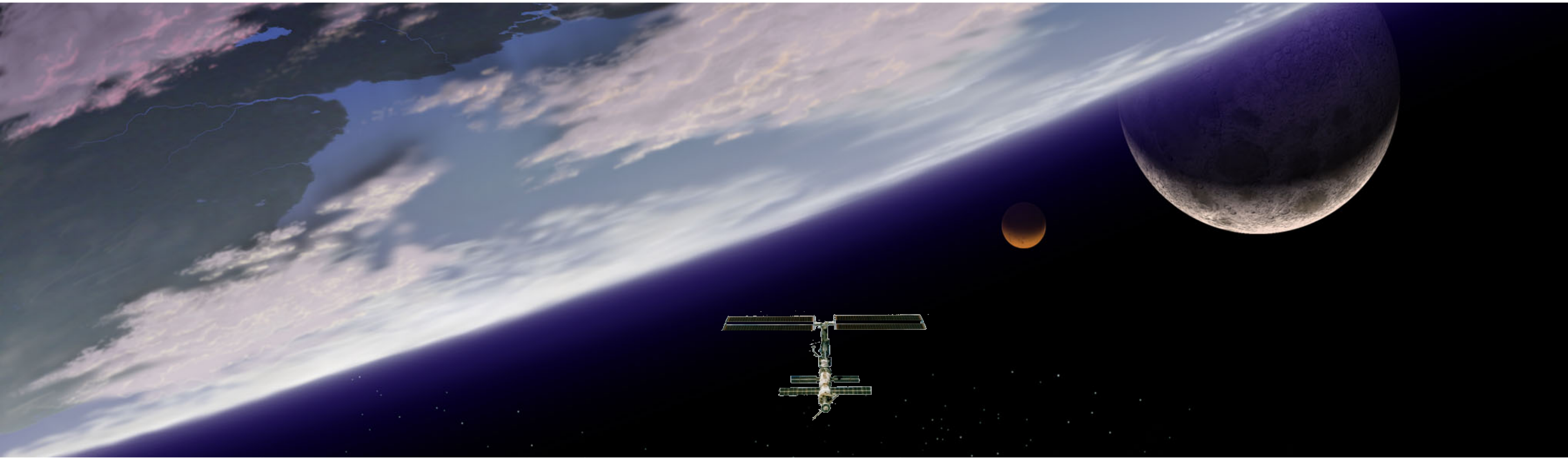
Cool Flame Investigation

Science Concept Review – Objectives and Requirements Definition



Science Definition Team

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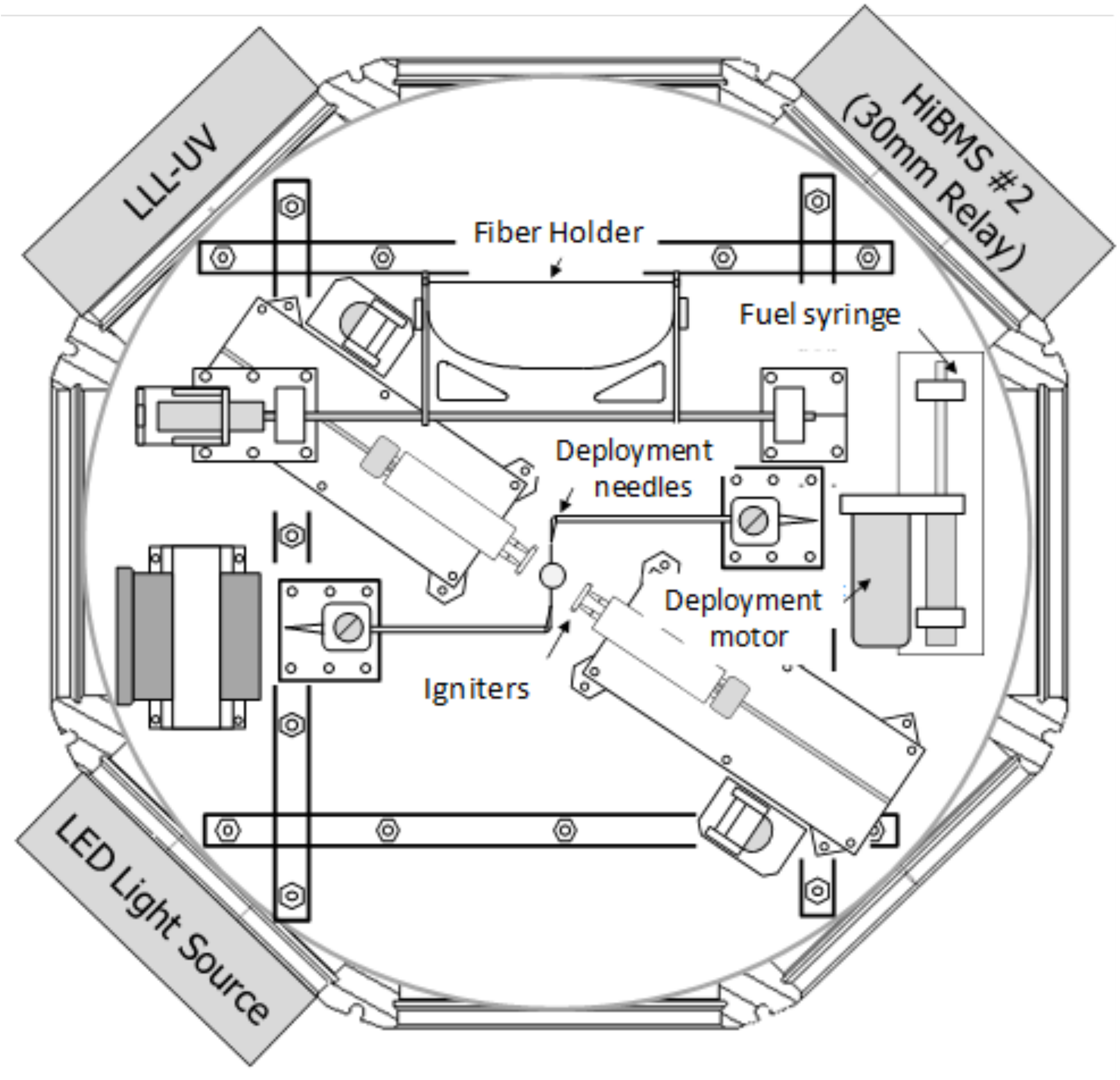
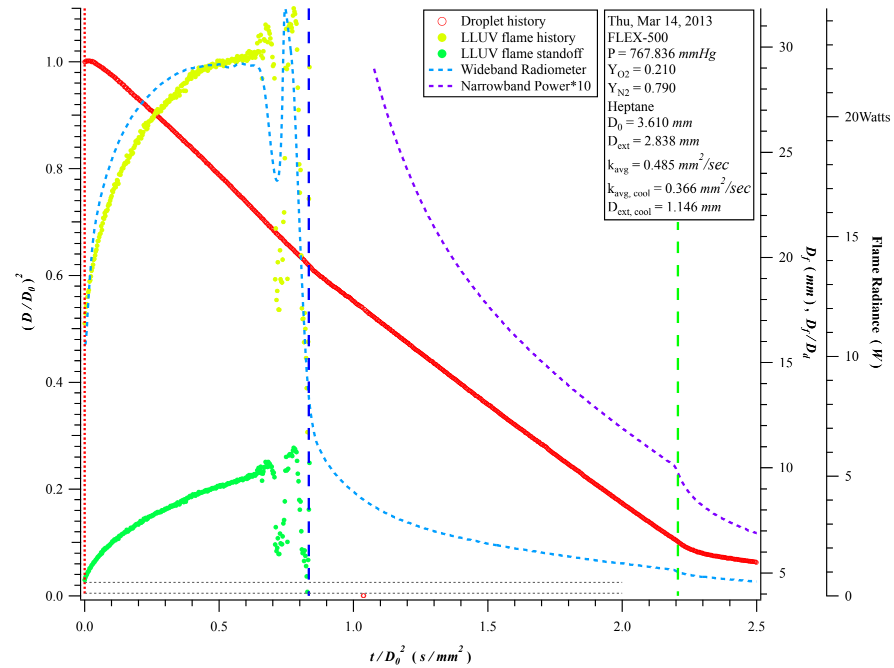
Cleveland, Ohio 44135
May 4, 2014

