Spacecraft Fire Protection

- Flame physics in microgravity
- ISS Fire Detection and Suppression (FDS) system description

- For class on Thursday, meet in Kim 1309

Fire Safety in Spacecraft

- "Spacecraft Fire Safety: Protecting Vehicles and Crews on Long-Duration Missions" Gary Ruff, NASA Lewis Research Center
- Talk from Future In-Space Operations (FISO) seminar series, November 15, 2017

National Aeronautics and Space Administration

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Space Administration

Spacecraft Fire Safety: Protecting Vehicles and Crews on Long-Duration Missions

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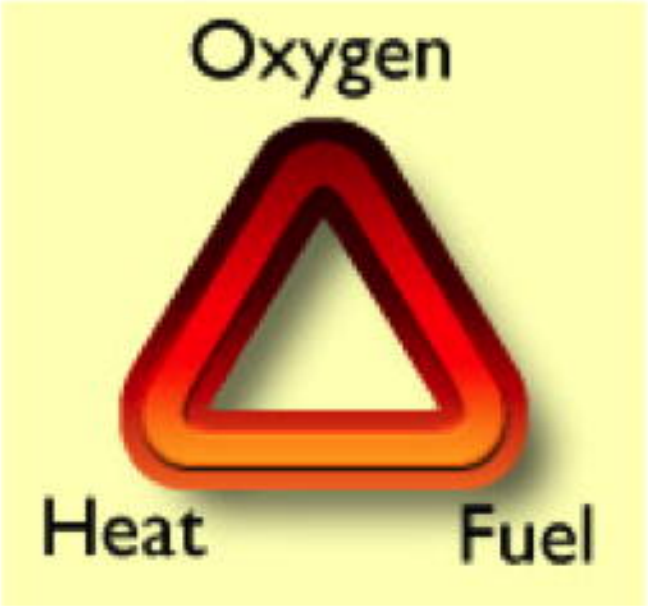
Future In-Space Operations (FISO) Seminar

November 15, 2017

NASA's Risk Management for Spacecraft Fire Safety

- Fire Safety Philosophies
  - Fire-proof design
    - Fire Triangle
  - Prevention
    - Maximize Use of Good Materials
    - Minimize Ignition Mechanisms
    - Utilize Good Practices



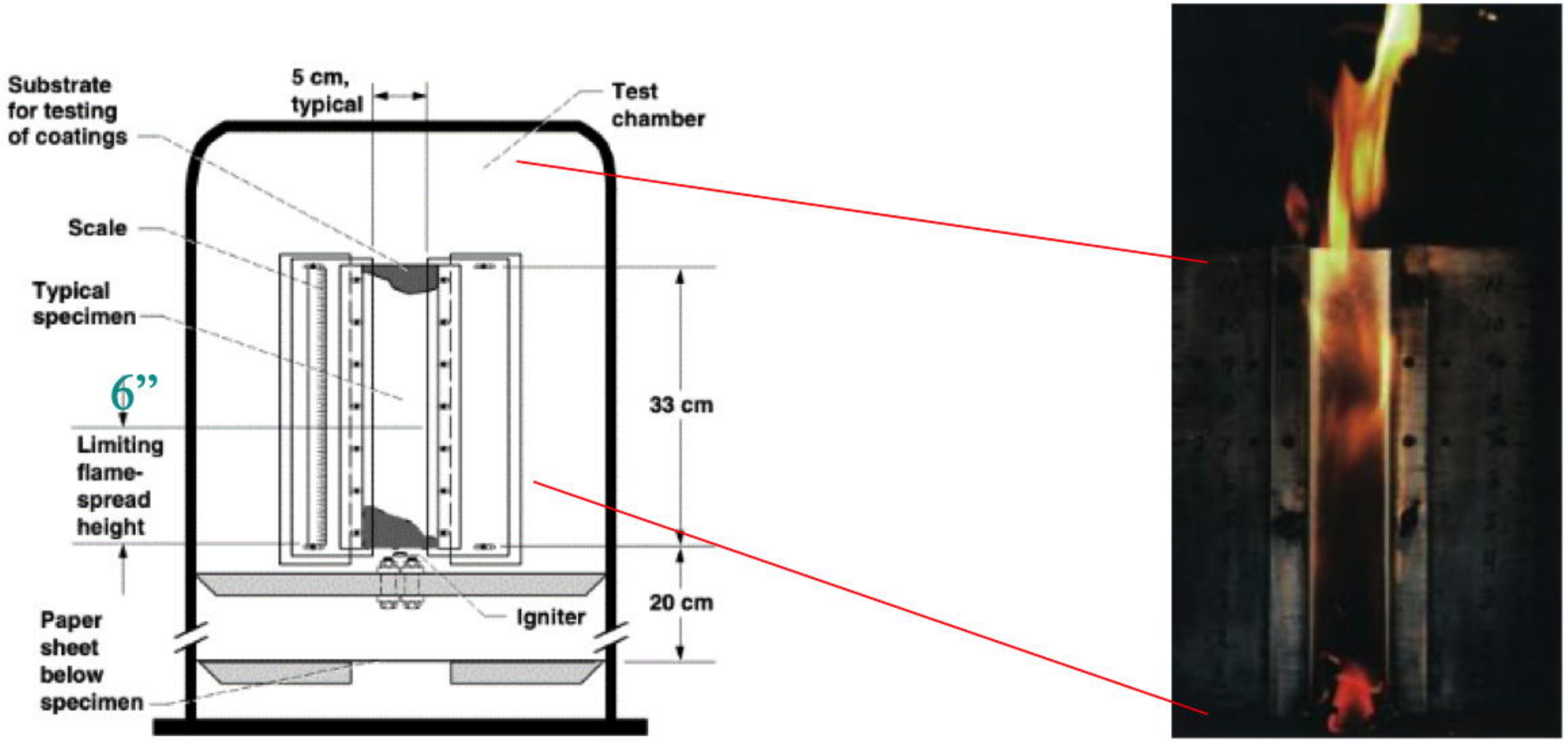
NASA's Risk Management for Spacecraft Fire Safety

These are the focus of our fire safety activities!

- Tasks "buy-down" the risk of fire for all manned exploration systems

Material Flammability Screening

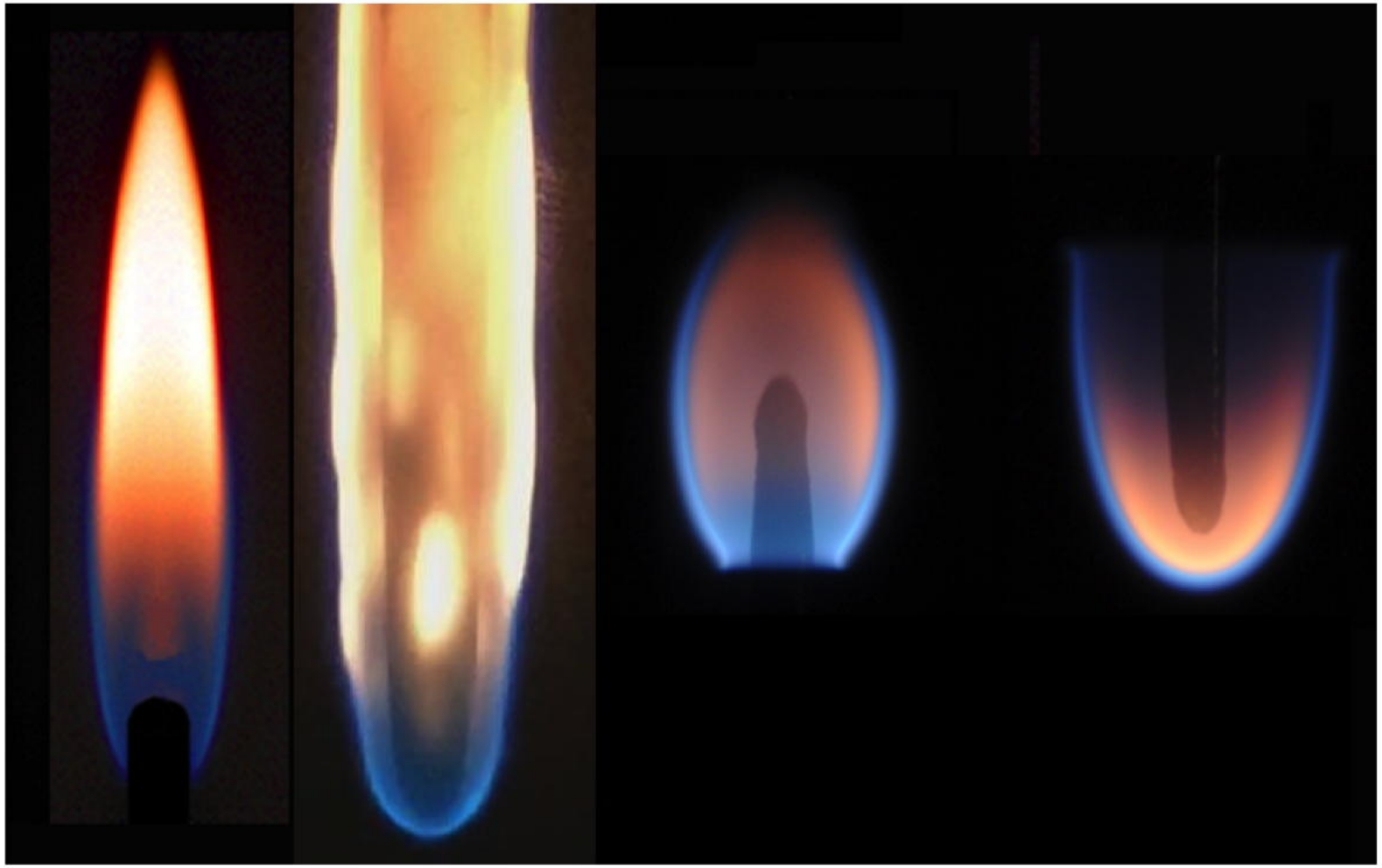
- NASA STD-6001 Test 1: Upward Flame Spread Test
- Test is conducted at the worst-case atmospheric conditions in which the material will be used
  - This has historically been 30% O_2, 10.2 psia (shuttle pre-EVA atm)
  - Future exploration atmospheres extend to 34% O_2, 8.2 psia
  - A material fails the test if it burns more than 15 cm (6 inches).



Sample failing NASA Test 1

Gravity

Air Flow is very Important to a Flame



Opposed *Concurrent* *Opposed* *Concurrent*

Normal Gravity (Buoyancy) **Microgravity**

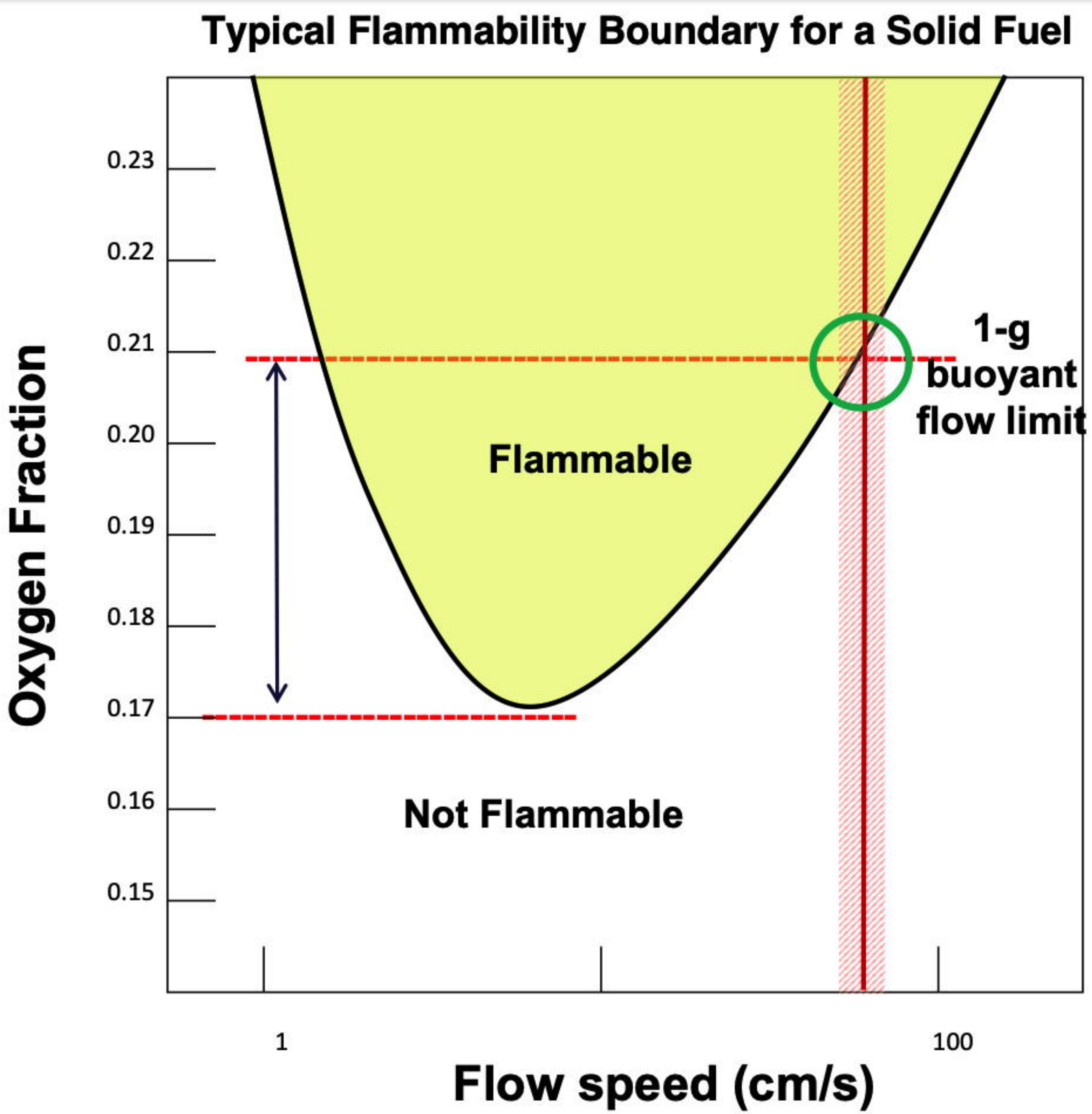
Buoyant or Forced Flow Direction

- **What does increasing flow do?**
  - Brings in oxygen
  - Removes heat faster
  - Reduces time for chemical reactions and heating
  - Makes flame closer to the surface (fuel)

