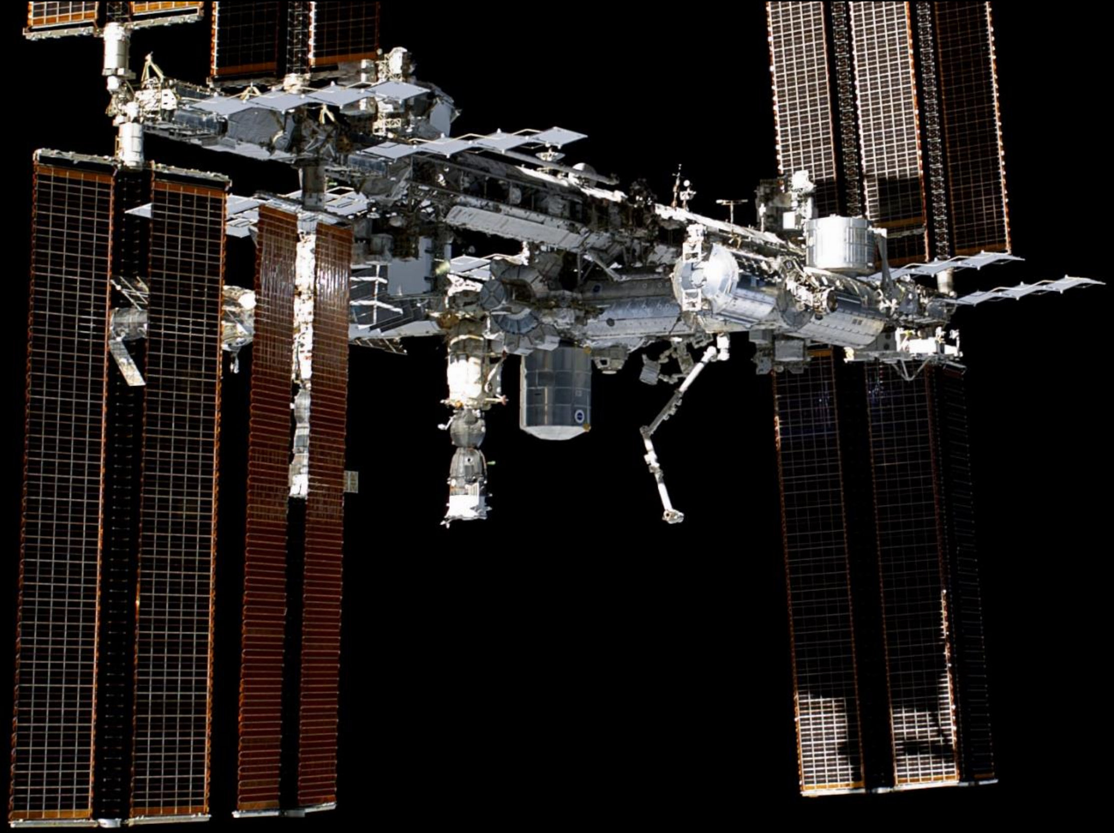
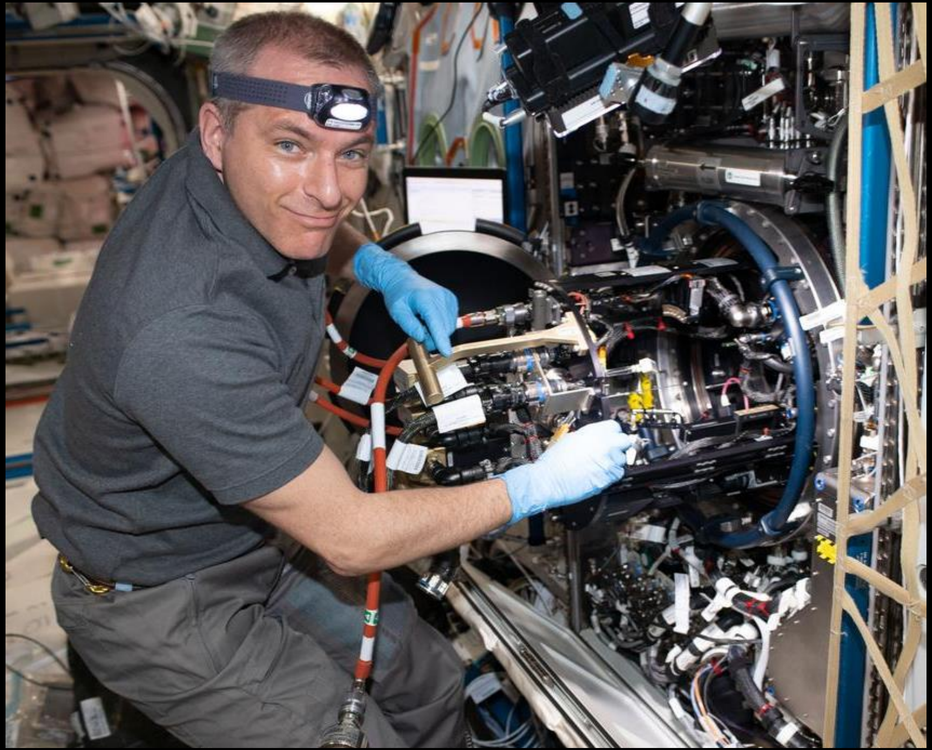




Laminar Non-Premixed Flames of Gaseous Fuel Aboard the International Space Station