FLEX Hardware



FLEX Experiment Summary

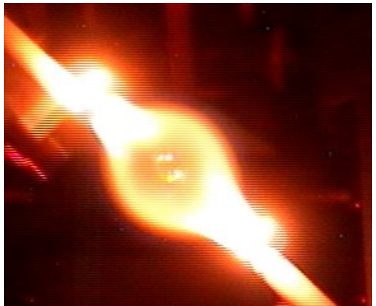
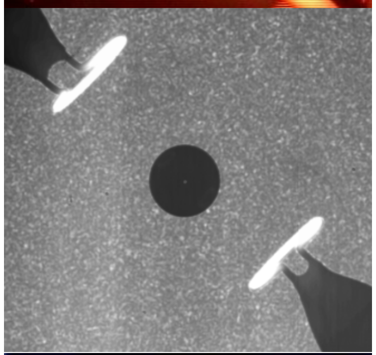
- Original of FLEX experiments was to observe and systematically study hot flame ignition and extinction in microgravity
- A new phenomenon where a hot flame extinction leads to a low-temperature, “cool-flame” burning in microgravity observed for the first time
- Cool flames are prevalent in FLEX experiments
  - Strong function of ambient pressure
  - Strong function of ambient environment – ambient oxygen mole fraction and diluent
  - Function of fuel composition
- No systematic study of cool flames and their presence inferred and not observed



Use the unique observation of quasi-steady burning and extinction of cool flames during microgravity droplet combustion to further our understanding of low temperature chemistry.

Enhance the diagnostic capability of the CIR and MDCA to better study cool flame behavior.