Material Flammability Maps

- Material flammability depends on the ambient flow
- In 1-g, the flame determines the flow by buoyancy (natural convection) …

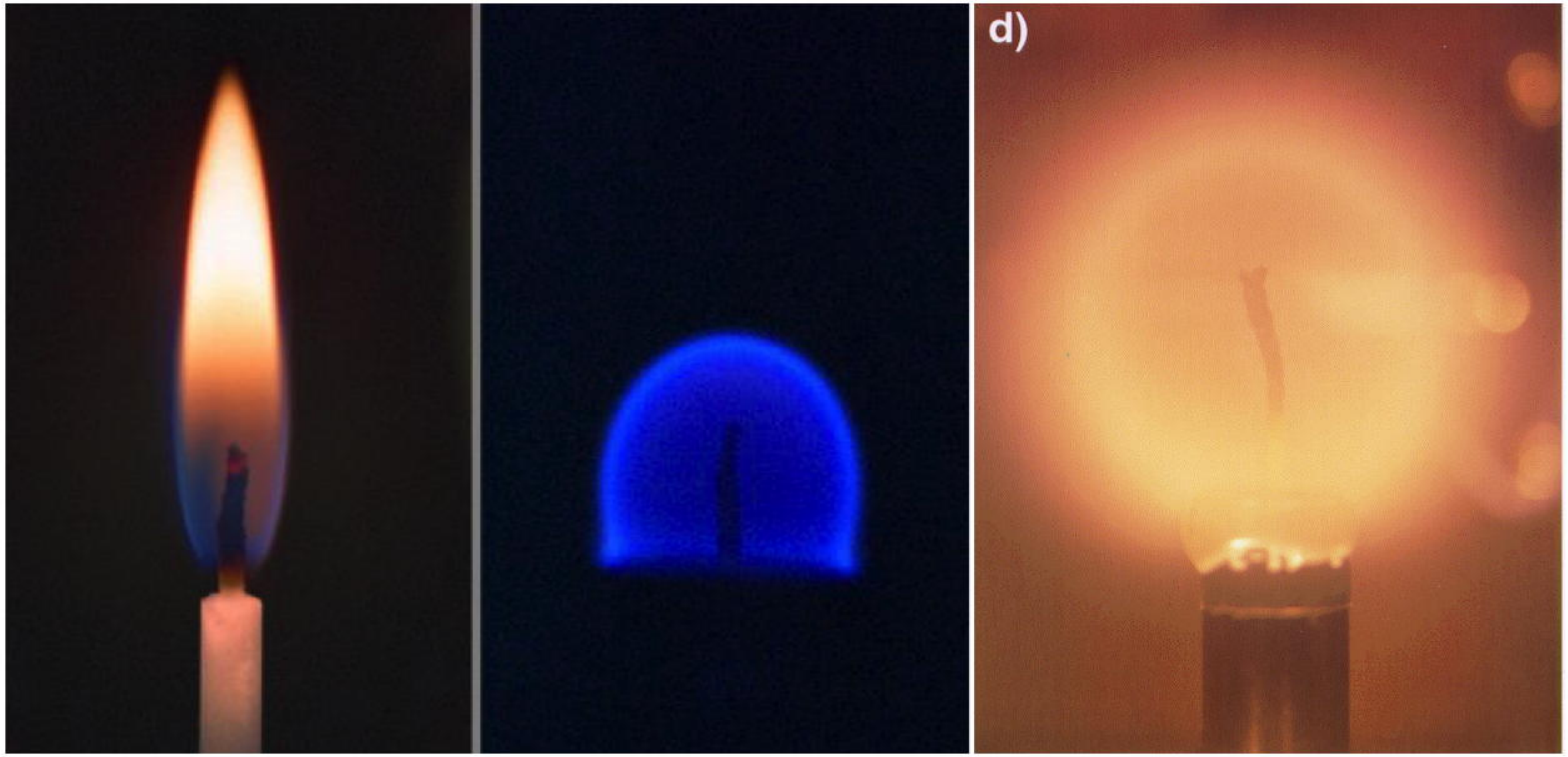
  … but the material can burn just fine with a lower flow and at a lower oxygen concentration
- The 1-g flammability limit can be determined by NASA-STD-6001 Test 1
- No flow (quiescence) is least flammable but the crew needs fresh air to breathe
- Environmental control and life support flows are around 15-20 cm/s
  - Right around the conditions where materials can still burn



A Lot of Other Low-Gravity Implications!

- Where there's fire, there's not necessarily smoke.

Candle flame in normal (left) and low-gravity (middle). The low-g flame emits little, if any smoke.

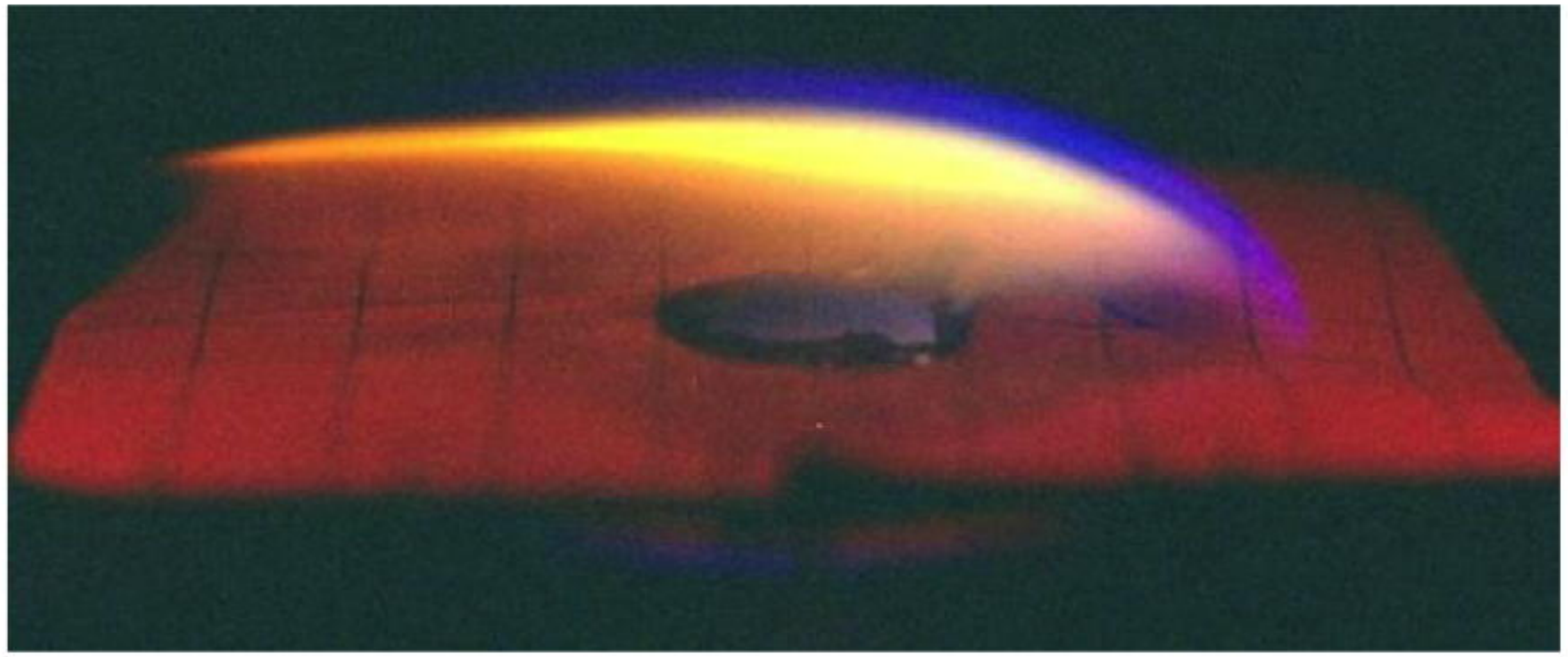


Cloud of condensed wax vapor after extinction of low-g flame

- When it's out, the hazard isn't necessarily gone.

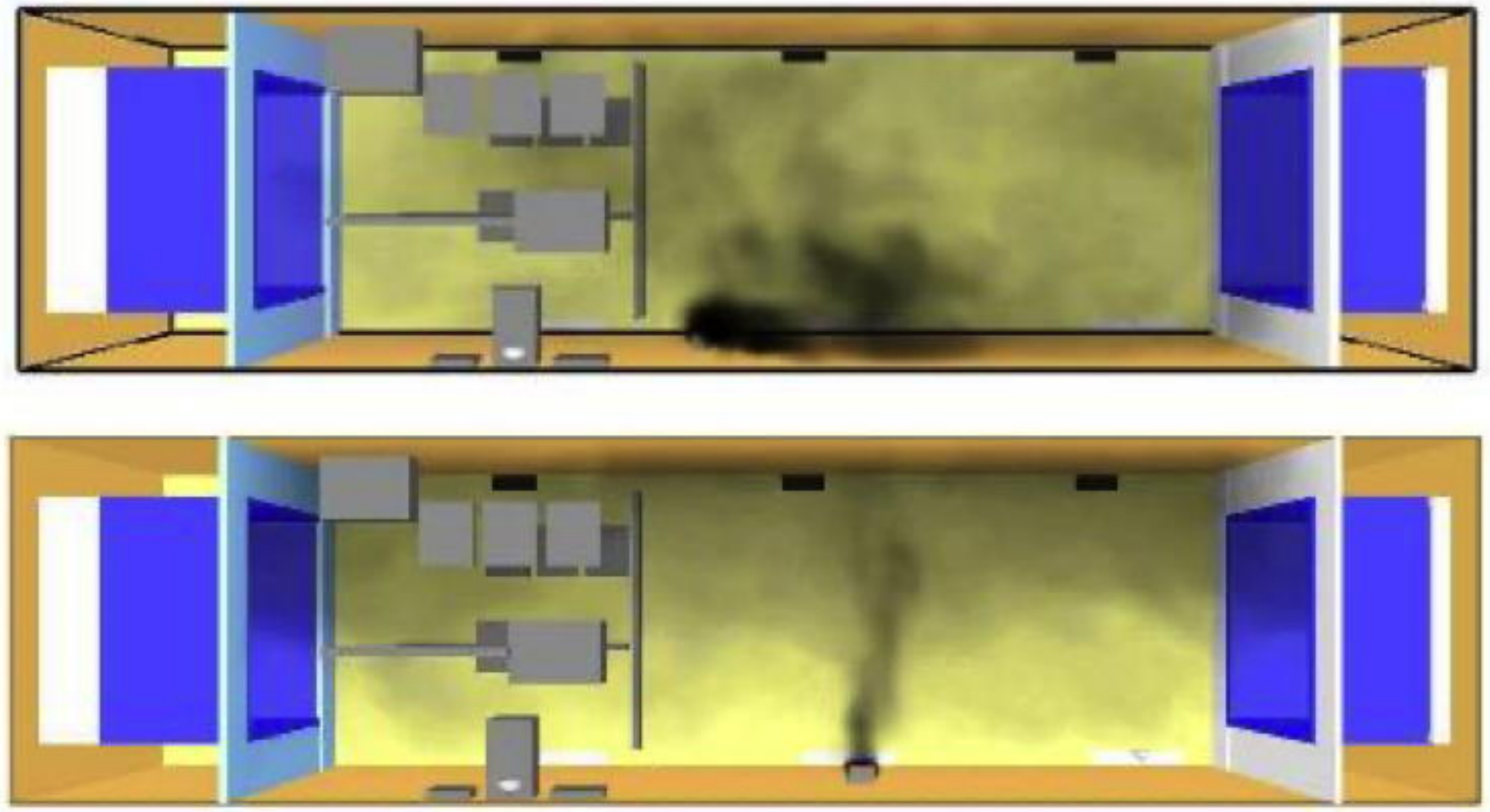
A Lot of Other Low-Gravity Implications!