Dennis P. Stocker, NASA Glenn Research Center, Cleveland, OH, USA

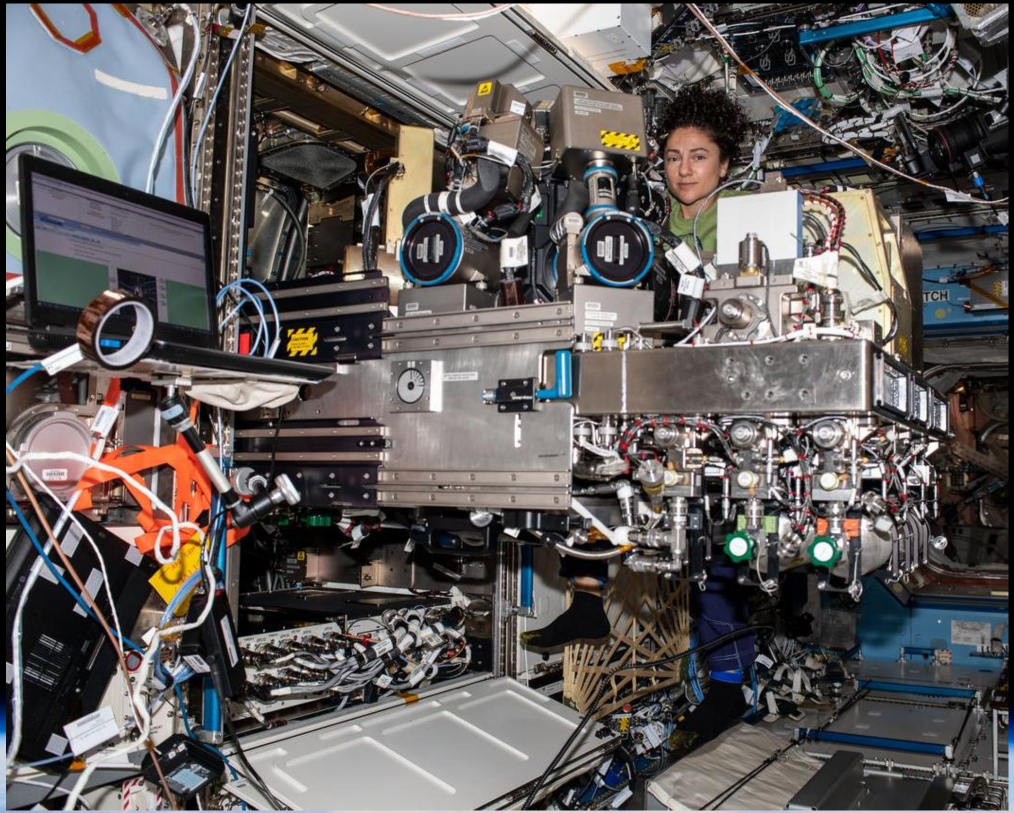
CSS/CI Meeting, 15-17 May 2022

Canadian astronaut David Saint-Jacques supporting the research [ISS059e060847]

Better burning on Earth through ISS research

- **WHAT?**
  - **Advanced Combustion via Microgravity Experiments (ACME)**
  - 6 independent studies of laminar, non-premixed flames of gaseous fuels
- **WHY?**
  - **Energy & environment** with improved efficiency & reduced pollutant emission in practical terrestrial combustion via **benchmark microgravity data** and resulting improvements in computational modeling, design tools, etc.

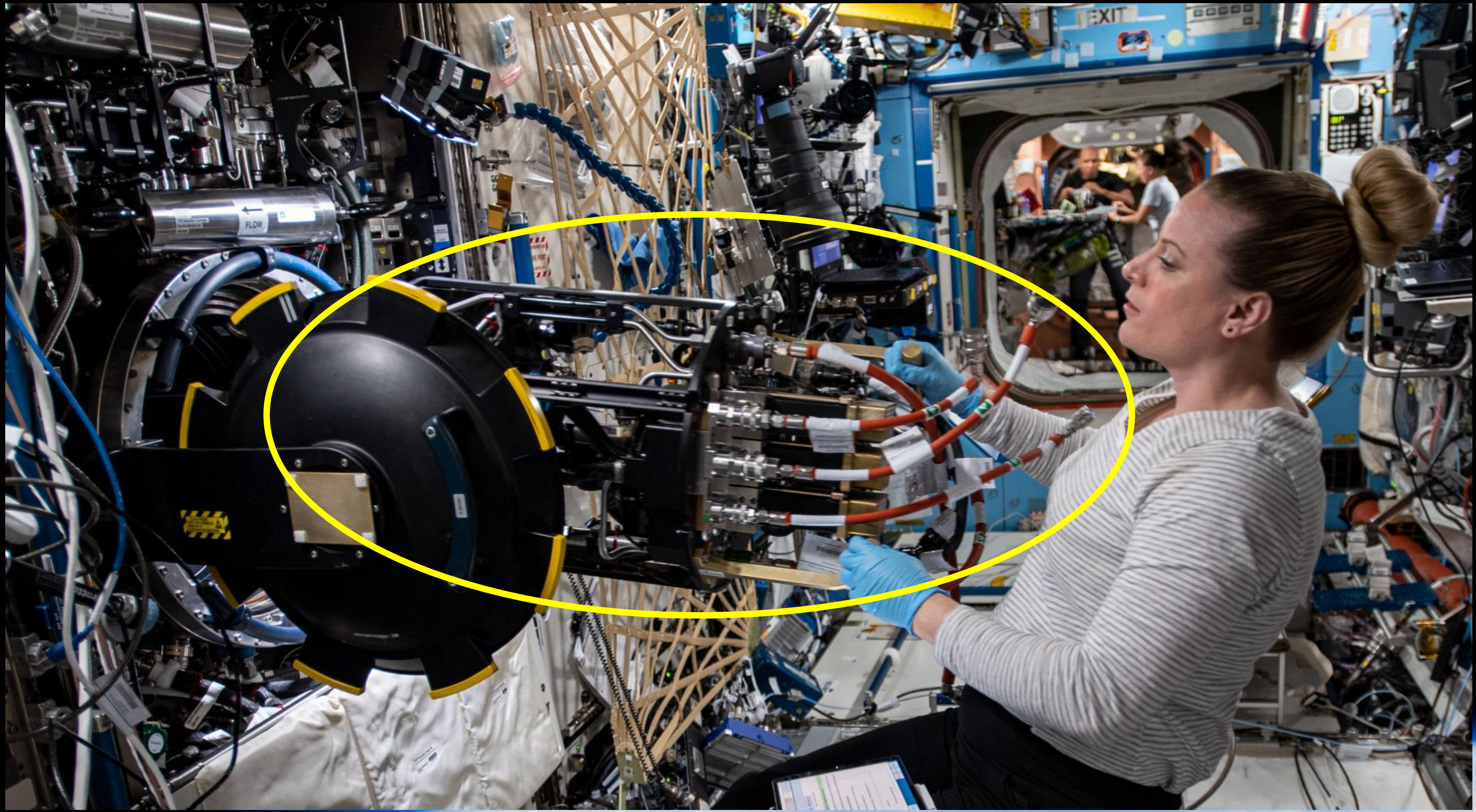
    Microgravity flame advantages?
    - No flicker
    - Spherical flames
    - Large length scales
    - Long residence times
    - Momentum-dominated at low velocities, etc.
  - **Spacecraft fire safety**
- **HOW?**
  - Modular hardware and the Combustion Integrated Rack (CIR)
  - ISS crew configured hardware
  - Tests remotely commanded from NASA Glenn
- **WHEN?**
  - ISS operations from Sept. 2017 to Feb. 2022
  - ISS testing complete



NASA astronaut Jessica Meir with the Combustion Integrated Rack [ISS061e013314]

Modular experimental hardware

- Combustion Integrated Rack (CIR)
- ACME chamber insert



Combustion Integrated Rack (CIR)

- ~100-liter chamber
- gas supply & venting
- imaging, etc.

