index (LOI) Investigation:

Rationale:

- Previous work suggests that the droplet LOI is substantially less in microgravity than is found in normal gravity
- Slow convective flows tend to lower this LOI even further
- The droplet test configuration allows an opportunity for a clearer understanding of the physical phenomena controlling the LOI and is useful in extrapolating results to more complex systems.
- Droplet configuration is a reasonable approximation to a very real fire hazard found in burning particles which may become dislodged (either by extinguisher deployment or fuel bubbling (Skylab tests)) from a primary fire site and float undetected to inaccessible regions of the spacecraft.

FLEX - *Flammability and Extinction Investigations*

1. Limiting Oxygen Index (LOI) Investigation (cont):

Approach:

- using n-heptane and methanol fuels provide a map of droplet extinction diameters (De) for different ambient O_2 concentrations
- tests initially performed in quiescent conditions (freely deployed droplet) using N_2 or other inerts as diluent and then repeated with slow convective flows, induced by translating droplet at speeds up to 1.5 cm/s.
- repeat tests with reduced total pressures (O_2 partial pressures similar to those used for a 1 atm total chamber pressure)
- extrapolate results to different flame configurations for follow-on flammability studies using FEANICS insert

FLEX - *Flammability and Extinction Investigations*

1. *Limiting Oxygen Index (LOI) Investigation (cont) :*

Typical Test Matrix:

Test number: 50

Fuel types: methanol, n-heptane

Total pressures: 0.5 atm, 0.75 atm, 1.0 atm

Diluent: N_2 or other

Droplet Sizes: 2.0 mm - 5.0 mm

Flow: 0 cm/s - 3 cm/s

Diagnostics:

- backlit images of droplet
- OH-emission and color flame images
- wide band and narrow band radiometric measurements

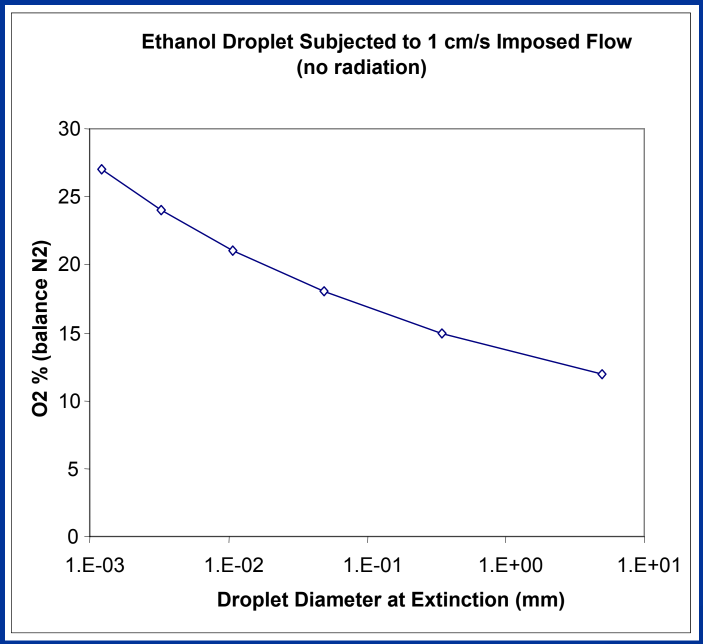
Science Data:

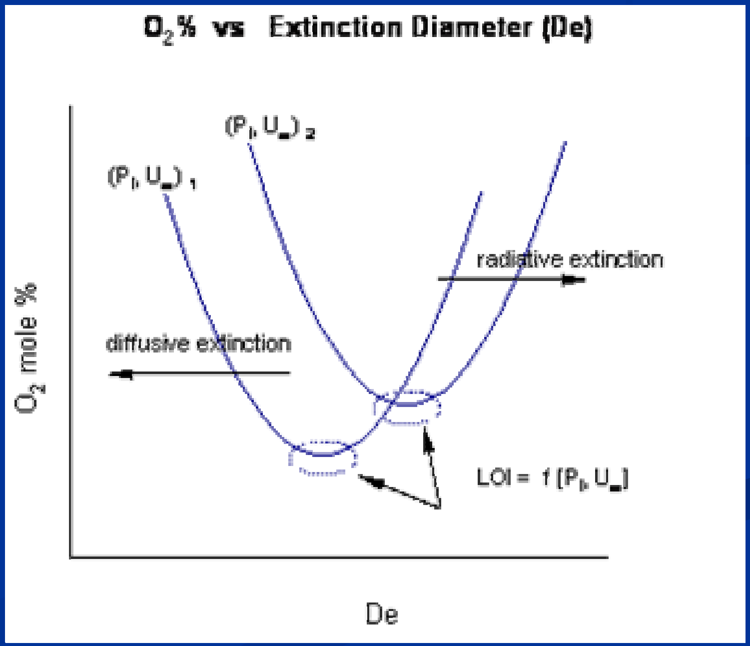
- Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions

FLEX - *Flammability and Extinction Investigations*

1. Limiting Oxygen Index (LOI) Investigation (cont):

- simplified theory (AEA) predicts extinction Damköhler number (D_a)
- Results of this nature can be extrapolated to other configurations





FLEX - *Flammability and Extinction Investigations*

2. Suppressant Effectiveness Studies:

Rationale:

- Effectiveness of passive suppressant agents (e.g., gaseous CO_2, N_2, He) in microgravity environments has not been systematically quantified
- In certain flame configurations, particularly in microgravity environments where buoyant forces no longer provide a contributing "blow-off" mode of extinction, increased suppressant concentrations, compared to that necessary for 1-g flames, may be necessary
- Effect of suppressant on the extinction Damköhler number can be used to relate results to other geometries (Hamins et al. C&F 1994)
- Effects on changing flame temperature can be assessed through changes in burning rates and radiant output.

FLEX - *Flammability and Extinction Investigations*

2. Suppressant Effectiveness Studies (cont):

Approach:

- chamber will be filled with various concentrations of suppressant and/or suppressant blends (both passive and chemical suppressant agents may be considered) and sufficient levels of O_2 to support a flame.
- droplet extinction diameters (De) [and possibly the droplet regression rates; $(D(t)/Do)^2$] will be used as a "figure-of-merit" in comparing suppressant effectiveness.
- a range of ambient pressures (0.5 atm to 1.0 atm) and flow conditions (up to 3 cm/s) will used.

FLEX - *Flammability and Extinction Investigations*

2. *Suppressant Effectiveness Studies (cont) :*

Proposed Test Matrix:

Test number: 178

Fuel types: methanol, n-heptane

Total pressures: 0.75 atm, 0.85 atm, 1.0 atm

Suppressants: He, CO_2, Halon, etc.

Diluent: N_2 and other

Droplet Sizes: 2.0 mm - 5.0 mm

Flow: 0 cm/s - 3cm/s

Diagnostics:

- backlit images of droplet
- OH and color flame images
- wide band and narrow band radiometric measurements

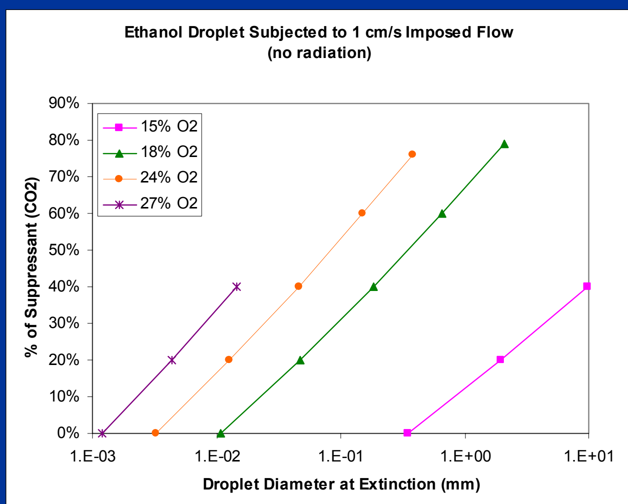
Science Data:

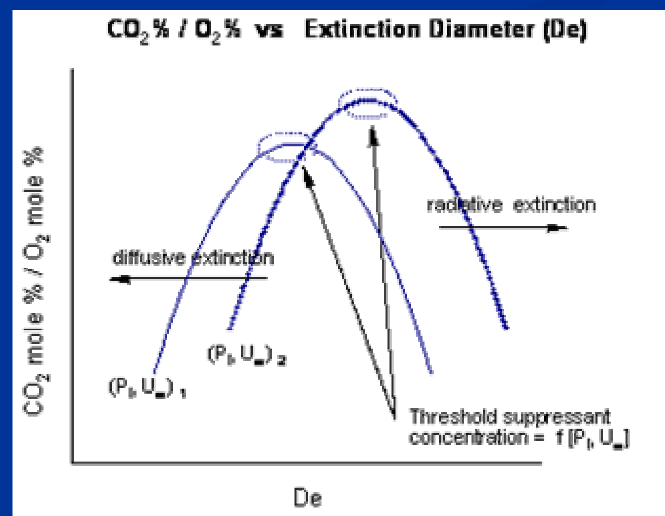
- Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions and suppressant concentrations

FLEX - *Flammability and Extinction Investigations*

2. Suppressant Effectiveness Studies (cont) :

- simplified theory (e.g., AEA) correlates De with suppressant concentration with a range of O_2 partial pressures.
- location of local maximum dependant upon gas phase participation and radiative characteristics of flame (i.e., sooting flames easier to extinguish in non-participating gas suppressants ??).