- Flames can spread preferentially upstream
  - Into the incoming fresh air
- Ejecta from a melting solid (or firebrands) don't settle and can travel farther in low-g
- Detection of aerosol or gaseous fire signatures depends on ventilation … which also aids flame spread



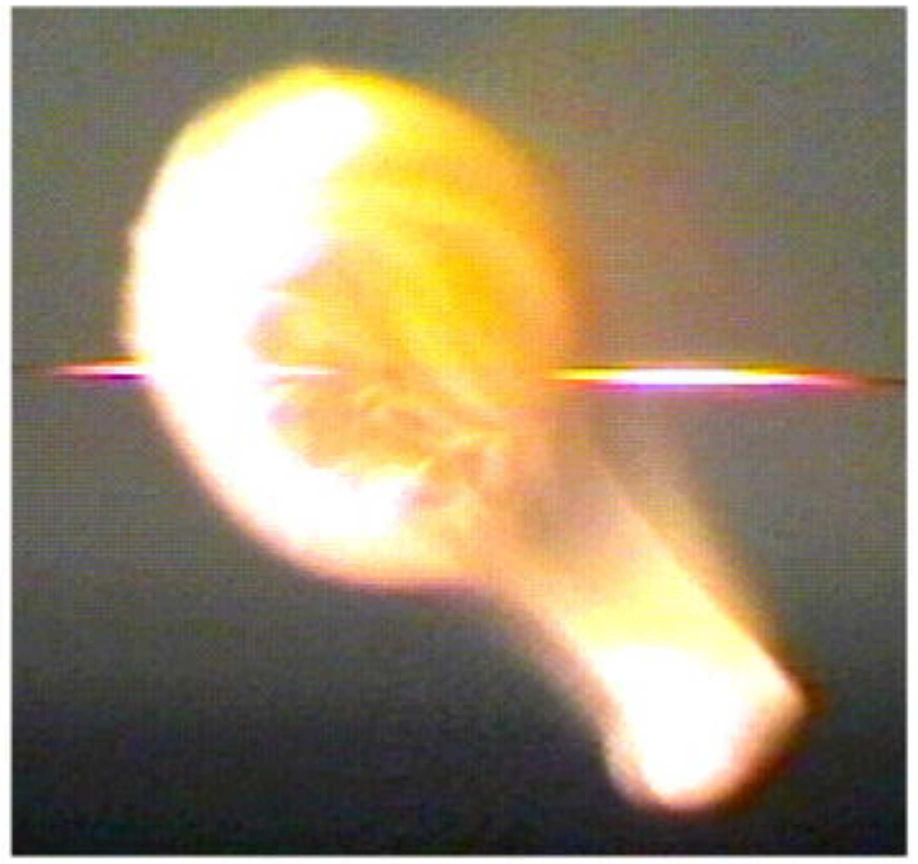
Flame spreads preferentially upstream, opposite that in 1g. Paper is centrally ignited in low-speed opposed-air flows (1 and 2 cm/s).

Low-gravity



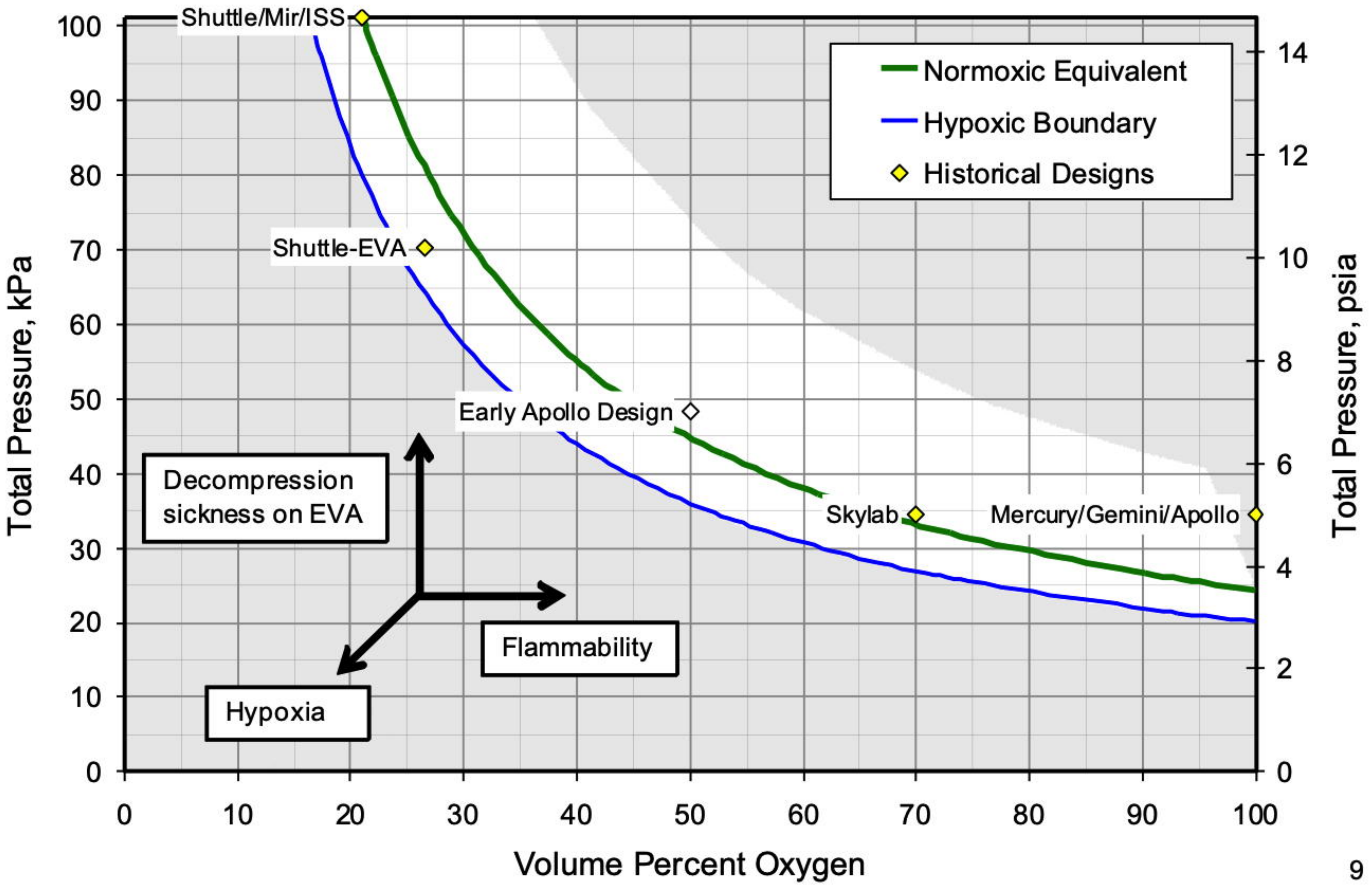
Normal-gravity

Ejection of burning material



Ambient conditions depend on mission objectives

- The Exploration Atmospheres Working Group convened in 2004 and 2012 to provide recommendations for the cabin atmosphere for exploration vehicles
- Selection attempts to balance competing effects of flammability, decompression sickness, and hypoxia
- Long-distance transport would favor standard atmosphere conditions
  - Known impact on crew and equipment
- Surface operations with frequent EVA would favor higher %O_2 and hypoxic operation
  - Trade crew performance against time for pre-breathe



What does NASA do to prevent/respond to fires?

- **Material Flammability**
  - NASA-STD-6001: Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion
    - Test 1: Upward Flame Spread Test
  - Materials that fail Test 1 must undergo additional testing and/or configuration control as defined by NASA Materials and Processes personnel
- **Minimize ignition sources**
  - To the extent possible, designs attempt to minimize sources of ignition
- **Fire Detection**
  - On ISS, smoke detectors are positioned near air return vents
  - FGB and SM smoke detectors use different technology (ionization) than US smoke detector (photoelectric)
- **ISS Fire Extinguishers**
  - US: gaseous CO_2, Fine water mist
  - RS: Water-based foam

Sample failing NASA Test 1

FGB SD

US CO_2 fire extinguisher

US SD

Engineering Development Unit of an ISS FWM PFE

SM SD

Engineering Development Unit of an Orion FWM PFE

Large-Scale Fire Demonstration

- We can conduct ground tests to assess many of these technologies but the data needs to be anchored using low-g data obtained at relevant length and time scales
- Testing requires:
  - Low-g
  - Large scale
  - Relevant range of conditions including reduced pressure and elevated oxygen
  - Large volume

➢ We proposed and developed the concept of conducting a large-scale fire on an ISS resupply vehicle after it left the ISS.

__Examples of Terrestrial Large-Scale Fire Experiments__

FAA full-scale aircraft test

NIST full-scale fire test

Ex-USS Shadwell

Submarine Fire Facility

Naval Research Laboratory

Coal dust test explosion

Saffire-I, II, & III Overview

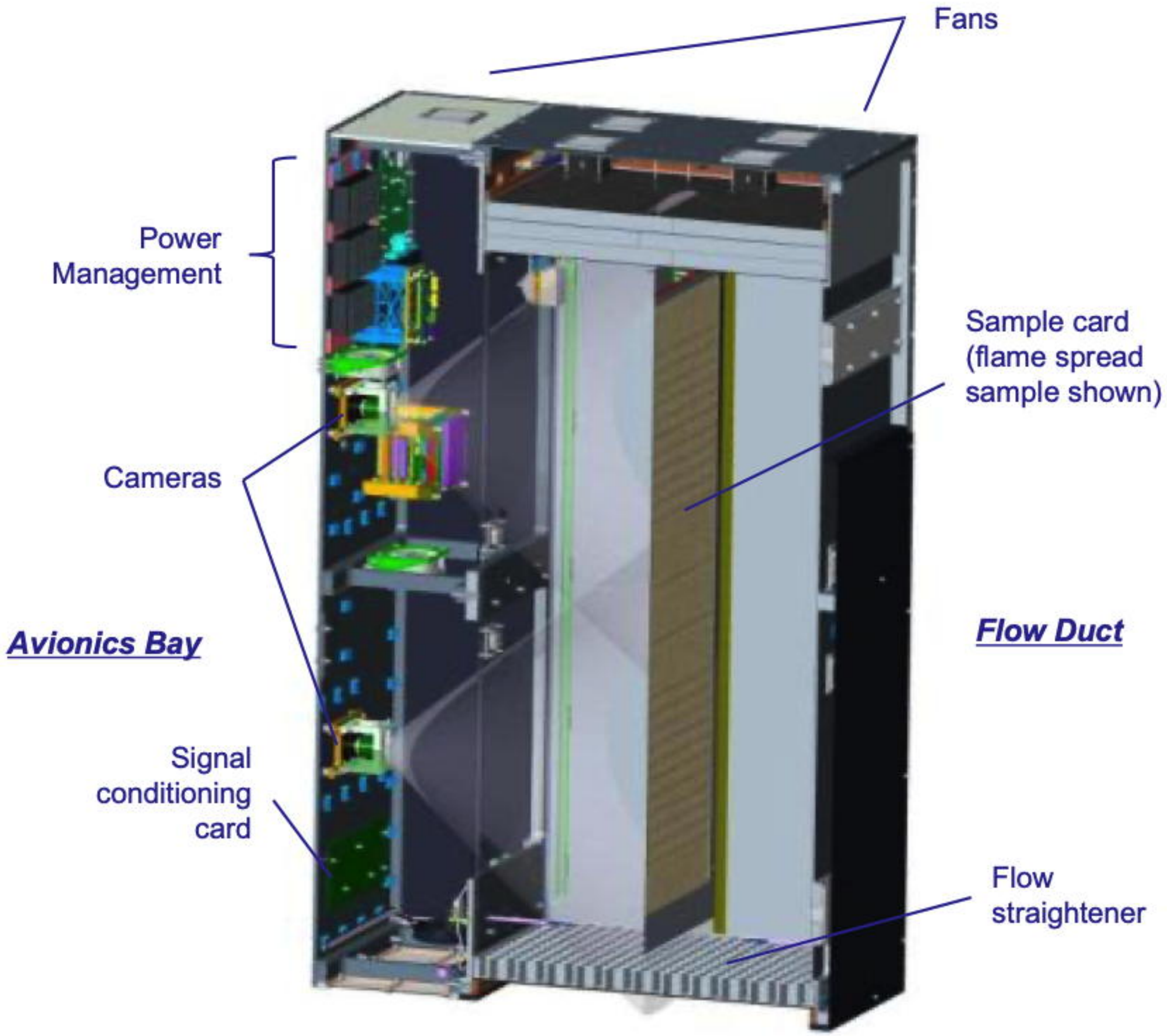
Needs:

- *Low-g flammability limits for spacecraft materials*
- *Definition of realistic fires for exploration vehicles*
  - *Fate of a large-scale spacecraft fire*

Objectives:

- *Saffire-I*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release)
- *Saffire-II*: Verify oxygen flammability limits in low gravity
- *Saffire-III*: Same as Saffire-I but at different flow conditions.