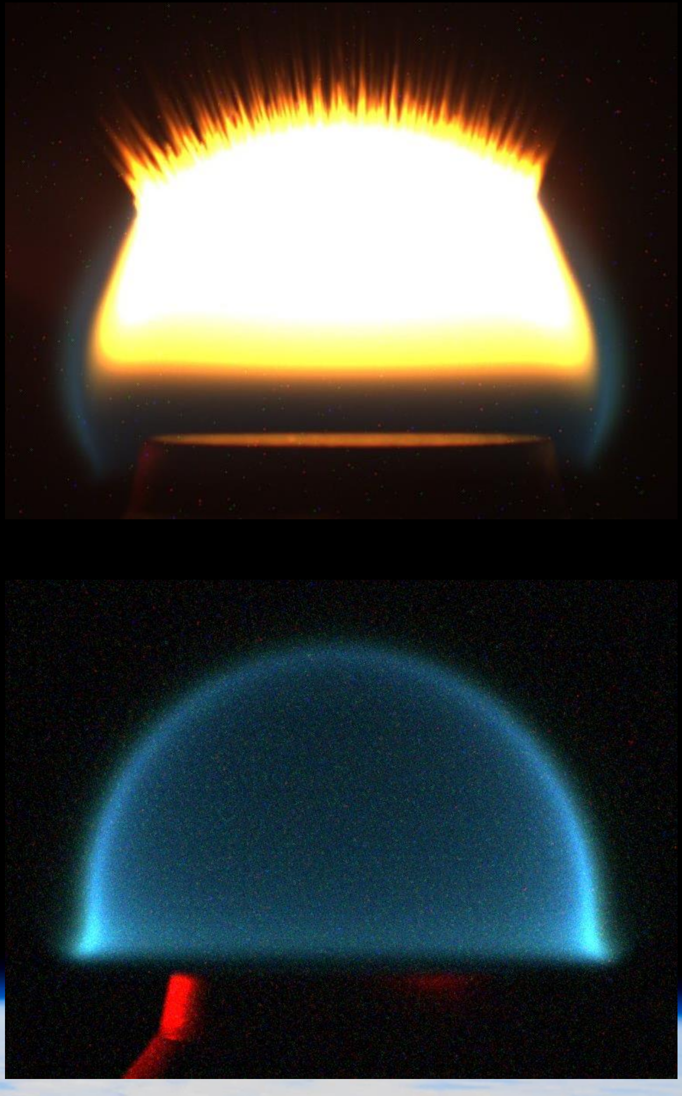
ACME chamber insert

- exchangeable burner
- hot-wire igniter
- gas delivery
- flame instrumentation such as radiometers, photomultiplier tubes, fibers for Thin Filament Pyrometry (TFP)
- experiment-specific hardware, etc.

CIR with chamber open; ACME chamber insert held by Kate Rubins [ISS064e029405]

Burning Rate Emulator (BRE)

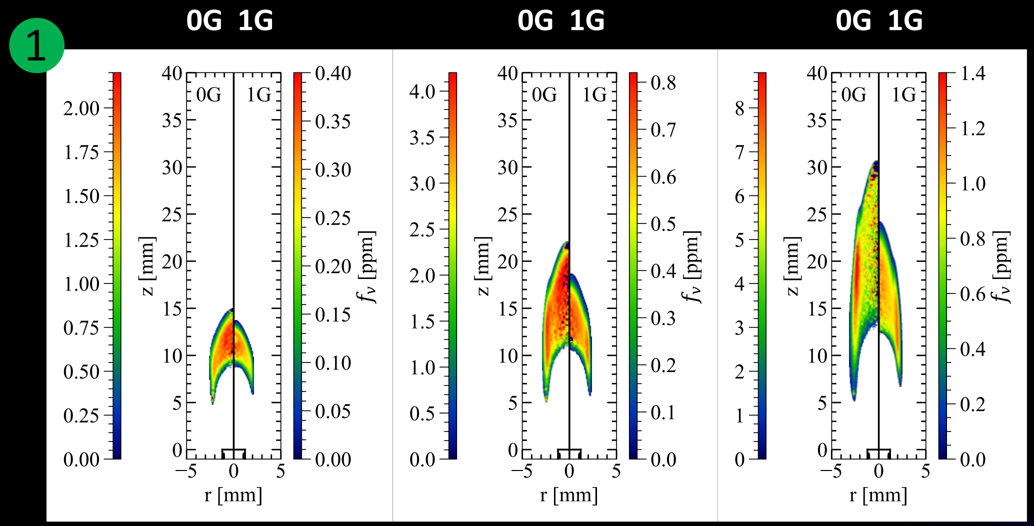
- **Investigators:** Jim Quintiere & Peter Sunderland (University of Maryland), John de Ris (FM Global, retired)
- **Objective:** Determine burning conditions in still atmospheres as a function of material properties.
- **Selected Findings:**
  - **Hazard!** Low-momentum microgravity flames can burn for minutes in the absence of an air flow or flame spread.
  - **Oxygen** While the flames can burn for minutes in elevated oxygen concentrations, like those being considered for future spacecraft, they were found to self-extinguish in concentrations below ~25% (by volume).
  - **Size** While smaller flames can burn for minutes at elevated oxygen concentrations, larger flames were generally seen to self-extinguish within 1.5 minutes.
  - **Fuel** While ethylene flames at elevated oxygen concentrations can burn for minutes, methane flames were seen to self-extinguish within a minute.
- **Significance:** Spacecraft fire prevention, including (1) microgravity flammability conditions and (2) assessment of flammability test methods for spacecraft materials.