FLEX - *Flammability and Extinction Investigations*

3. *Gas Phase Radiative Absorption Investigation:*

Rationale:

- Gaseous CO_2 is the suppressant of choice on ISS; however, this is largely based on ground based experience where radiation losses are often minimal for most small scale fires.
- At elevated temperatures CO_2 becomes an effective thermal absorber and emitter ... effectiveness of suppressant may diminish in space applications.
- Earlier numerical work (Ju and Ronney, '98) showed a decrease in flammability limits of CH_4 when radiative reabsoprtion was considered (equivalence ratio, at the lean flammability limit, changed from 0.68 to 0.44).
- This is of particular concern in post-fire scenarios where large amounts of CO_2 may have been injected into inaccessible spaces (e.g., behind an experimental rack).
- Temperatures of the gaseous CO_2 would be elevated creating conditions where smoldering particles, dislodged from a primary fire site, would be kept at elevated temperatures and possibly re-ignite.

FLEX - *Flammability and Extinction Investigations*

3. Gas Phase Radiative Absorption Investigation (cont.):

Approach :

- droplets will initially be freely deployed in atmospheres of 21% O_2 with varying levels of diluent comprising mixtures of CO_2/N_2
- concentrations of CO_2 up to 75% (i.e., CO_2 displaces only N_2)
- measurements of extinction diameters (De), flame dimensions, and droplet burning rates
- since optical thickness in a participating gas is pressure dependent ... a series of tests will be performed at elevated pressures (up to 3 atm)

NASA/CP—2004-213205/VOL1

FLEX - *Flammability and Extinction Investigations*

3. Gas Phase Radiative Absorption Investigation (cont.):

Proposed Test Matrix:

Test number: 40

Fuel types: methanol, n-heptane

Total pressures: 1.0 atm, 2.0 atm, 3.0 atm

Suppressants: CO_2

Diluent: N_2

Droplet Sizes: 5.0 mm

Flow: 0 cm/s

Diagnostics:

- backlit images of droplet
- OH and color flame images
- wide band and narrow band radiometric measurements

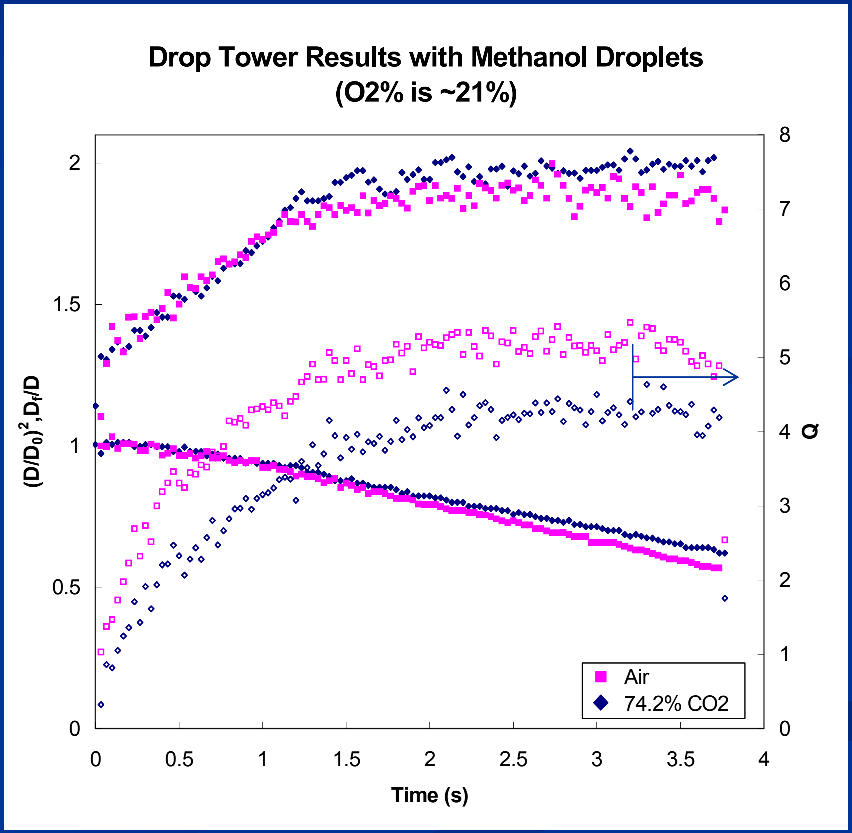
Science Data:

- Extinction diameter, burning rates, flame dimensions, radiative output, all as a function of time for different environmental conditions and suppressant concentrations