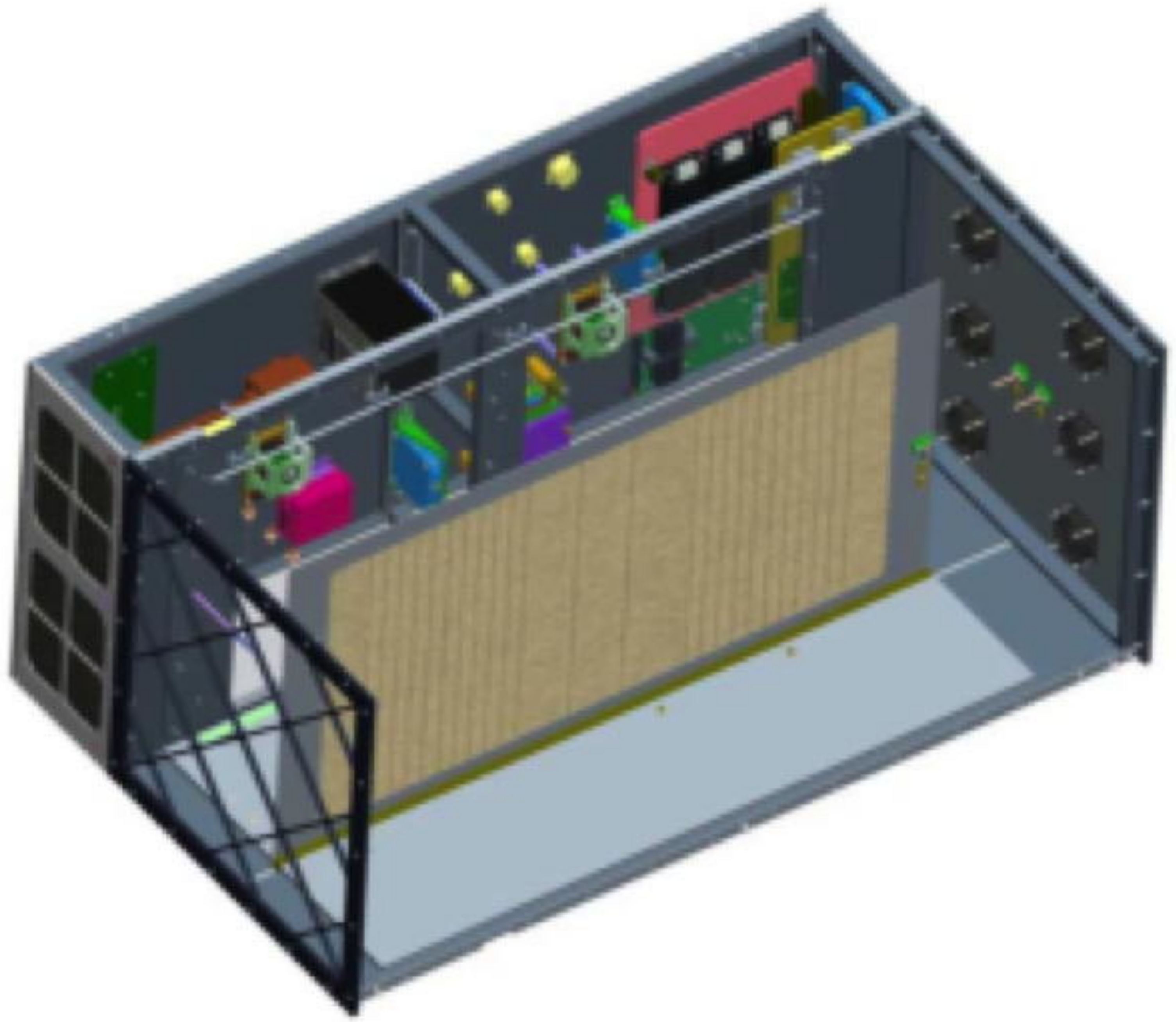
- *Data obtained from the experiment will be used to validate modeling of spacecraft fire response scenarios*
- *Evaluate NASA's normal-gravity material flammability screening test for low-gravity conditions.*



Saffire module consists of a flow duct containing the sample card and an avionics bay. *All power, computer, and data acquisition modules are contained in the bay. Dimensions are approximately 53- by 90- by 133-cm*

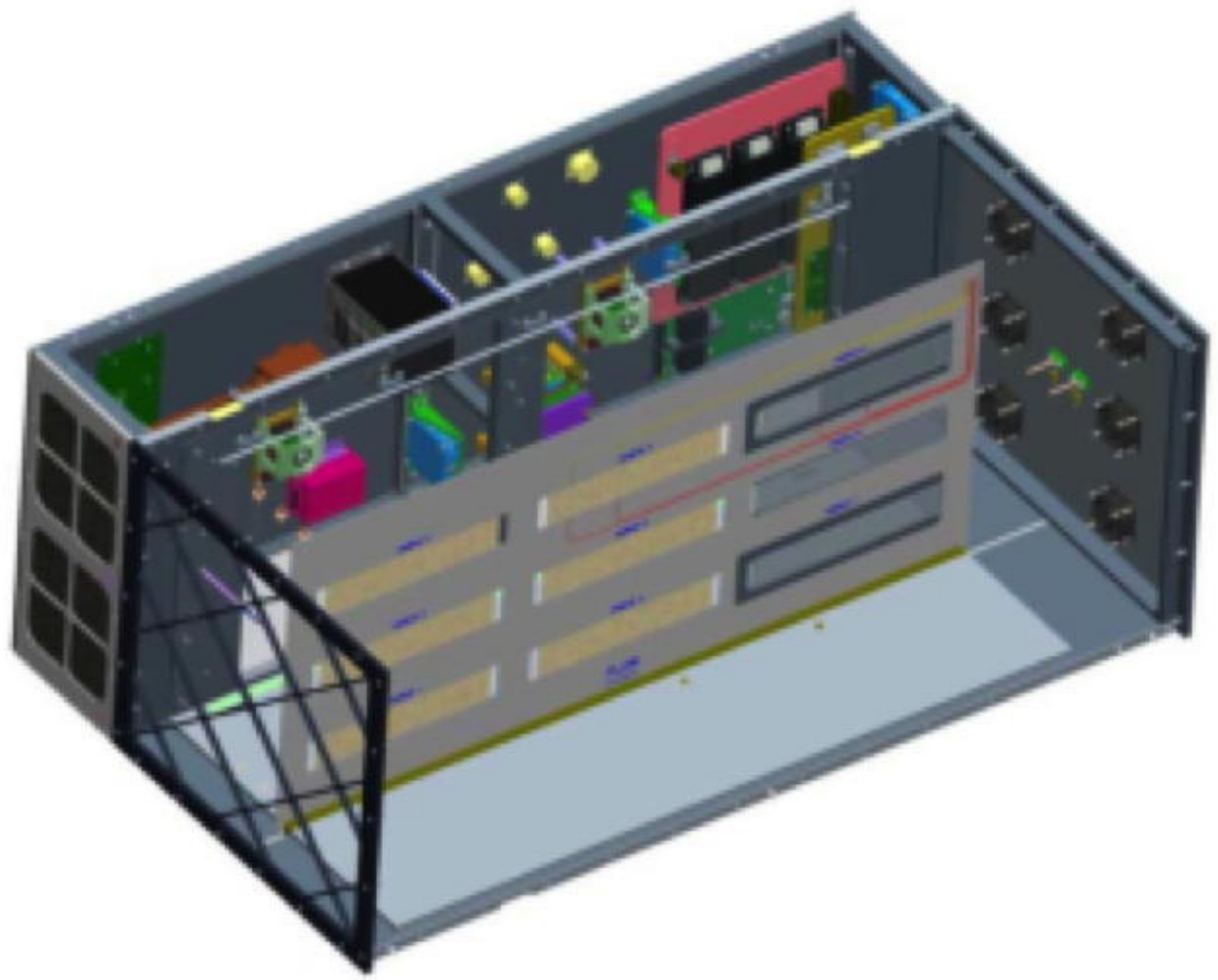
Sample Card Holder Configurations

- Sample card and samples are the only differences between the three flight units



Saffire-I, -III Sample Card

Composite fabric (SIBAL cloth)
(75% cotton – 25% fiberglass by mass)
(0.4 m x 0.95 m)

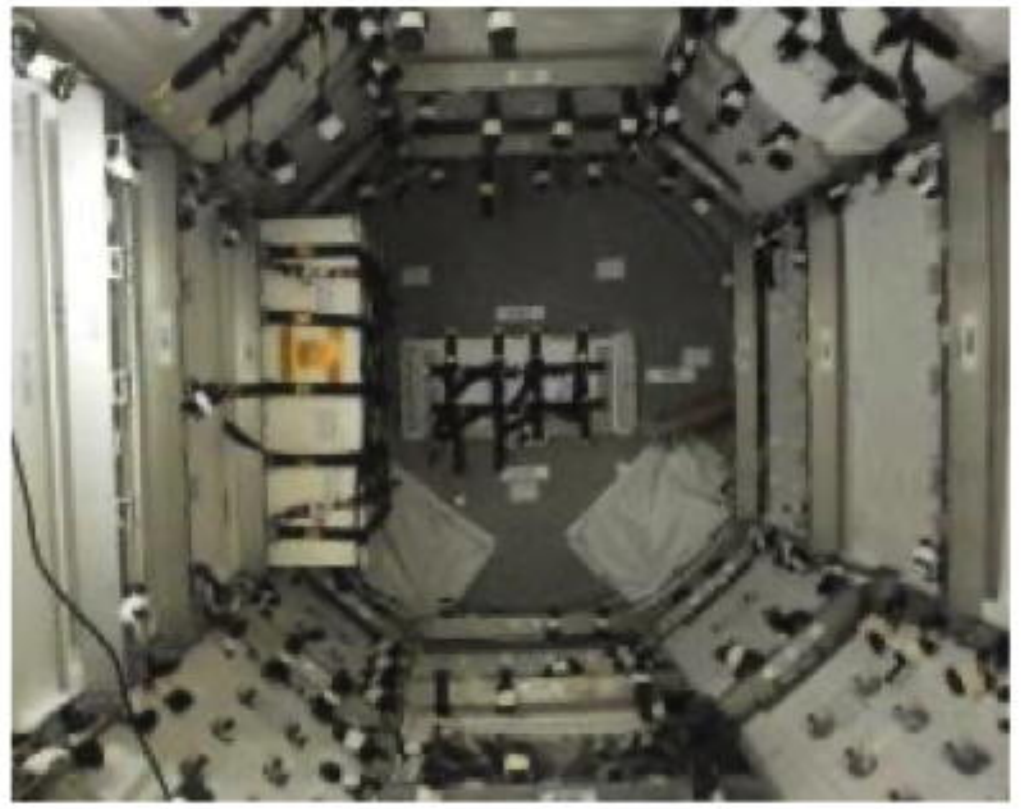


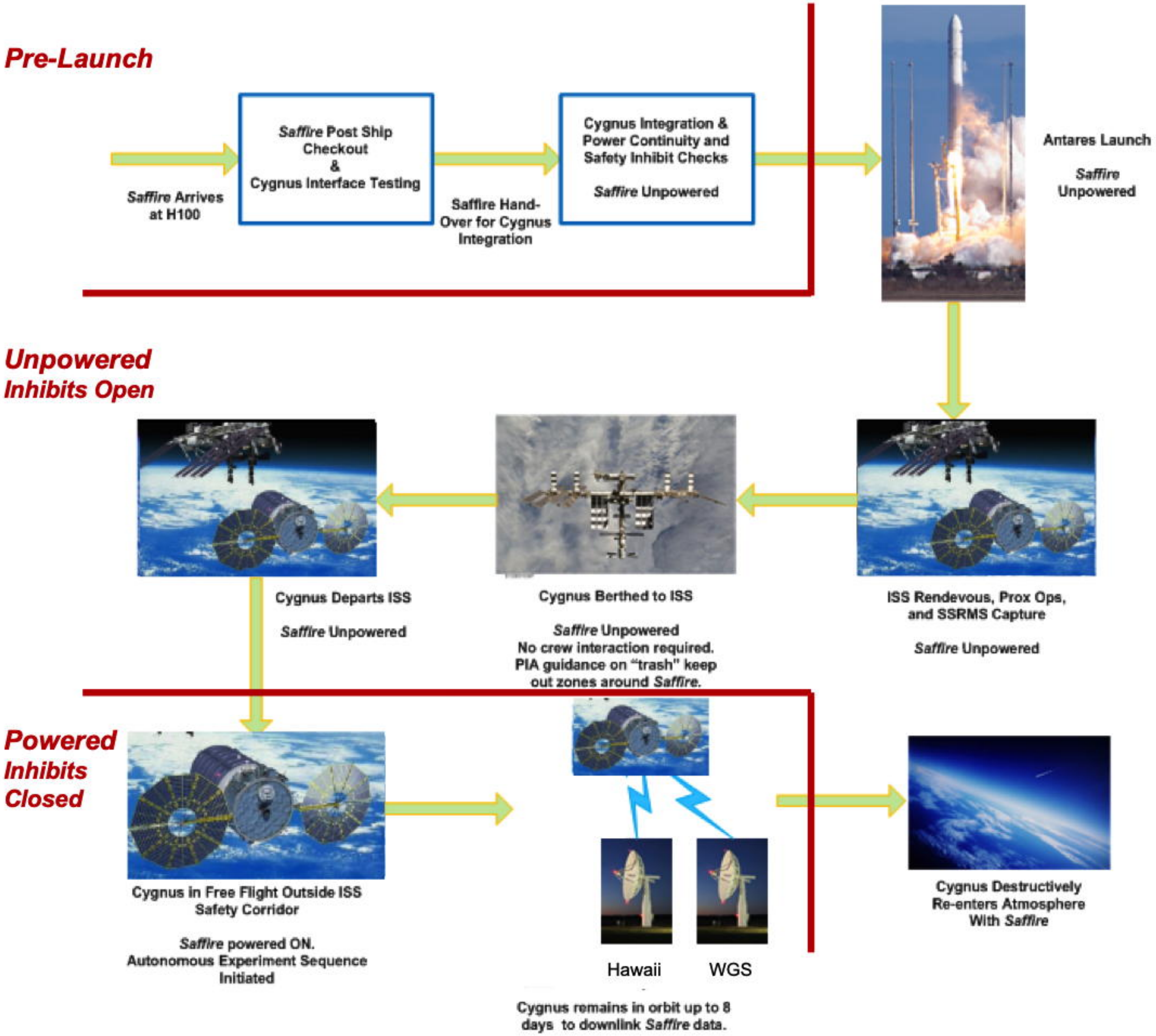
Saffire-II Sample Card

<u>Saffire-II Samples (5 cm x 29 cm)</u>

- PMMA (flat and structured)
- Silicone (3 thicknesses, different ignition direction)
- SIBAL
- Nomex (with PMMA ignition)