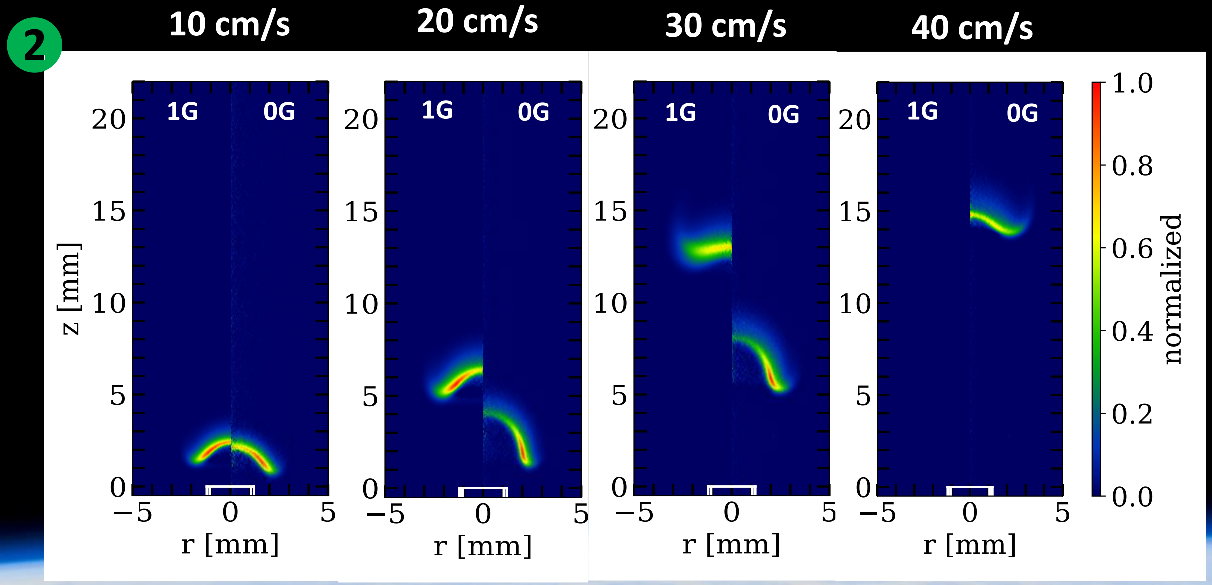
Example BRE flames, where the sooty top image is just after ignition.

Coflow Laminar Diffusion Flame (CLD Flame)

- **Investigators:** Marshall Long & Mitch Smooke (Yale University)
- **Objective:** Improve computational flame models with benchmark quantitative data for sooty and extremely diluted microgravity flames.
- **Selected Findings:**
  1. Sooty microgravity flames are taller & wider and contain 5x to 8x more soot than equivalent 1G flames.
  2. Microgravity increases the limits of fuel dilution. Near limits, microgravity flames are more stable, allowing for lifted flames at lower fuel concentrations.
- **Significance:** Should lead to significant improvements in combustion simulation capabilities and contribute to new design tools.



Soot volume fraction per C_2H_4 concentration



CH* profile as a function of matched fuel and coflow velocities

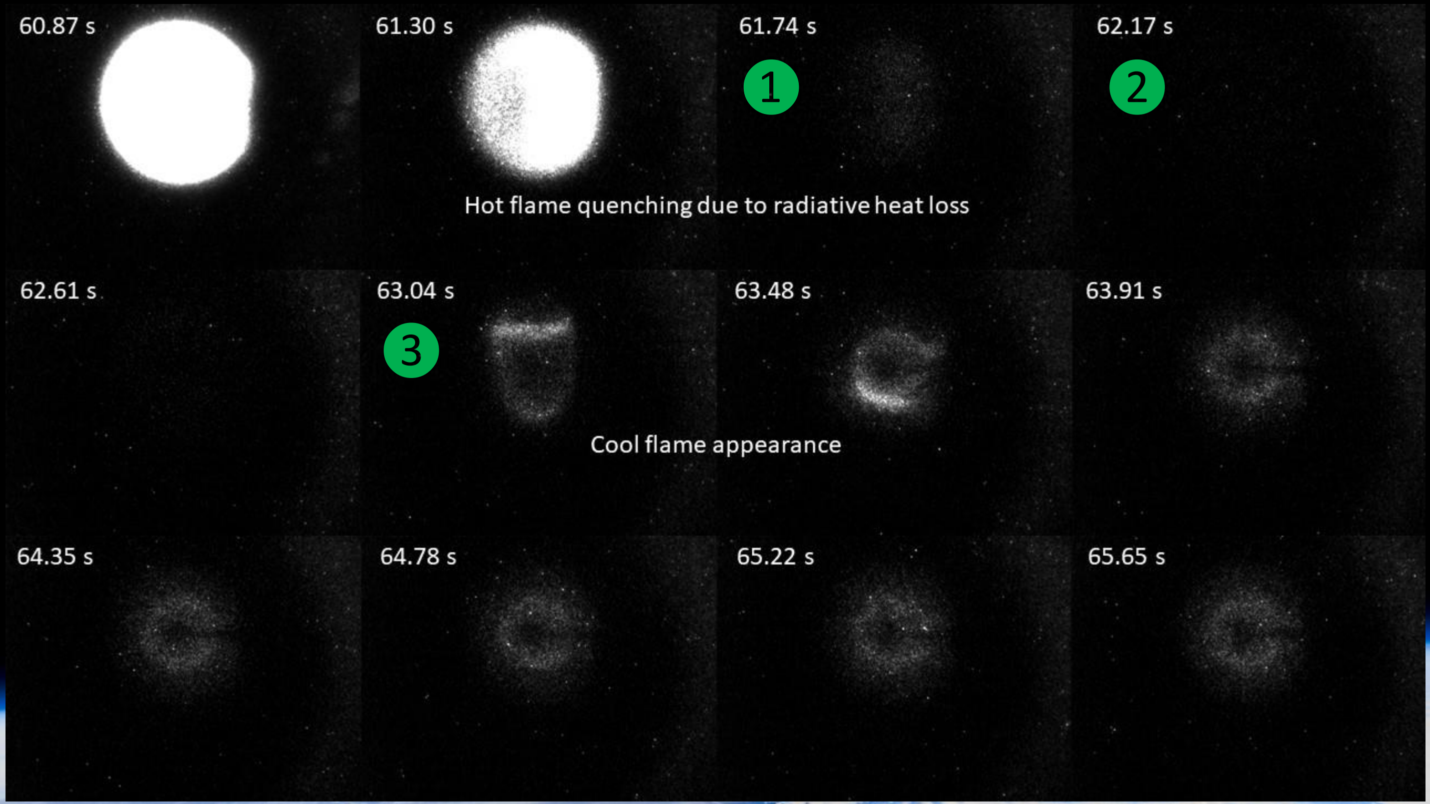
Flame lifting

Cool Flames Investigation with Gases (CFI-G)

- **Investigators:** Peter Sunderland (U. Maryland), Rich Axelbaum (Wash. U. in St. Louis), Forman Williams (UC San Diego)
- **Objective:** Observe non-premixed quasi-steady spherical cool flames on porous burners.
- **Selected Finding:** Observed the first spherical, quasi-steady, burner-supported cool flames!
- **Significance:** Improved and quantitative understanding of cool flame chemistry is critical to advanced engine design concepts that can simultaneously increase efficiency and reduce pollutant emissions.