Experiment Objectives – Cool Combustion, CFI

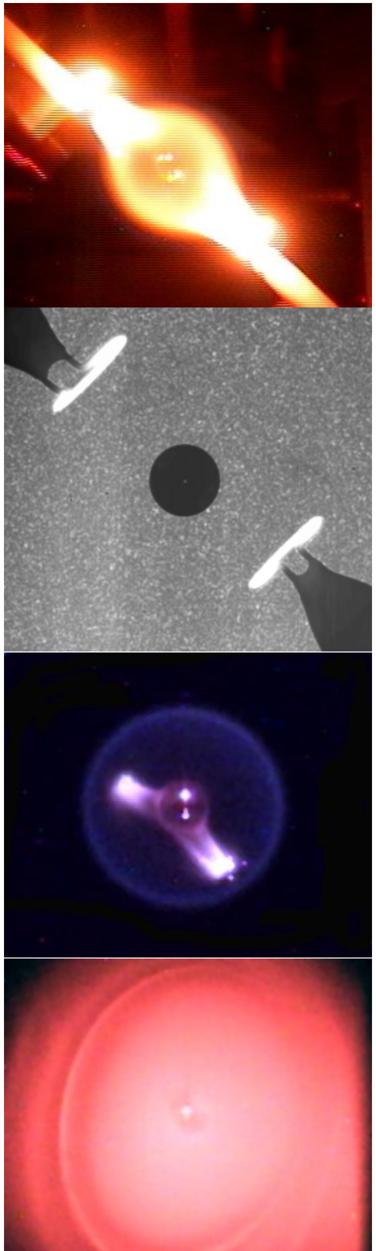



1. *Further understanding of the combustion characteristics of normal alkanes, particularly in the low temperature region by conducting droplet combustion experiments in low gravity with fuels that supports cool flame burning and extinction.*

2. *Investigate the low temperature burning behavior of droplets consisting of pure fuels and bio-fuel constituents (and mixtures of them), as well as surrogate reference fuels to determine the relationship between the cool flame burning characteristics in microgravity droplet combustion and the octane/cetane behavior of the fuel.*

3. *Explore the low temperature chemistry of alkanes further by mixing additives to the fuel that disrupt the low temperature chemical pathways. [**Ground-based only]***

Justification for Long-Duration Microgravity

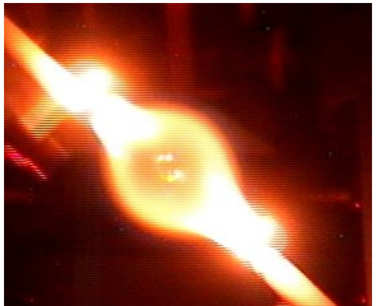


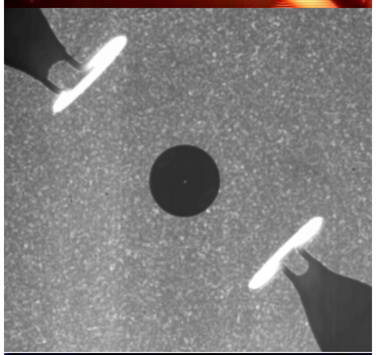
- Requires spherical symmetry to simplify mathematics

$$\frac{\tau_k}{\tau_b} = \frac{\sqrt{g\,D^3}}{\alpha_g} \qquad \frac{\tau_m}{\tau_b} = \frac{\sqrt{g\,D^3}}{\mathcal{D}_g}$$

- Spherical symmetry requires g-levels less than $10^{-4} g_0$
  - Precludes experimentation using aircraft flying parabolic trajectories
- Drop towers have appropriate g-levels
  - Currently limited to 5 seconds microgravity time
- Proposed experiments involve:
  1. Droplet growth and deployment (~ 10 seconds)
  2. Droplet ignition and hot-flame burning (5 - 10 seconds)
  3. Hot-flame extinction
  4. Cool-flame burning (5 – 60 seconds)
  5. Cool-flame extinction
- Long-duration microgravity facilities are required for detailed parametric study