Operations Concept

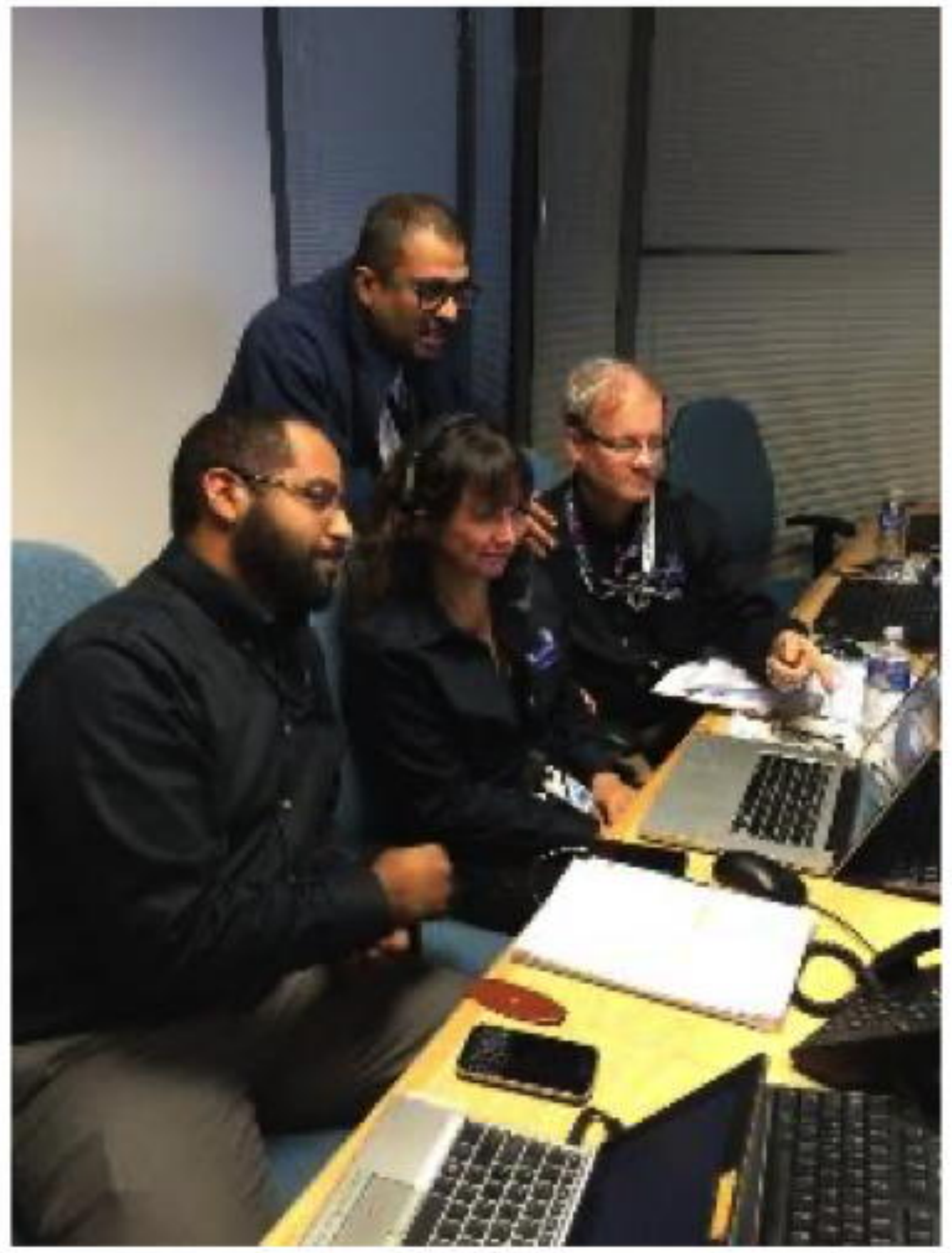




Saffire Operations

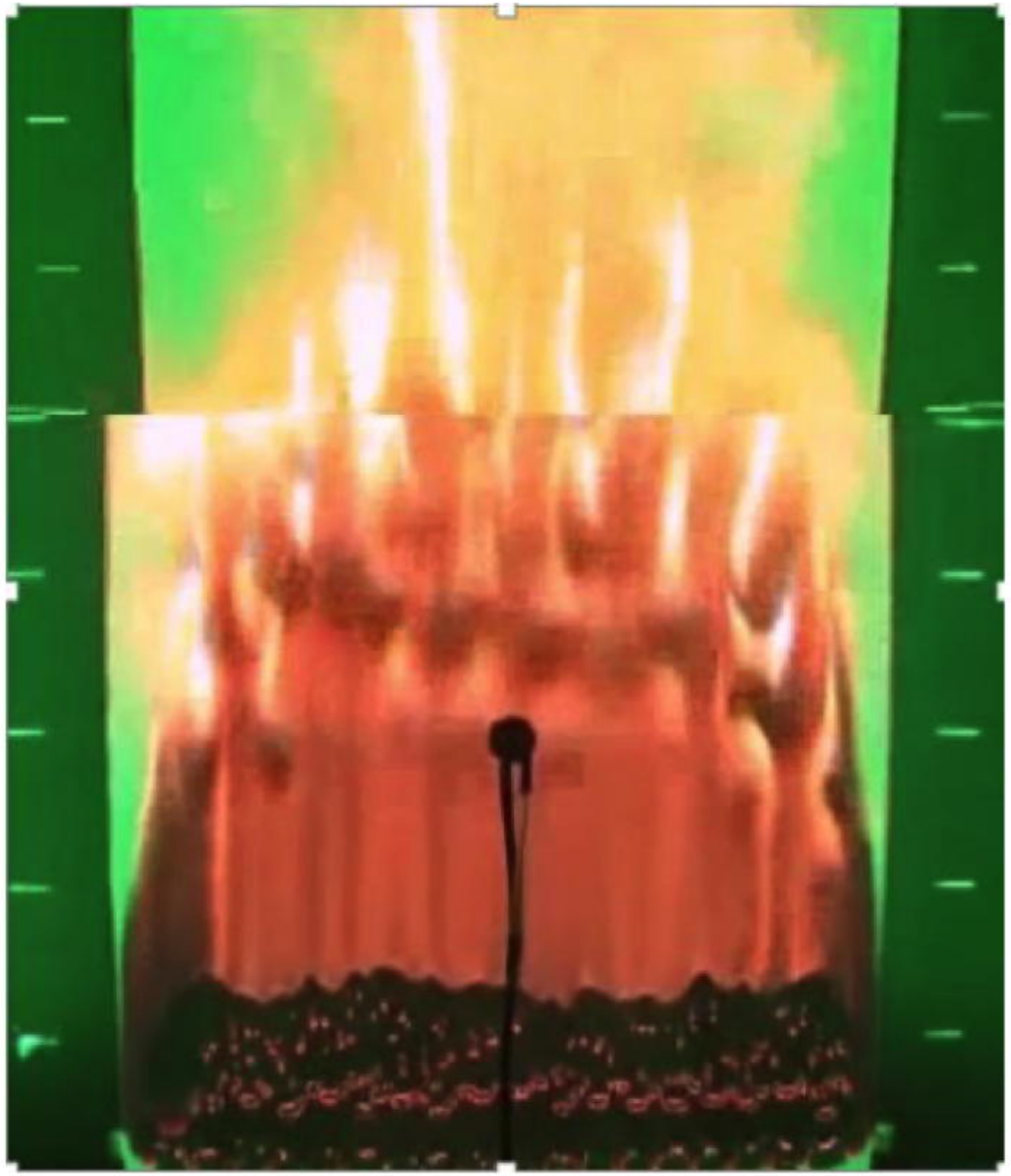
	Mission	Launch Site	Launch Vehicle	Integration	Launch	Mission Ops
Saffire-I	OA-6	KSC	Atlas	Jan 25, 2016	Mar 22, 2016	June 14, 2016
Saffire-II	OA-5	WFF	Antares	May 12, 2016	Oct 17, 2016	Nov 21, 2016
Saffire-III	OA-7	KSC	Atlas	Feb 3, 2017	Mar 27, 2017	June 4, 2017

- **Operations received considerable coverage on social media**
  - NASA GRC and AES



Above: Saffire-II Mission Support Teams at NASA-GRC; **Left:** Saffire-II Flight Operations Team at Mission Control Dulles (backroom data assessment); **Far Left:** Saffire and Orbital ATK Flight Operations Teams at Mission Control-Dulles

Saffire-III Operations
Concurrent Flow Igniter



Still image of the Saffire-I material burning in normal gravity.

- Images were taken 20 sec after ignition
- Both samples are 40 cm wide

- Two of the most important factors for crew safety during on-board fires are:
  1. How bad can the cabin conditions get during a fire?
  2. How quickly can they get bad?
- Fire is only the beginning – combustion products (smoke, CO, acid gases, …) also contribute to the hazard

Gravity ↓

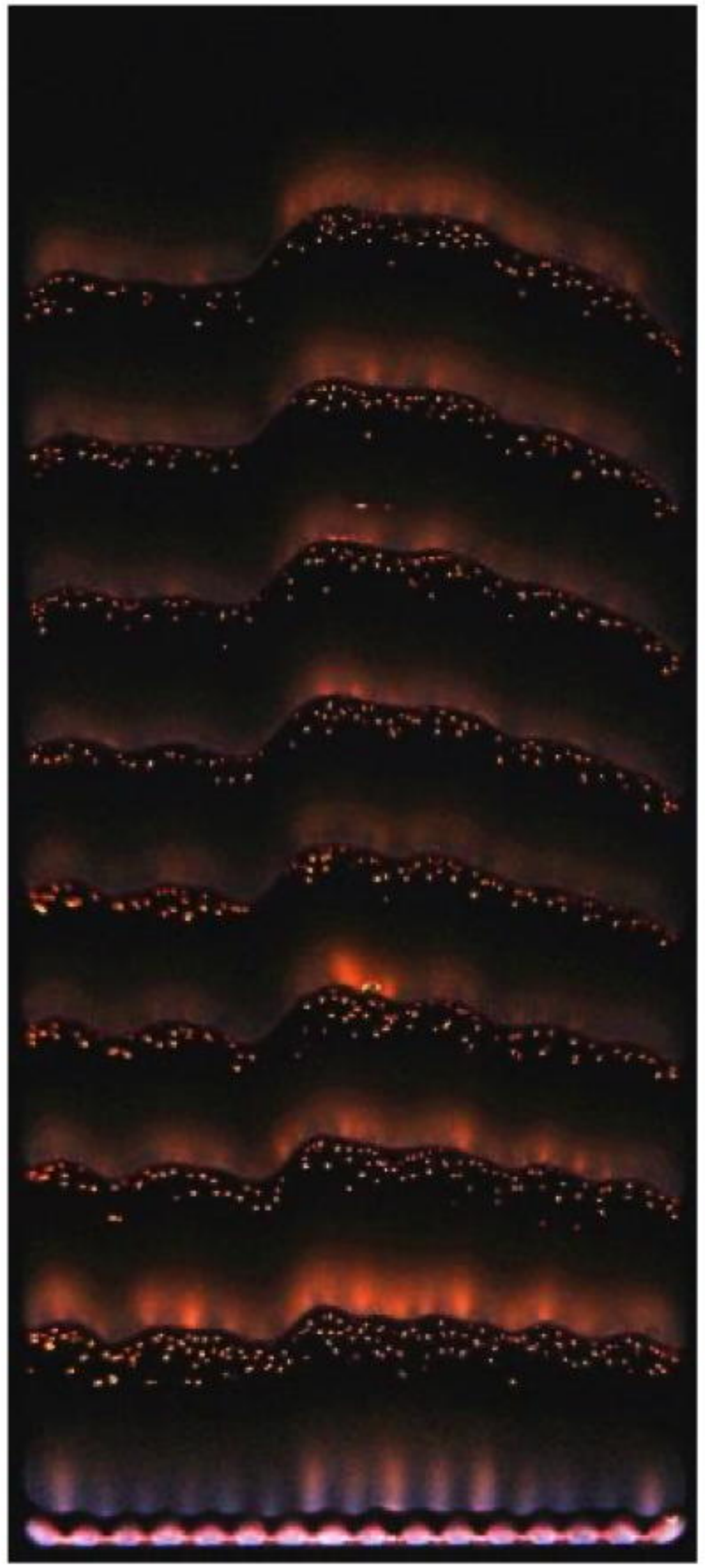
Flow (25 cm/s) ↑

Image of the Saffire-III concurrent (upstream) burn.