Composite time sequence:
1 quenching of a hot flame due to radiative heat loss
2 ~1-s dark period
3 appearance of a cool flame much smaller than hot flame.

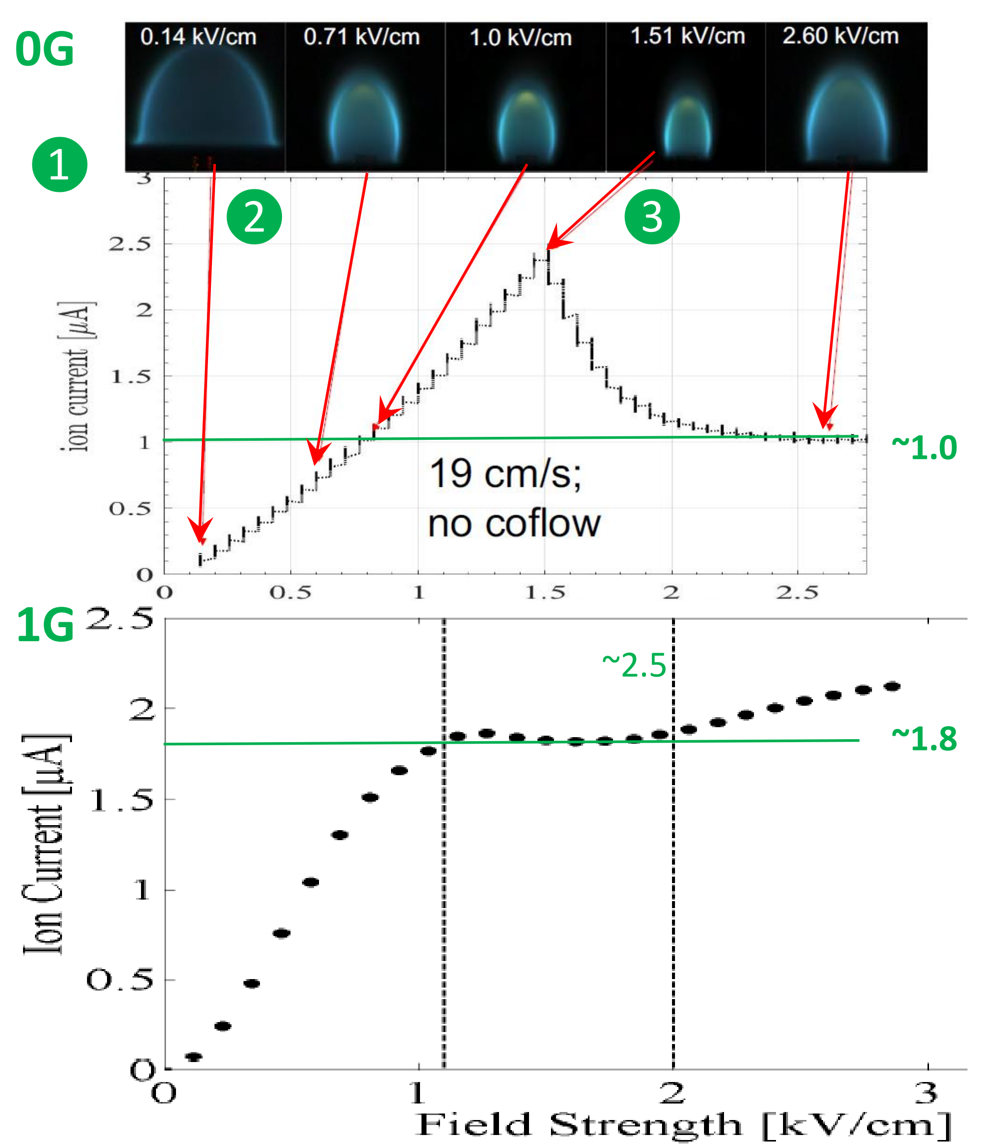
Intensified camera imaging with filter for formaldehyde emissions associated with cool flame chemistry.



6.35-mm porous spherical burner

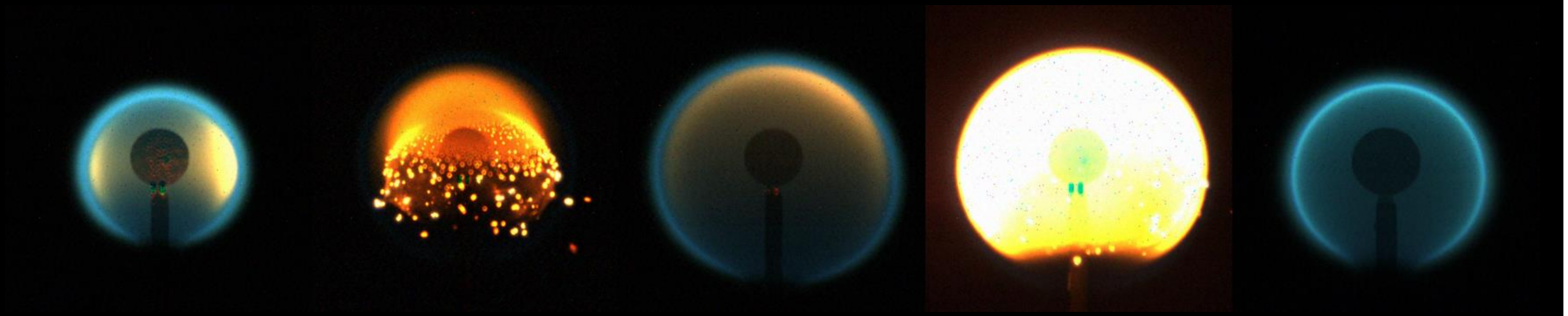
Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)

- **Investigators:** Derek Dunn-Rankin & Yu-Chien (Alice) Chien (University of California, Irvine)
- **Objective:** Understand chemi-ionization in flames and the interplay between ion generation and ion-driven flows.
- **Selected Findings:**
  1. There are clear correlations between flame luminosity, combustion intensity, and ion current.
  2. Highly-diluted flames can be stabilized with very weak electric fields.
  3. In microgravity, flames exhibit a distinct peak ion current that corresponds to the most compact flame.
  - When soot is present in a flame, electric fields create a wide range of behaviors.
- **Significance:** Ion transport and induced ion wind can modify the flame shape, alter the soot or flammability limits, direct heat transfer, and reduce pollutant emission.