FLEX - *Flammability and Extinction Investigations*

3. Gas Phase Radiative Absorption Investigation (cont.):

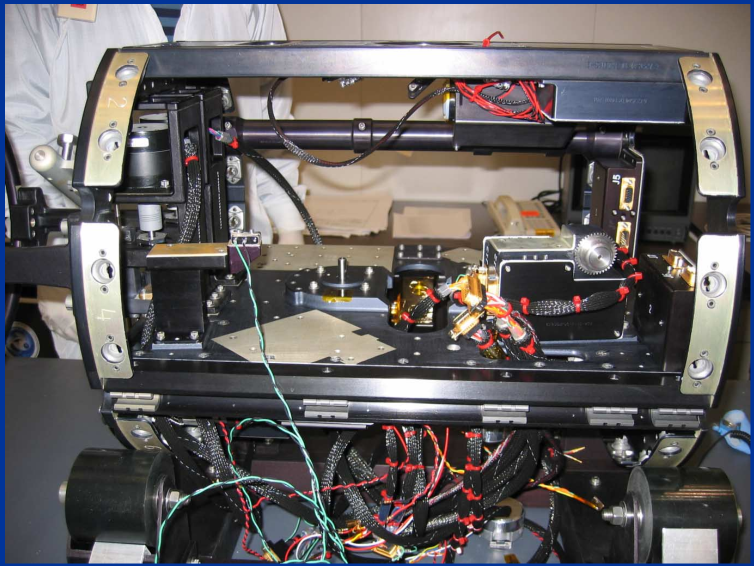
- preliminary results from recent testing show high concentrations of CO_2 (i.e., 0.74 mole fraction) yield lower burn rates, higher flame radiation, and similar flame dimensions
- results suggest lower flame temperature (possibly due to higher effective gas mixture Cp)
- increase in radiation due to thermal absorption and re-radiation from larger gas volume

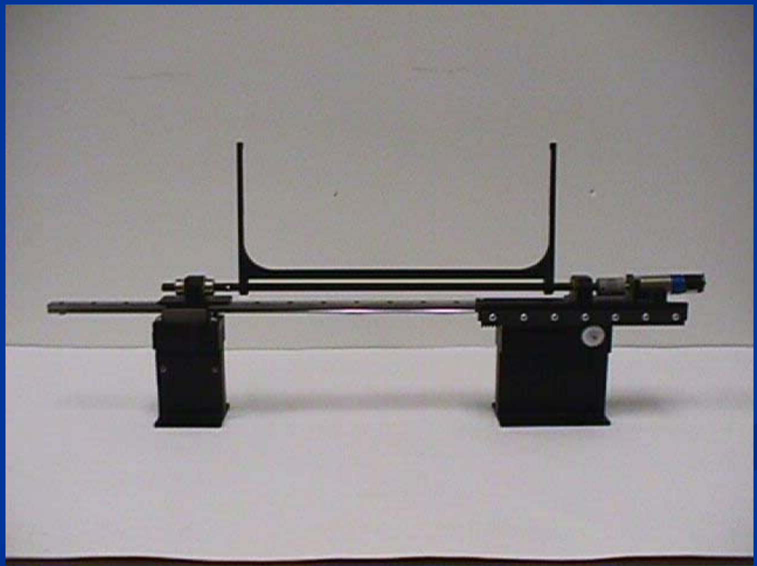


FLEX - *Flammability and Extinction Investigations*

MDCA Capabilities (as currently configured):

- Provides for spherical and axisymmetric flame configurations using droplets
- Symmetric ignition and fuel deployment allows for un-tethered droplets.
- Slow convective flows (up to 3 cm/s) over the burning droplets can be obtained.
- Chamber pressures controllable from 0.02 atm to 3.0 atm with wide range of suppressant/oxidizer mixtures.





FLEX - *Flammability and Extinction Investigations*

MDCA Capabilities (cont):

Potential exists for extended capabilities in MDCA hardware ...

- PI specific hardware could add capabilities without the need to alter the existing hardware
- dynamic environments to simulate a suppressant discharge

  ... addition of suppressant during combustion
- reduction of pressure during combustion
- solid particles (e.g., PMMA spheres) placed on a fiber and ignited
- wider range of velocities and/or accelerations with the inclusion of small cameras moving with droplets

FLEX - *Flammability and Extinction Investigations*

Summary:

Benefits of FLEX testing ...

- Hardware already exists (i.e., MDCA)
- Provides a reasonable geometric approximation of realistic spacecraft fire hazards floating embers, molten wire insulation, other ejected particles
- Strong modeling base already exists
  ... simplified one- and two-dimensional geometry allows for refinements to modeling (detailed chemistry, gas-phase radiation, etc.)
- Easily reproducible and controlled test conditions
  ... consistent initial droplet diameters, precisely controlled flow rates, ignition energy
- Allowance of a large test matrix with a range of parameters (on the order of 300 test points/investigation)
  ... less up mass than other configurations, multiple tests per chamber fill