Saffire-I and III Results

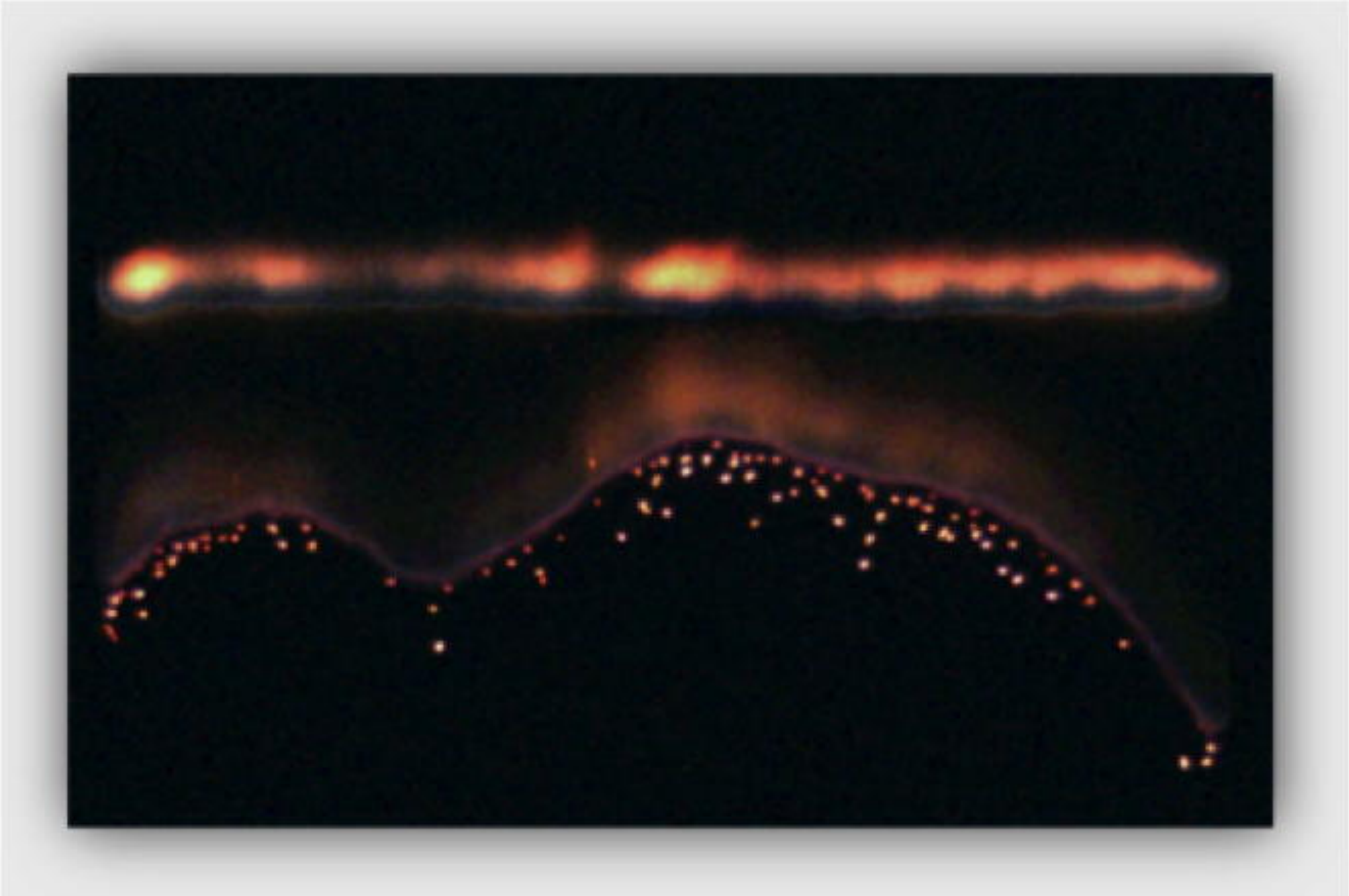
Saffire-I (20 cm/s)

Saffire-III (25 cm/s)



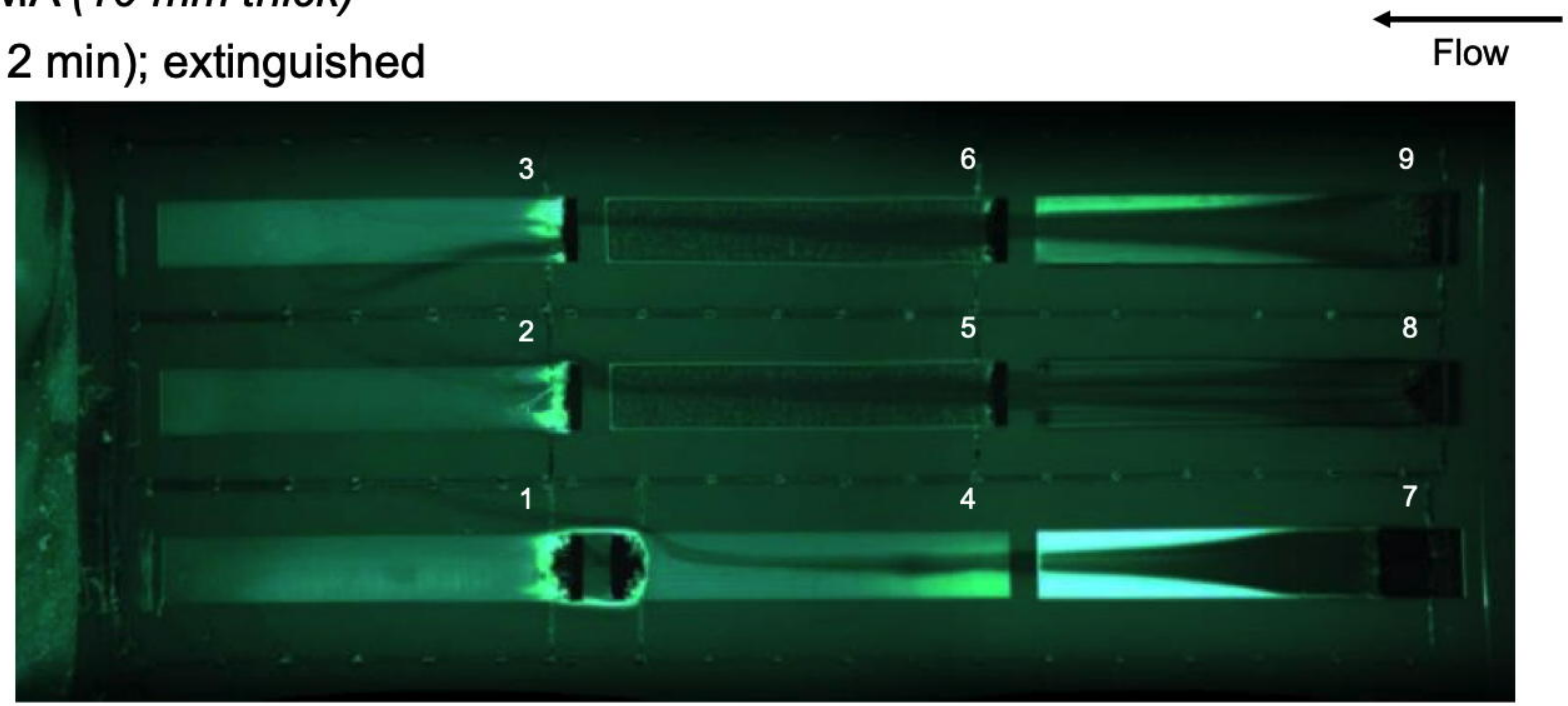
- **Left: Sequence of concurrent flame images from Saffire-I and III.**
  - *Each image is 40-sec apart.*
  - *Saffire-I burned for 400 sec*
  - *Saffire-III burned for 320 sec*
    - ➢ The flame speed is proportional to the air flow velocity
- **Below: Comparison of the opposed (upper) and concurrent (lower) flames from Saffire-III.**
  - *The flame images were taken at different times (near the end of each burn) and superimposed.*

25 cm/s



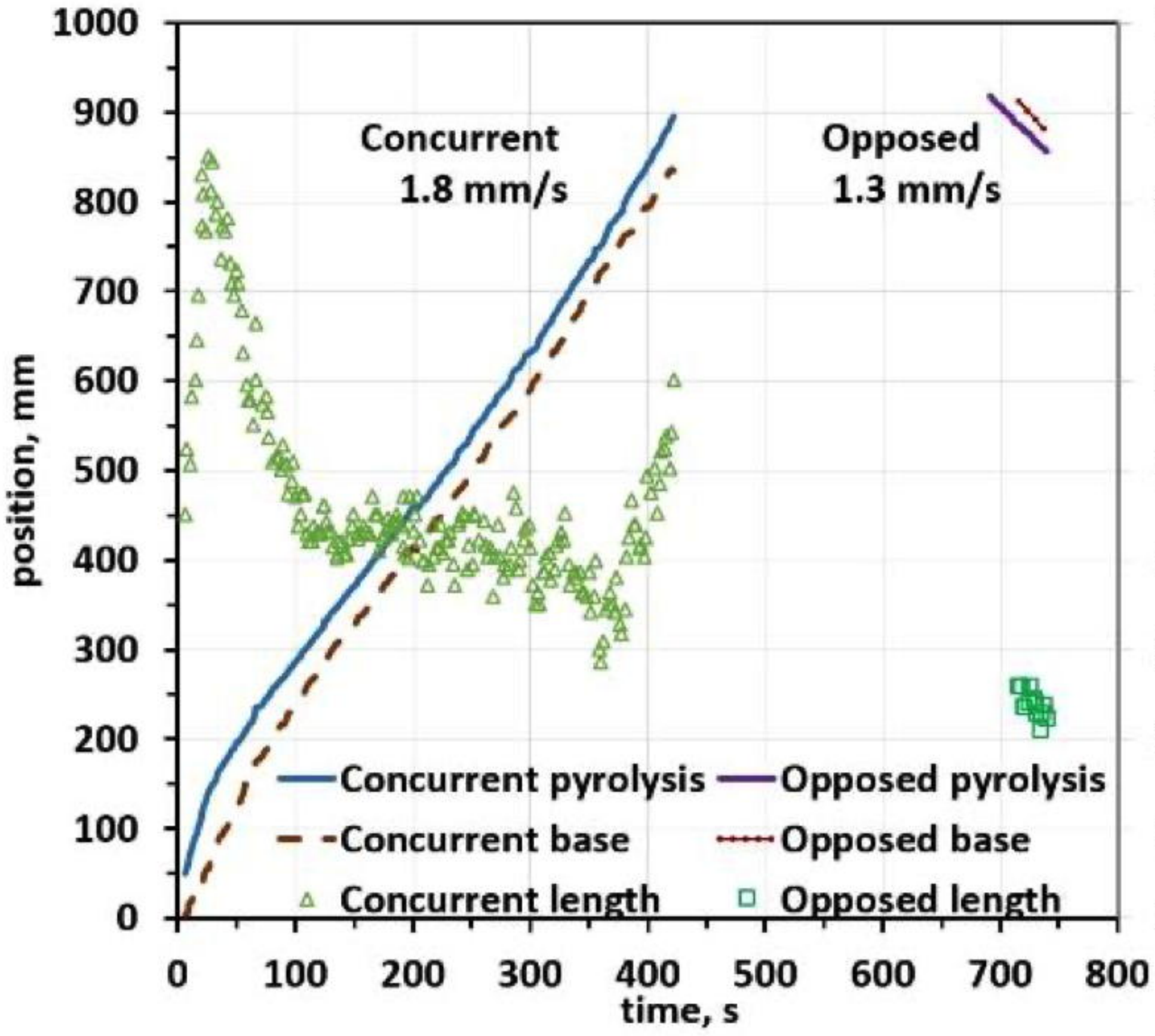
Saffire-II Summary

- Samples 1-4: Silicone sheets of varying thickness *(0.25 mm, 0.61 mm, 1.03 mm, 0.36 mm respectively)*
  - Samples ignited but flame did not propagate
- Samples 5-6: SIBAL cloth *(20 cm/s and 25 cm/s - same as Saffire-I and III)*
  - Burned to completion
- Sample 7: Nomex with PMMA igniter *(1 mm thick PMMA)*
  - PMMA burned ; flame did not propagate into Nomex
- Sample 8-9: Structured and Flat PMMA *(10 mm thick)*
  - Burned for the entire duration (6; 12 min); extinguished when flow ceased

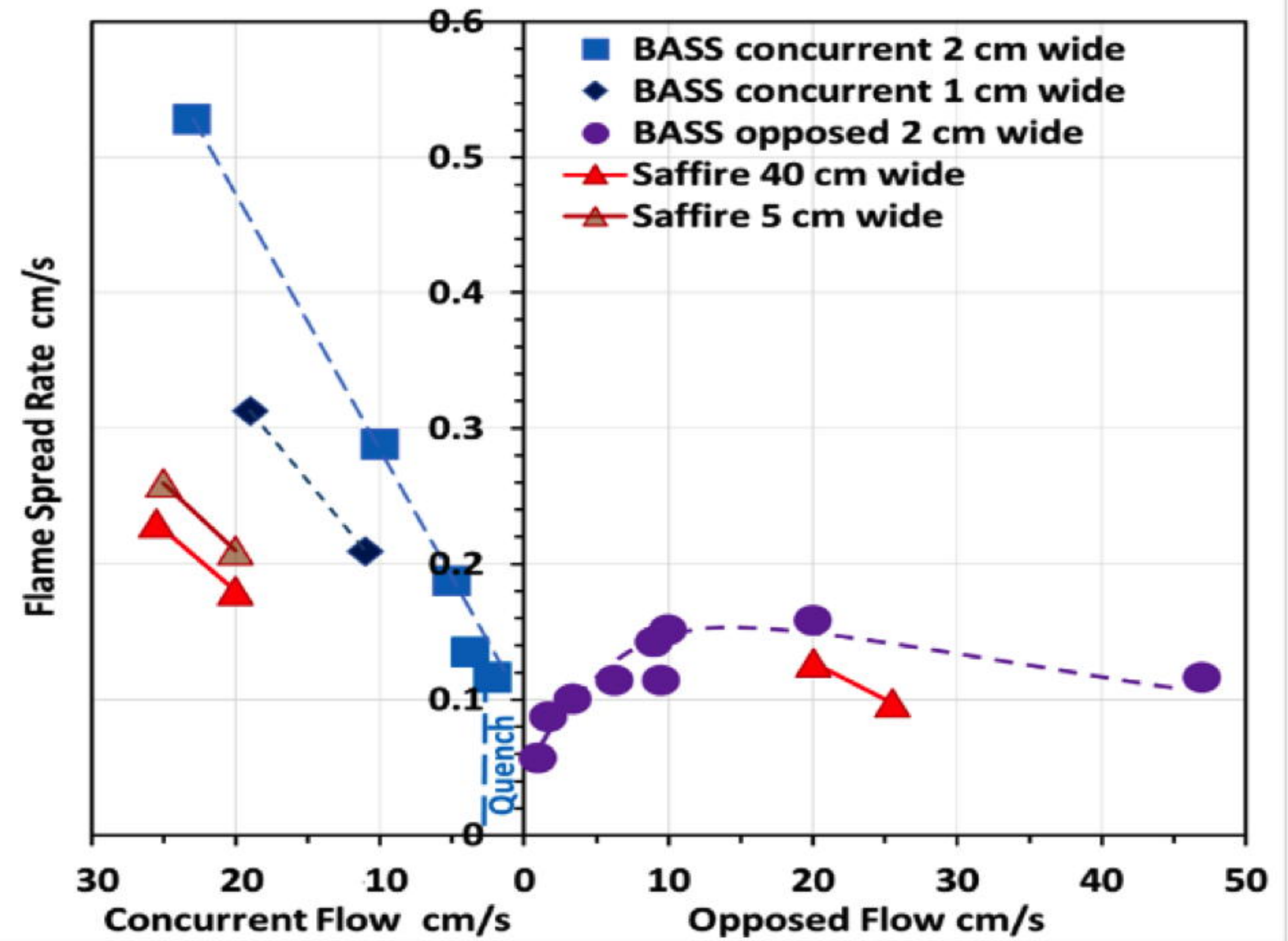


Composite picture of samples 1-9 at end of experiment. *Streaks are soot from Samples 7-9 deposited on card.*