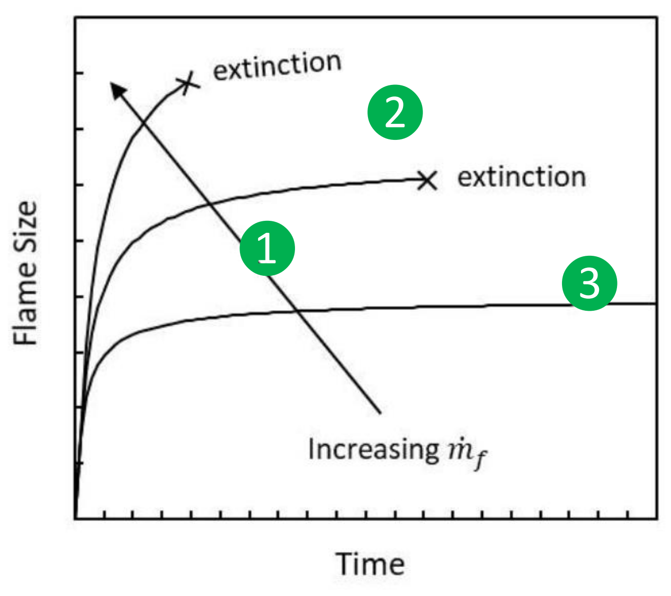


Flame Design

- **Investigators:** Rich Axelbaum (Washington University in St. Louis), Peter Sunderland (University of Maryland)
- **Objective:** Improve understanding of soot inception and control.
- **Selected Findings:**
  1. Flame size increases with reactant flow rate and decreases with ambient oxygen concentration.
  2. Large flames increase in size over time until the flame extinguishes due to radiative heat loss.
     - Before total extinction, these flames experience an unstable, oscillatory mode, in which they partially extinguish and reform. The oscillations grow in magnitude until total extinction.
  3. Very small flames have low radiative loss and asymptotically approach steady-state behavior.
- **Significance:** Optimization of O2-enriched combustion and the "design" of non-premixed flames that are both robust and soot free.

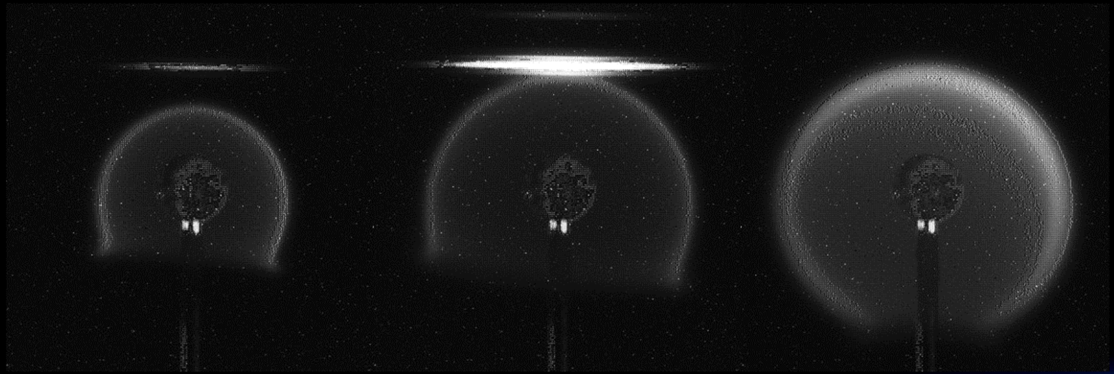


Flames with a variety of sooting characteristics

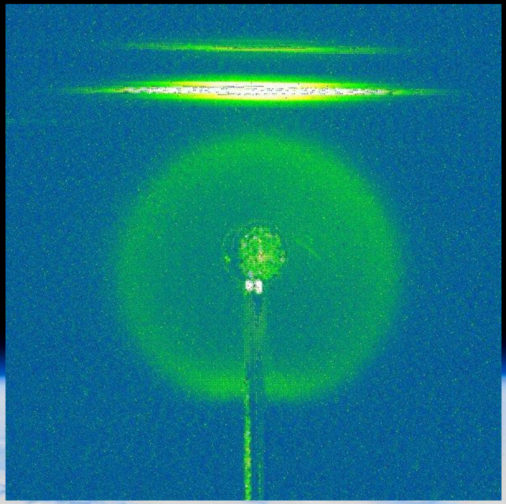


Structure and Response of Spherical Diffusion Flames (s-Flame)

- **Investigators:** C.K. (Ed) Law (Princeton University), Stephen Tse (Rutgers University)
- **Objective:** Characterize and gain predictive capability of spherical diffusion flames; interrogate and possibly modify chemical kinetic mechanisms and transport sub-models.
- **Selected Findings:**
  - Both radiative and kinetic (i.e., convective) extinction of the spherical flames appear to have been observed.
  - Radiative extinction seems to occur at high flow rates and kinetic extinction at low flow rates. The latter may seem counterintuitive but at low flow rates the flames are close to the burner where the velocities are highest.
  - With helium, rather than nitrogen, dilution of both the fuel and oxygen, the extinction limits are shifted and kinetic extinction is generally difficult to discern.
- **Significance:** Relevant to energy conversion, pollutant formation, green house gas emission, and fire safety.



LEFT: Gray-scale images of 3 nitrogen-diluted CH_4 flames, where Thin Filament Pyrometry (TFP) measurements are being made in 2 tests.