Requirements – Test Fuels

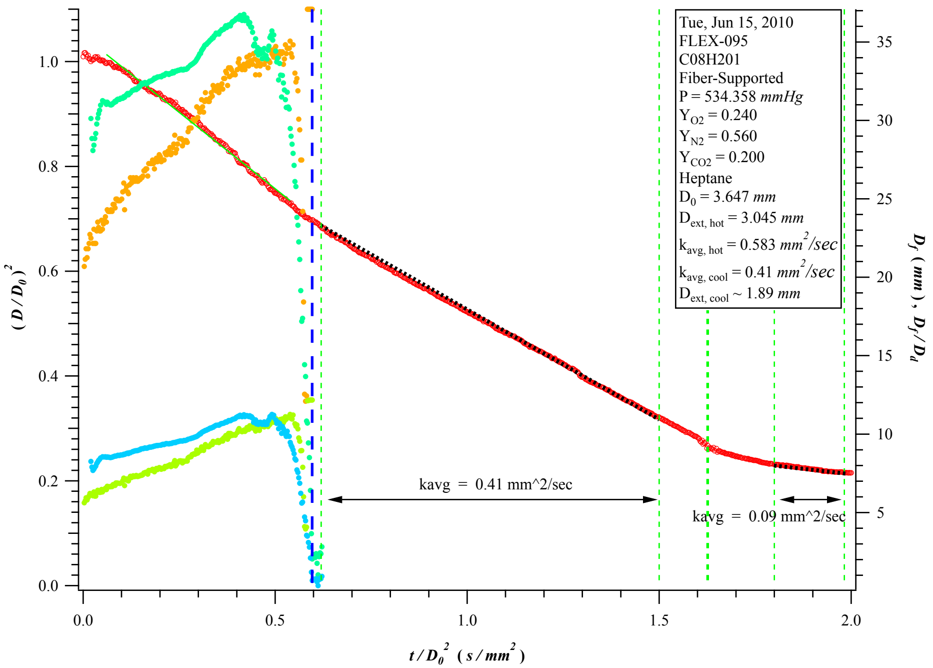


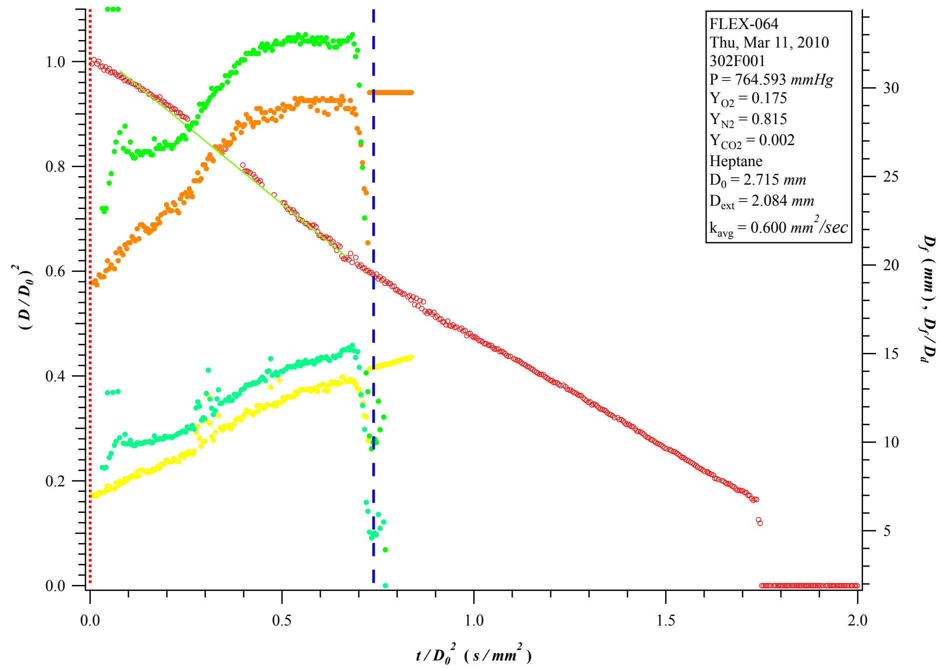


- Objective 1: Study the ignition, hot-flame burning and extinction, cool flame burning and cool flame extinction of a model normal alkane fuel.
  - Normal dodecane
- Objective 2: Investigate the low temperature burning of pure fuels, mixtures of pure fuels that are surrogates for real fuels and bio-fuel constituents to determine the relationship between a fuels octane/cetane behavior and the cool flame burning characteristics.
  - 2,6,10 trimethyldodecane (farnesane)
  - n-dodecane/2,6,10 trimethyldodecane mixtures (3 mixtures ea., ratios TBD)
  - n-dodecane/2,2,4,6,6 pentamethylheptane mixtures (3 mixtures ea., ratios TBD)
  - n-dodecane/iso-octane/n-propyl benzene/1,3,5 trimethyl benzene (2 mixtures ea.)
  - n-heptane/2,2,4 trimethylpentane mixtures

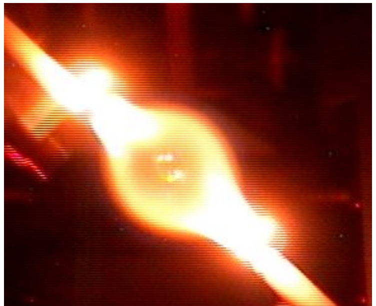
Requirements – Droplet Deployment and Ignition

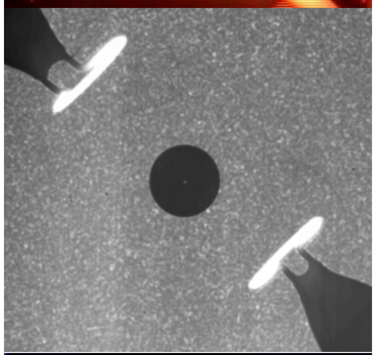
- No changes to MDCA deployment and ignition hardware
- Reduce the size of the support fiber to 40 μm
  - Required in some cases to keep the droplet in the FOV
  - Allows an estimate of the hot-flame temperature in FLEX
  - 80 μm fiber in FLEX experiments created disturbances to droplet near cool flame extinction in almost all tests





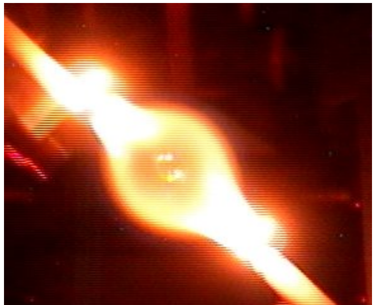
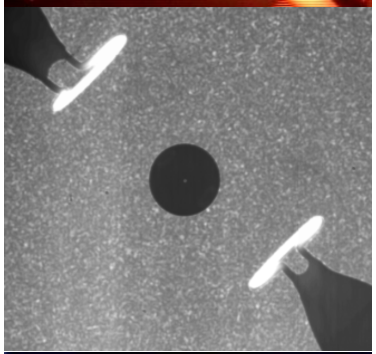
Requirements – Ambient Environment