Saffire-I-III Results



Measurements of flame base, pyrolysis tip, and pyrolysis length from concurrent and opposed burns from Saffire-I. *The flame base is the most upstream portion of the flame and is bright and well-defined. The pyrolysis tip is the most downstream portion of the blackened (charred) fuel. The fuel was a 40.6-cm-wide cotton-fiberglass fabric. Air flow speed was 20 cm/s.*



Spread rate summary for Cotton/Fiberglass fabric burning in microgravity

Summary of Saffire Results…*So Far!*

Saffire-I & III

- Flame reaches a limiting length in forced convective concurrent flow even for very wide sample
  - Implies a steady spread rate and a limiting heat release rate
  - *A fire on a spacecraft vehicle may reach a steady size (?)*
- Concurrent flame spread is proportional to the flow velocity
- Concurrent flame spread rate was much slower than expected from previous space experiments
  - 65% less than observed in Burning and Suppression of Solids experiment on ISS
  - *What is the impact of slower growth on release of combustion products? On fire detection? How does this depend on flow velocity?*
- Proximity to and interaction with side walls appears to impact the flame more than expected
  - *Needs to be better understood through computational models; Review results of previous microgravity experiments*
- Opposed flames spread at about the same rate as concurrent flames
  - *How does this depend on flow velocity?*
  - *Are concurrent flames always the worst case for microgravity fires?*
- We need to make a bigger fire to impact the vehicle

Summary of Saffire Results…*So Far!*

Saffire-II

- Materials that burned all had slower spread rates than expected
  - *Composite fabric, PMMA*
- Flame spread rates on composite fabric were similar to those seen in Saffire-I
  - Rapidly reached a steady spread rate and a limiting heat release rate
- Examining material flammability limits in microgravity using a limited number of experiments is difficult
  - Repeat cases are required to understand the competing phenomena

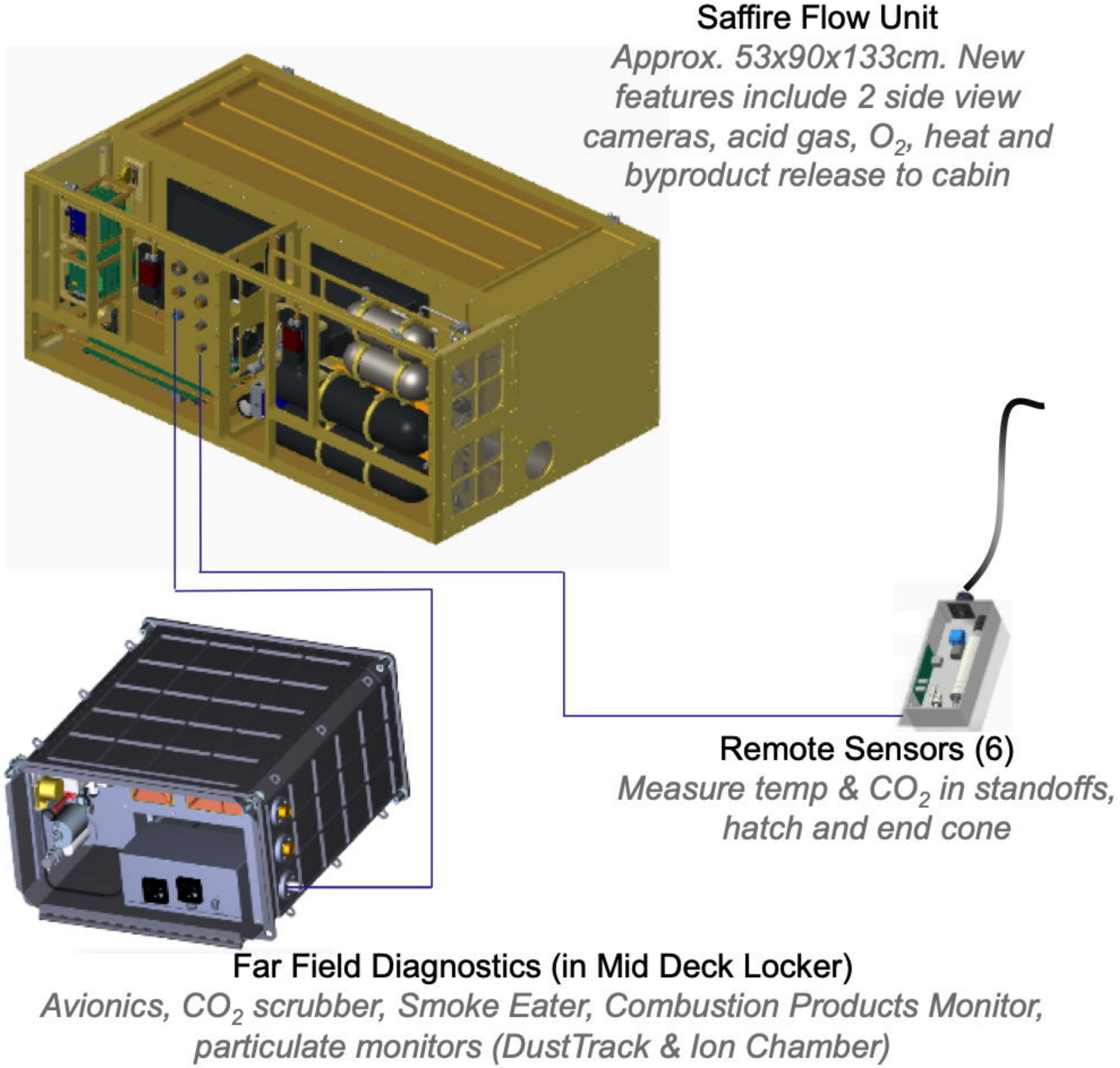
Saffire-IV, V, and VI Summary

Needs:

- Demonstrate spacecraft fire monitoring and cleanup technologies in a realistic spacecraft fire scenario
- Characterize fire growth in high O_2, low pressure atmospheres
- Provide data to validate models of realistic spacecraft fire scenarios

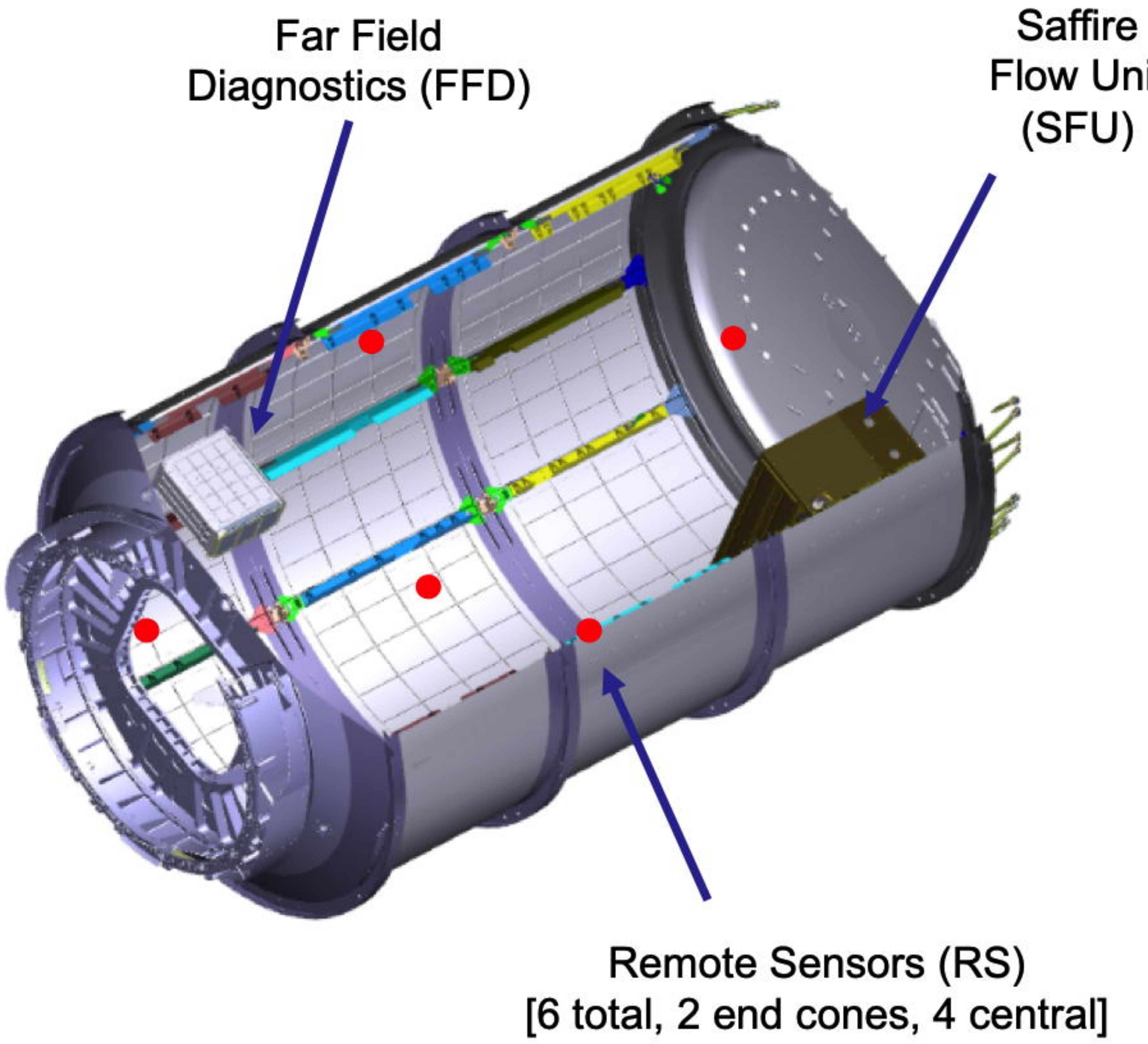
Objectives:

- *Saffire-IV*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release) in exploration atmosphere
- *Saffire-V*: Evaluate fire behavior on realistic geometries
- *Saffire-VI*: Assess existing material configuration control guidelines
- All flights will demonstrate fire monitoring and response technology



Saffire-IV, V, and VI Experiment Concept

- Concept consists of three distinct hardware locations
  - Saffire flow unit
  - Far-field diagnostic
  - Distributed sensors
- Far-field diagnostic module
  - Combustion product monitor
  - CO and CO_2 sensors
  - Post-fire cleanup module
- Distributed sensor network
  - Temperature
  - CO_2