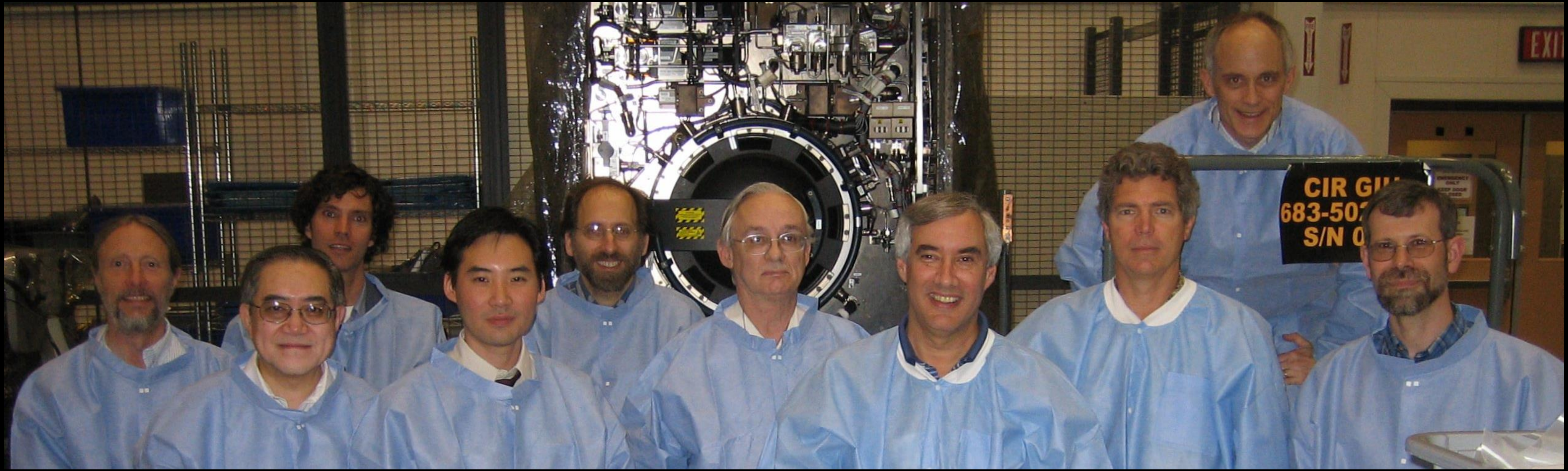


False-colored He-diluted H_2 flame in an O_2/He atmosphere with TFP diagnostic.

TFP fibers are 14-micron silicon carbide (SiC)

QUESTIONS?

With grateful acknowledgement to the investigators, graduate students, engineers, operations team, ISS crew, and all others who have contributed to the success of the research.



Long	Law	Sunderland	Tse	Axelbaum	King	Smooke	Dunn-Rankin	Urban	Stocker
Yale	*Princeton*	*Maryland*	*Rutgers*	*Wash. U.*	*NASA HQ*	*Yale*	*UC Irvine*	*NASA Glenn*	*NASA Glenn*
CLD Flame	s-Flame	BRE, CFI-G, Flame Design	s-Flame	CFI-G, Flame Design		CLD Flame	E-FIELD Flames		

LEARN MORE

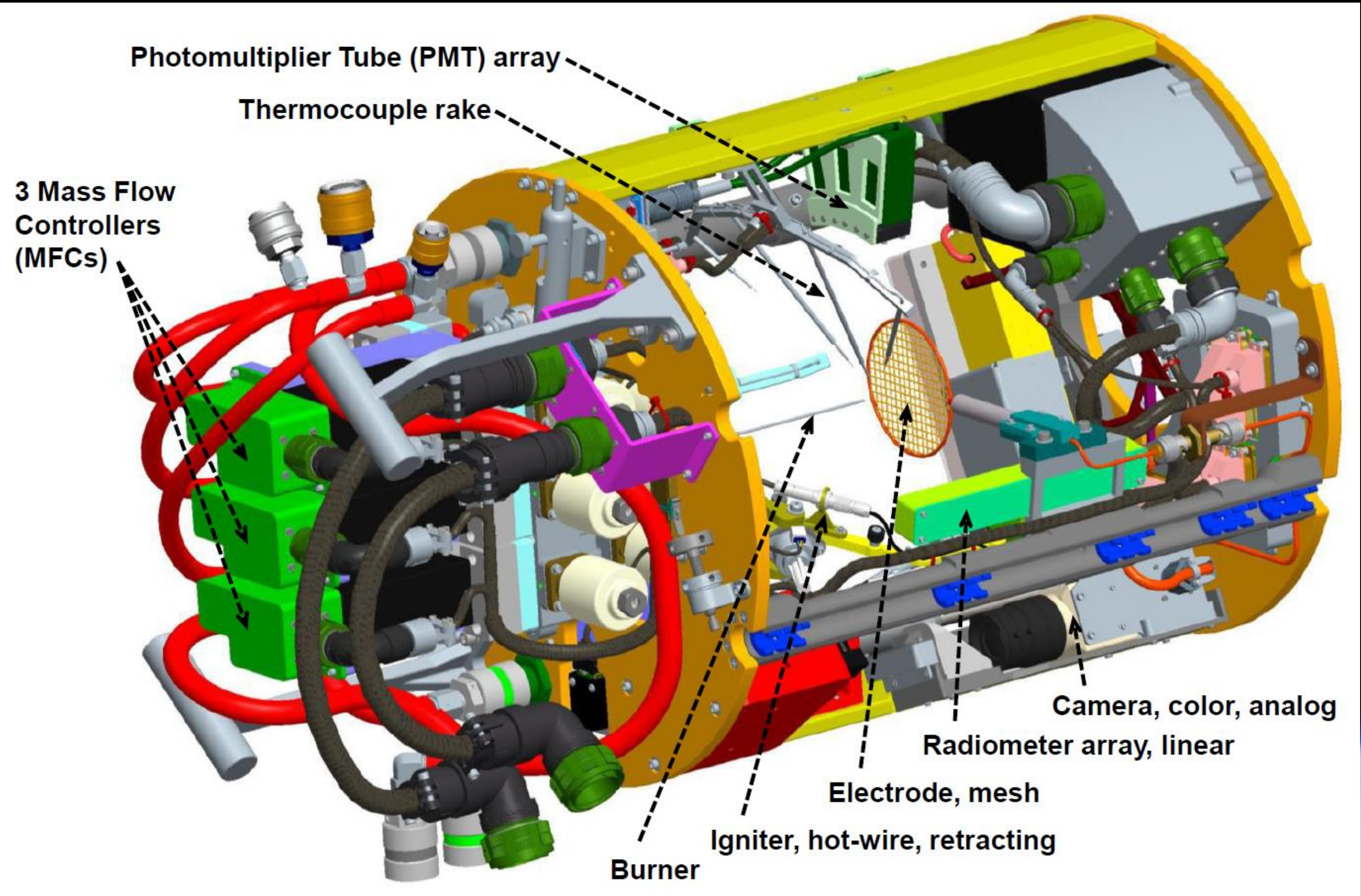
- www1.grc.nasa.gov/go/acme
- www.facebook.com/space.flames
- www.flickr.com/photos/space-flames