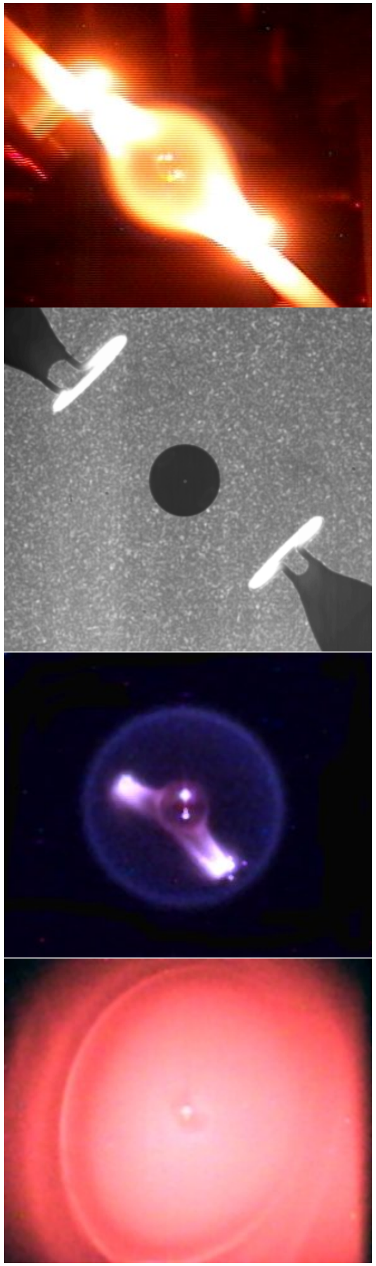
- **Pressure**
  - Strongly influences cool flame burning and extinction – both hypo- and hyper-baric pressures
  - 0.5 – 3.0 *atm* required, up to 5 *atm* desired (hardware limit)
- **Oxygen Mole Fraction**
  - 0.10 – 0.40, similar to the range in FLEX experiments
- **Ambient Diluent**
  - Primarily nitrogen (Objective 1 and 2)
  - Helium and xenon (Objective 1)
    - Strongly influence cool flame burning and extinction
- **Misc. Ambient Requirements**
  - Similar to FLEX requirements
  - Ambient humidity less than 10% (FLEX had lower requirement for methanol)
  - g-levels $\leq 10^{-5} g_0$

Requirements – Droplet Imaging

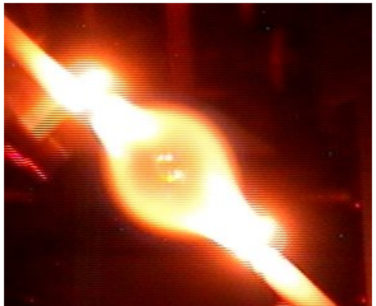
- Measure droplet size and shape, droplet dynamics, soot volume fraction, etc. as functions of time
- No change to camera or backlight for new experiment necessary
- Increase FOV from 30 *mm* (FLEX) to 50 *mm* (CFI)
    - Increases success rate by allowing for greater free deployment droplet drift
    - FLEX requires drift less than 1 *mm/sec* to stay in FOV
    - Reduces spatial resolution (30 μm to 50 μm)

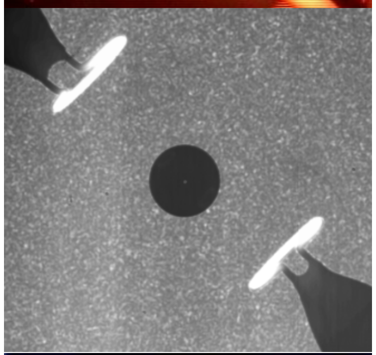
Requirements – Hot Flame Imaging



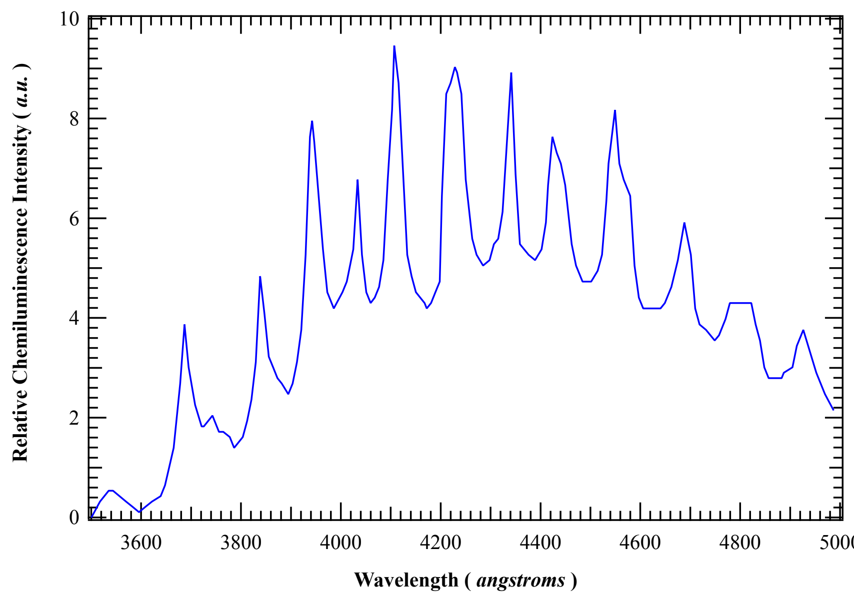
- Currently measure either $OH*$ or *CH* chemiluminescence using intensified black and white camera
  - $OH*$ (310 nm) images very dim, required pixel binning (2*x*2) to get good images, but reduced spatial resolution
  - *CH* (430 *nm*) images have improved contrast and reduced noise – possible to eliminate binning (increases data storage/downlink requirements)
- Increase FOV from 50 *mm* (FLEX) to 80 *mm* (CFI)
  - Increases success rate by allowing for greater droplet drift
- Current camera configuration acceptable for hot-flame imaging
  - Unlikely to be able to perform chemiluminescence of both the hot-flame and cool flame with current camera configuration
- Require the capability to image the hot-flame
  - Either $OH*$ or *CH (preferred)* chemiluminescence
  - 100 μm spatial resolution
  - 30 *fps*
  - Adjustable gain required (almost impossible to know appropriate gain based on ground-based testing)

Requirements – Cool Flame Imaging

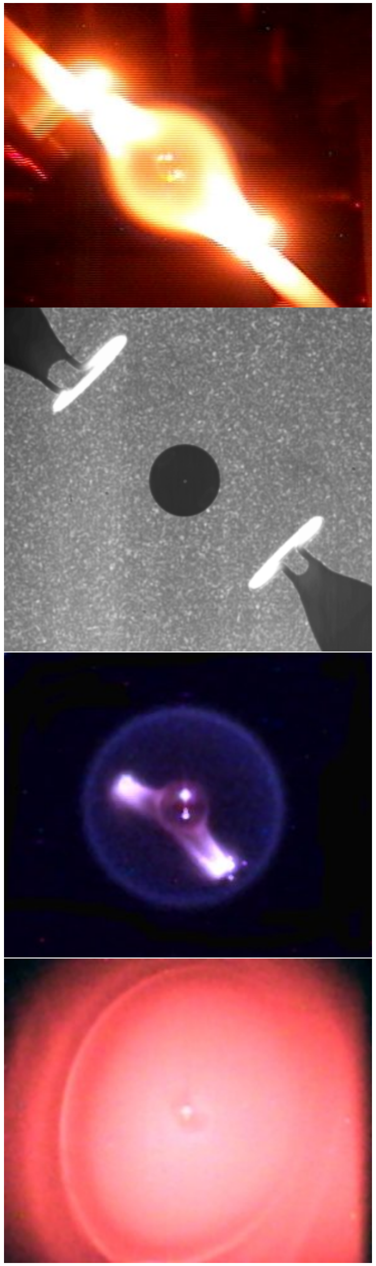




- Currently have no way to image cool flames on CIR/MDCA
  - Removing/changing filter and/or increasing gain on LLUV possible, no way to shield the camera from ignition or hot flame
- Cool flame expected to be approximately ½ size of hot flame
  - FOV, spatial resolution and framing rate requirements similar to hot flame
  - Can use the same camera for both hot and cool flame imaging, but spectral ranges are different and required gain is much different
- Based on literature search and FLEX radiometer data, cool flames are expected to be very dim