ACME chamber insert

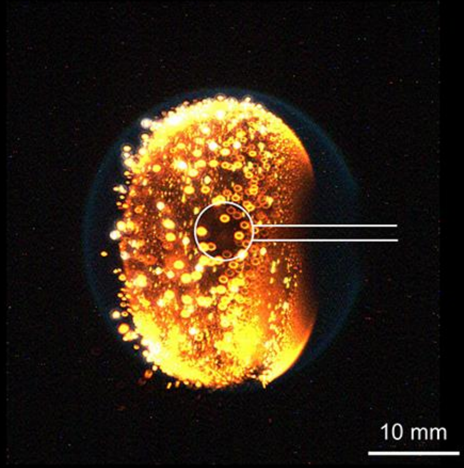
NASA astronaut Christina Koch reconfiguring the ACME chamber insert for a different experiment [ISS059e017074]

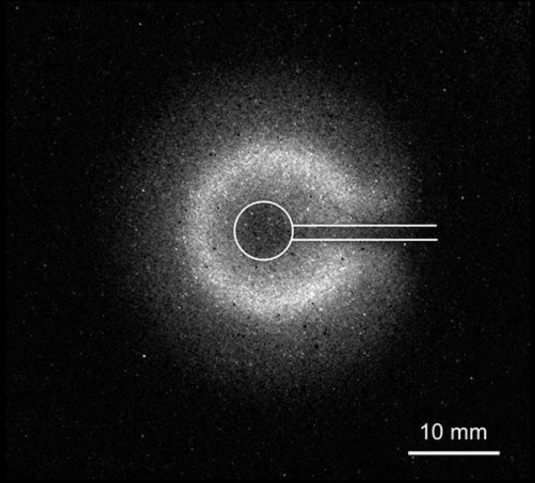
- **Crew-exchangeable & removeable hardware**
  - Burner, igniter arm & tip
  - Mass Flow Controllers (MFCs)
  - High-voltage power supply & electrode mesh
  - Analog operations camera
  - Thermocouple rake
  - Photomultiplier Tube modules (PMTs)
  - Radiometer array

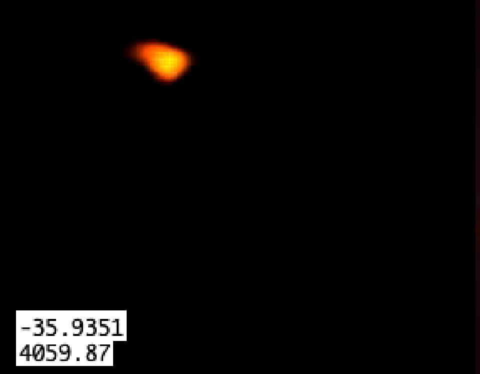
Key elements of the chamber insert

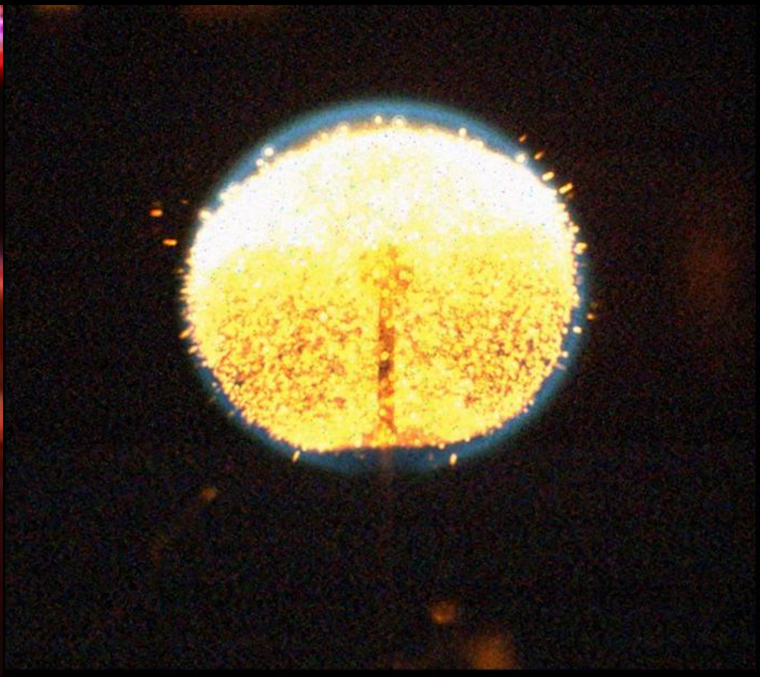


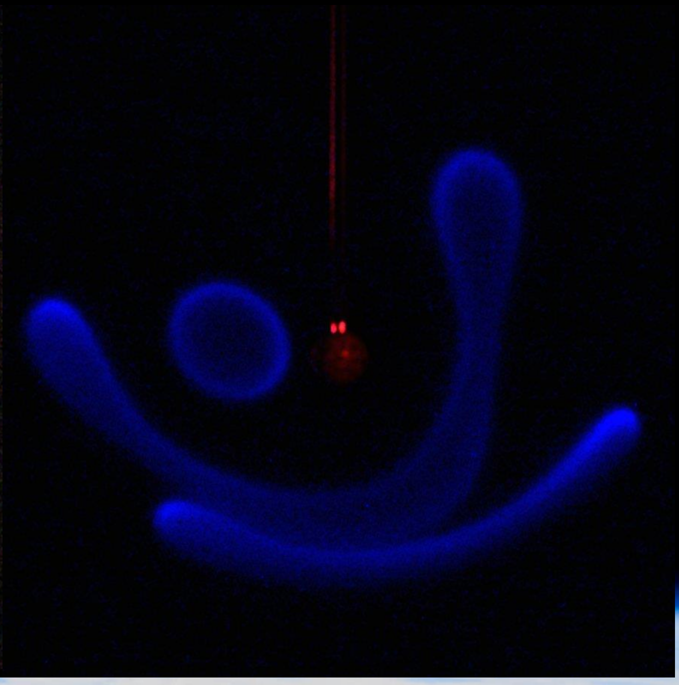
Example ACME flames











Top: BRE, CFI-G (hot & cool); Bottom: CLD Flame, E-FIELD Flames, Flame Design, s-Flame