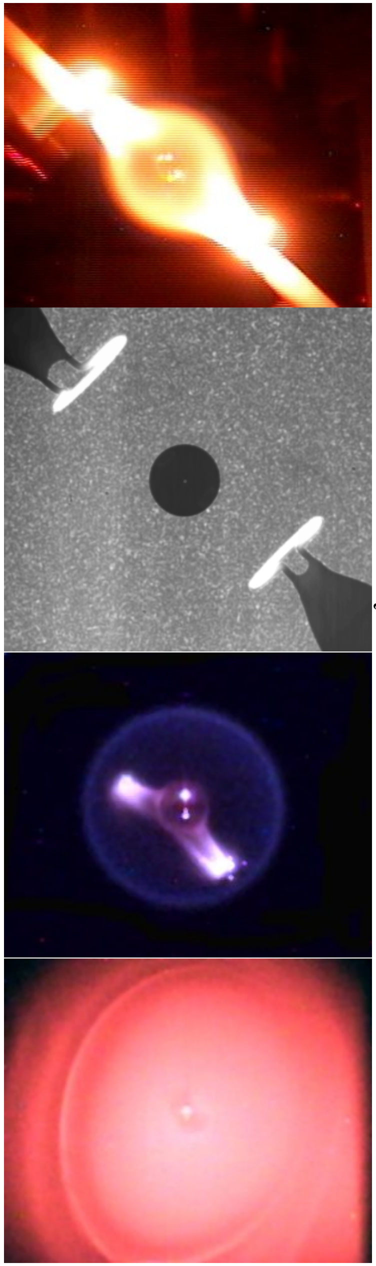


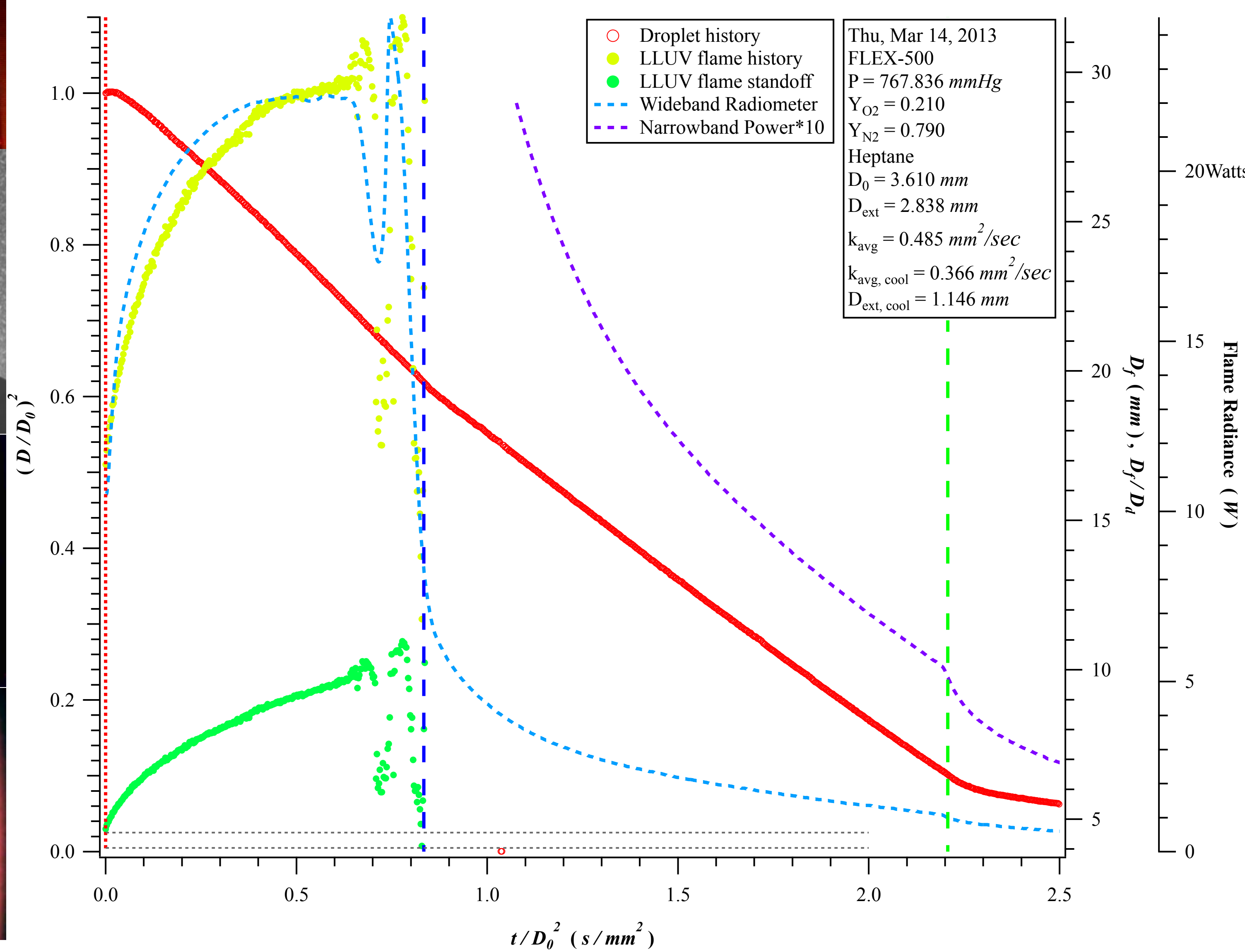
Requirements – Color Camera Imaging



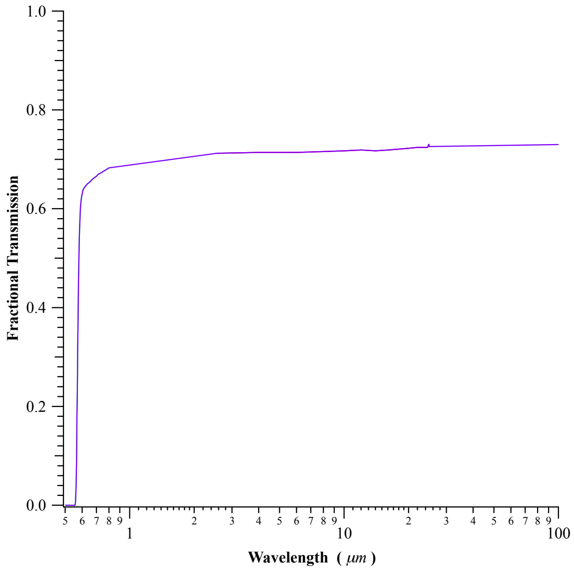
- Necessary for droplet deployment, hardware diagnostics, etc.
- Closest thing to being able to look into the chamber.
- FLEX color camera with internal chamber light is acceptable for CFI
  - Zoom capability is critical. Zoom-in for droplet dispense, hardware diagnostics, igniter positioning. Zoom-out to view droplet burn.
  - Will not be able to image the cool flame
  - Must be able to image the vapor cloud and hot flame.
  - Must monitor radiation damage to image array over time
- Require downlink of this view (recorded at TSC) during experiment. Also record on CIR because of image quality loss during ISS video compression).

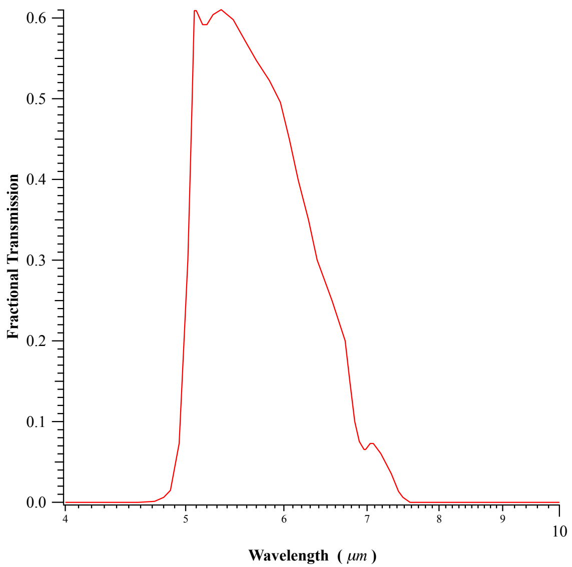
Requirements – Flame Radiation





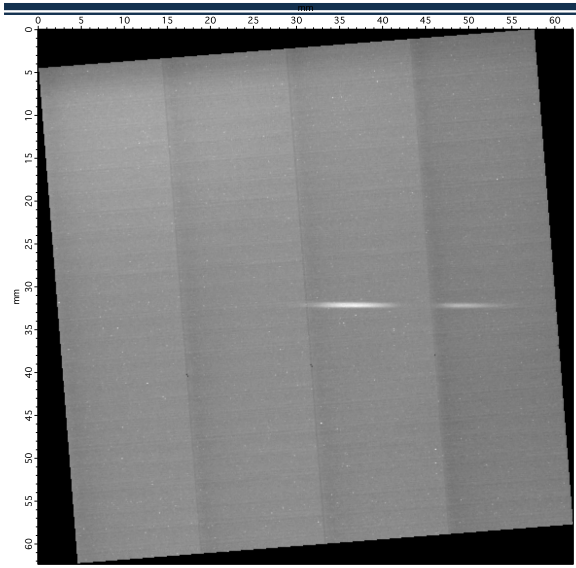
Requirements – Flame Radiometer

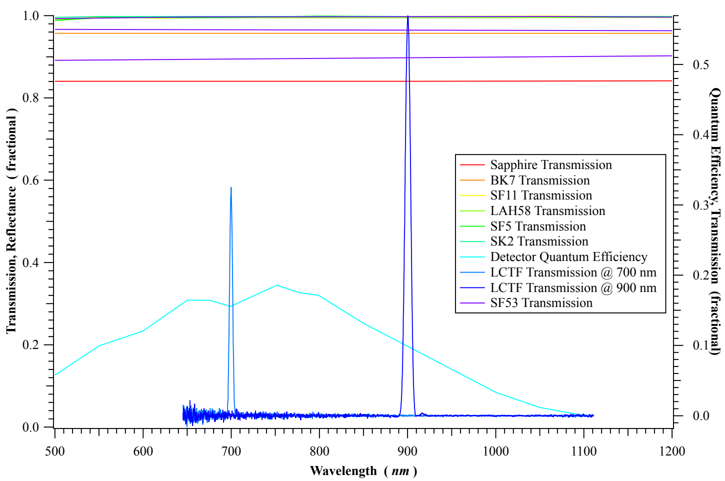




- Original FLEX radiometers not sensitive enough to adequately detect dim (hot) flames and had unacceptably low SNR
- Starting in 2011, FLEX testing used replacement radiometers
  - Broadband: 0.6 – 10.0 μm sensitivity, images hot flame
  - Narrowband: 5.0 – 6.5 μm (H_2O), sensitive to cool flame
  - 10 Hz frequency response, sampled at 100 Hz
  - Fixed gain, not sensitive to both hot and cool flames
- Require flame radiometric measurements for CFI
  - Same wavelength bands as current radiometer package
  - Require auto-gain so each radiometer can capture both hot and cool flame
    - ~ 0.1 – 100 W flame radiance range
    - May not be able to capture flame radiance during re-ignition
- Require at least 10 Hz sampling (same as FLEX)
- Same FOV as FLEX radiometers

Desire – Flame (Hot and Cool) Pyrometry



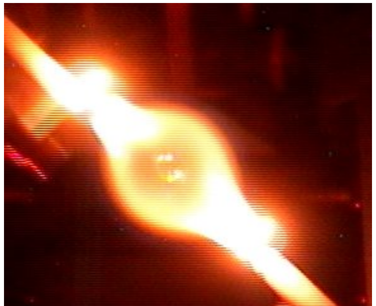
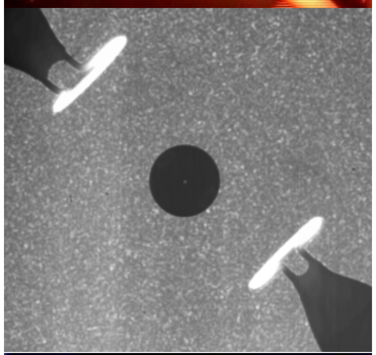


- Original intent of HiBMS-2/LCTF was SiC fiber pyrometry
  - Two-color pyrometry
  - Cycling time of LCTF too slow
  - Detector QE * LCTF transmission too small
- Request capability to perform SiC pyrometry for fiber-supported CFI tests
  - Hot and cool flame, but not necessarily simultaneously
- Requires changes to current HiBMS-2 configuration
  - Remove LCTF
  - Replace with wideband bandpass IR filter
  - Calibration insert to igniter circuit ???

Requirements – Misc.

- Require chamber pressure measurement
  - CIR/FOMA capability sufficient for CFI
- Require chamber temperature measurement
  - CIR capability sufficient for CFI
- CIR/FOMA gas mixing capability sufficient for the CFI experiments
- All measurements time referenced to GMT within 0.03 sec
  - Current MDCA/CIR capability sufficient for CFI
- Require measurement of g-level during experiment
  - Current SAMS capability sufficient for CFI
- Require experiment isolation from ISS structure
  - PARIS sufficient for CFI

Experiment Procedures and Test Matrix

- Experiment procedures similar to FLEX experiments
  - FLEX looked for flammability limits and did a few tests in gradually decreasing oxygen ambients
  - CFI will examine fewer ambients, but more tests in each ambient
- Exact test matrix will be determined based on further analysis of FLEX data and companion theoretical/numerical analysis
  - Test matrix in SRD used for resource estimation
  - Require interactive experimentation, i.e., future experiments guided by the results of the current experiments
    - Requires timely downlink of experimental data.
  - Requires detailed interaction with engineering team
    - Tests planned to optimize resource utilization
- Pressure range: 0.5 – 3.0 *atm* required (5.0 *atm* desired)
- Ambient oxygen mole fraction: 0.10 – 0.40
- Ambient gas mixture: O2/N2, O2/He, O2/Xe, tertiary mixtures possible