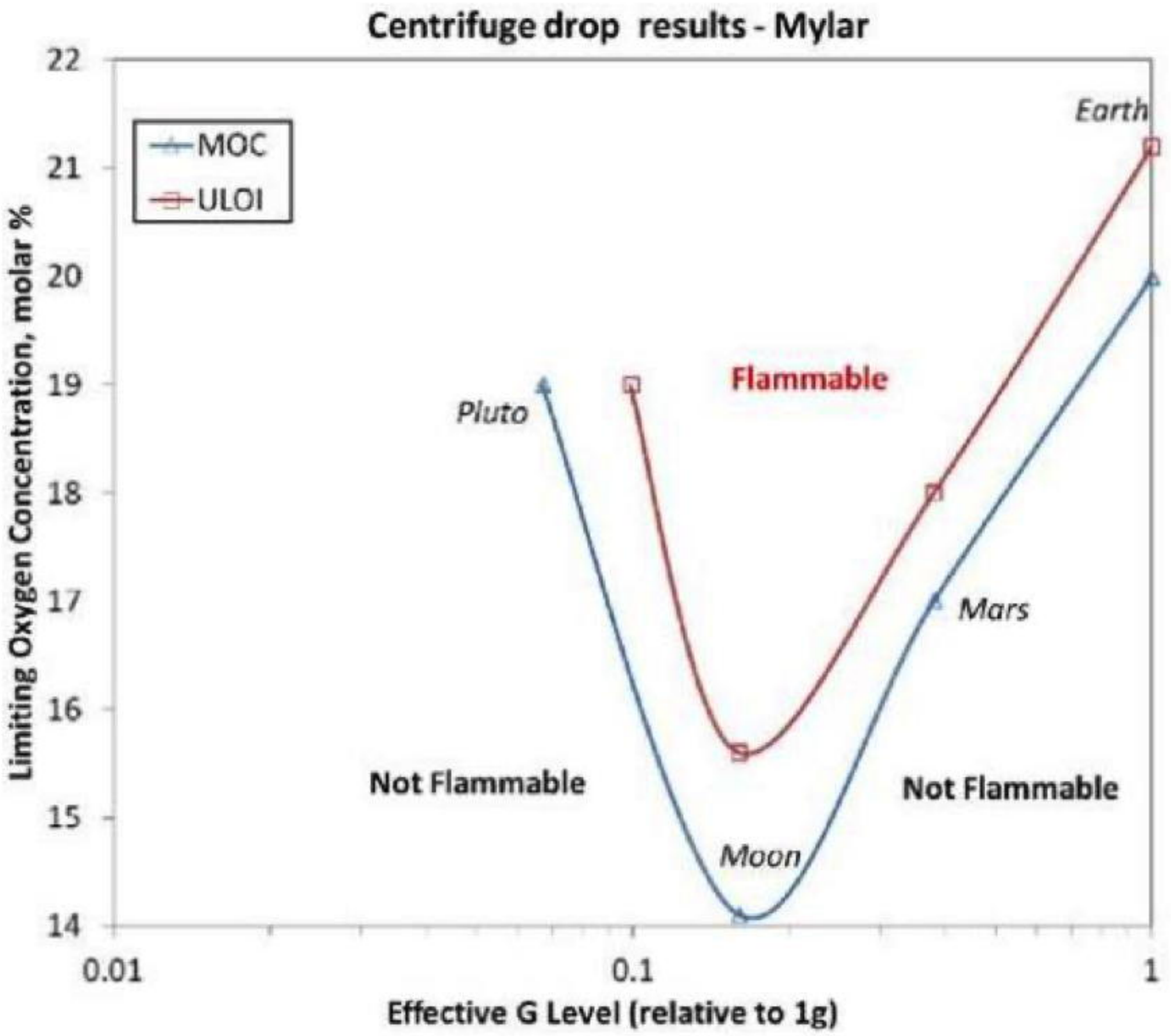


Expected Results of the Saffire-IV, V, and VI Experiments

- Flammability in normal and exploration atmospheres
  - Traceability to Saffire-I, II, and III
- Oxygen calorimetry for a large-scale microgravity fire
  - Rate of heat release for fire scenario modeling
- Rate of change of cabin pressure and temperature during a large-scale fire
- Transport and mixing of an inert gas (CO_2)
  - Fire detection
  - Fire scenario modeling
- Demonstration of advanced combustion product monitor to quantify CO, CO_2, and acid gases (HF, HCl)
- Transport/decay of acid gases in a post-fire environment
- Demonstration of advanced sorbents for cleanup of CO and CO_2
  - Sizing of smoke-eater for exploration applications

Other Considerations for Exploration

- Dormancy
  - Many of the mission scenarios include vehicles that are uncrewed and in a dormant state for extended periods of time.
  - Dormancy impacts protocols for detection, suppression and cleanup
    - Dormancy before crew arrives
    - Dormancy between crew visits
- Partial Gravity
  - Habitats on a anticipated planets, moons, or asteroids will have buoyant convection but at a smaller flow velocity than Earth
  - There are limited facilities on Earth in which we can conduct partial-gravity flame spread tests



Ferkul, P.V. and Olson, S.L., "Zero-gravity Centrifuge Used for the Evaluation of material Flammability in Lunar-Gravity," AIAA 2010-6260, 40th International Conference on Environmental Systems, Barcelona, Spain, July 11-15, 2010.

Fire Safety Strategy Depends On Vehicle State During Dormancy

- Is there ECLSS ventilation?
  - Pro: can use ventilation for fire detection
  - Con: first response is to terminate ventilation after a fire alarm
  - *Impact: When can ventilation be re-initiated?*
- What is the atmospheric composition?
  - Lower O_2 mole fraction (<15%), lower P, T reduces fire risk - periodic monitoring
  - Maintaining habitable environment requires continuous monitoring
  - Pro: can make the atmosphere unable to support combustion
  - Con: must increase O_2 mole fraction before crew returns
  - *Impact: Does increasing O_2 for a "short" time increase risk significantly?*
- What systems are powered during dormancy?
  - Pro: can monitor system state for abnormal current draw; terminate power if an electrical short is detected
  - Con: powered systems are the most likely ignition source
  - *Impact: When can power be restored?*

Fire Safety Strategy Depends On Vehicle State During Dormancy

- Is there gravity?
  - Pro: In microgravity, termination of ventilation and power will most likely be effective for fire suppression
  - Con: In a gravity field, propagation of fire is uncertain even if ventilation and power is removed
  - *Impact: When can power and ventilation be re-initiated?*
- If a fire is detected, at what point do you initiate an active response?
  - How do you confirm that any passive responses were not effective?
    - Monitoring is effective but takes time
    - Visual confirmation of the vehicle state would be effective
  - Pro: An active response can assuredly extinguish a fire
  - Con: (1) An active response changes the state of the vehicle
    (2) Active response during dormancy requires a fixed fire suppression system; mass, risk of failure (on or off)
  - *Impact: Clean-up of the suppression agent. When can power and ventilation be re-initiated?*

Summary

- Low- and partial-gravity impacts many areas of the combustion process and, therefore, spacecraft fire safety
- Mission scenarios play a major role in determining the fire hazard…
  … and fire safety is never the driving factor!
- The Saffire missions were developed to investigate many of the knowledge gaps in spacecraft fire safety
  - Saffire-I-III primarily investigated flame spread and material flammability limits
- Future Saffire missions will investigate advanced material flammability questions as well as fire/vehicle interactions
  - Missions will also demonstrate technologies needed to protect the spacecraft and crew
- Periods of spacecraft or habitat dormancy pose unique hazards for fire safety
  - Primarily operational issues rather than new technology development
  - Need to have data in hand so that the operational environment and configuration can be appropriately analyzed

ISS Fire Detection and Suppression System

- Slides from Alana Whitaker, ISS ECLS Subsystem Manager, Fire Detection and Suppression Systems, NASA Johnson Space Center
- June 25, 2001

Intro to FDS on ISS

- Fire Detection and Suppression (FDS) includes:
  - Detection of smoke
  - Isolation of fires
  - The means to extinguish fires
  - The means to recover from fires

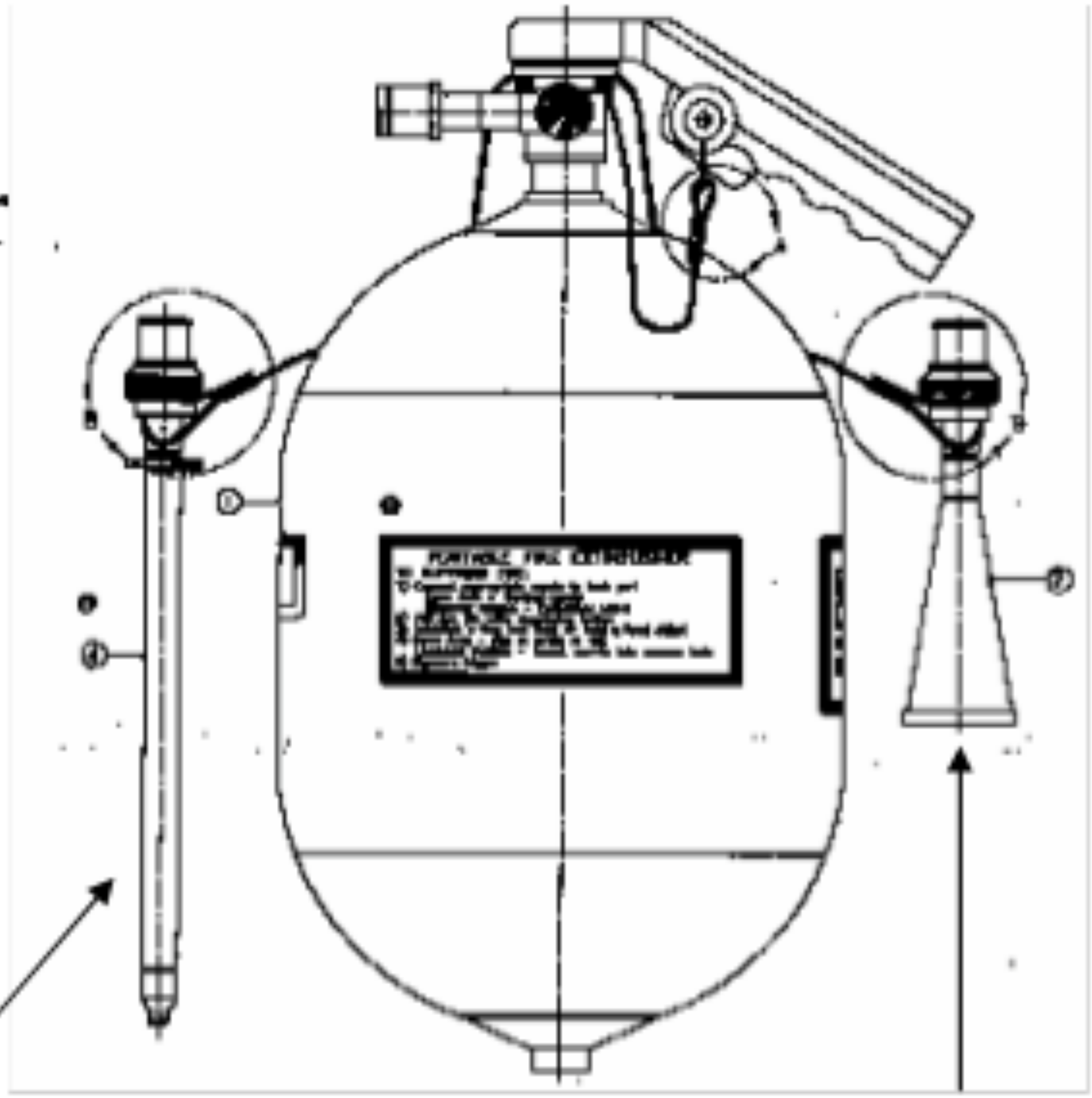
Portable Fire Extinguisher (PFE)

PFE w/Cover (config. on orbit)

PFE w/o Cover

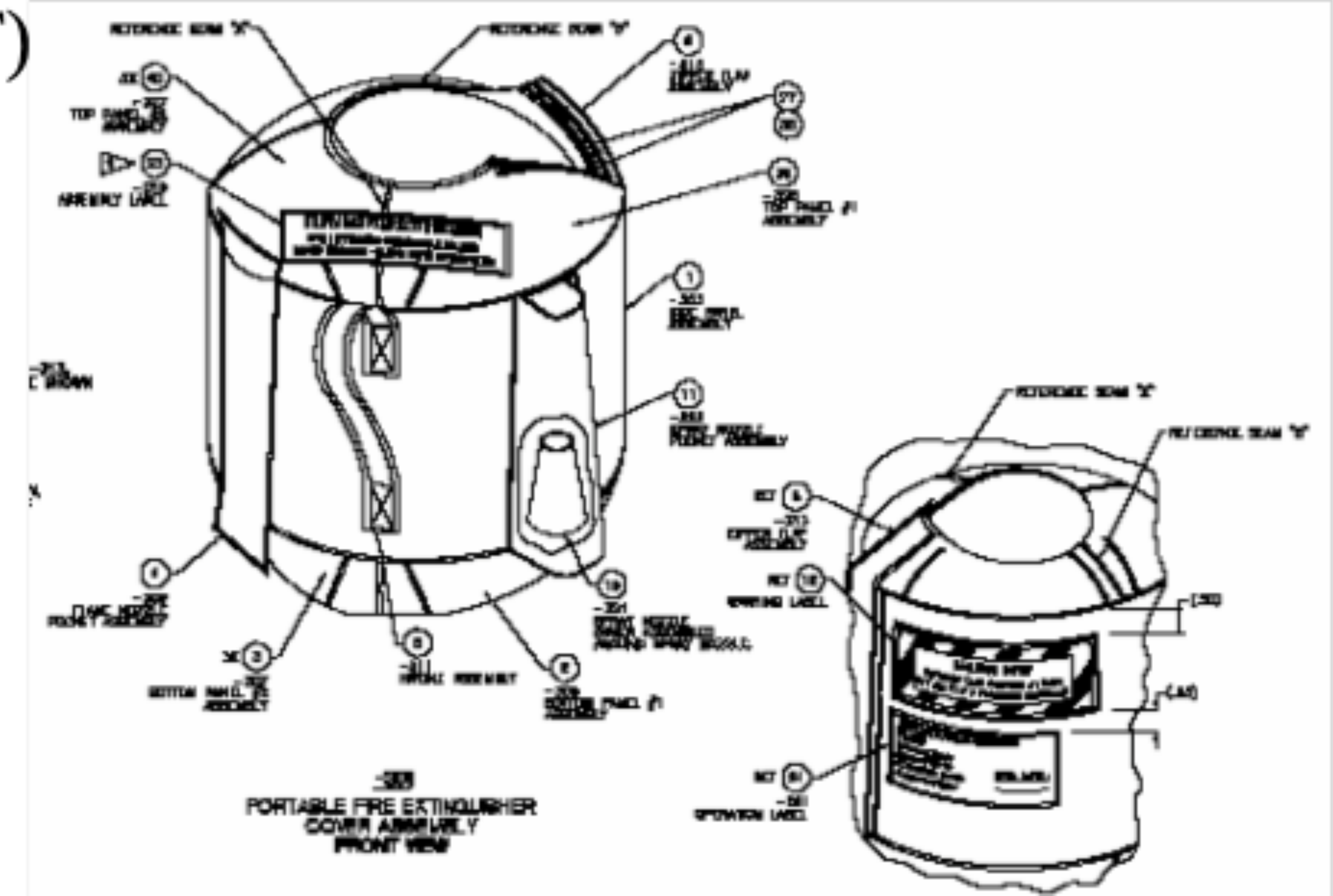
Portable Fire Extinguisher (PFE)

- PFE Characteristics
  - Contains 6 lbs CO_2 at 850psi
  - Discharges in 45 sec.
  - Has two nozzles:
    - Conical Nozzle (open area nozzle) for open area suppression
    - Cylindrical Nozzle (closed volume nozzle) for suppression
      in closeout fire ports



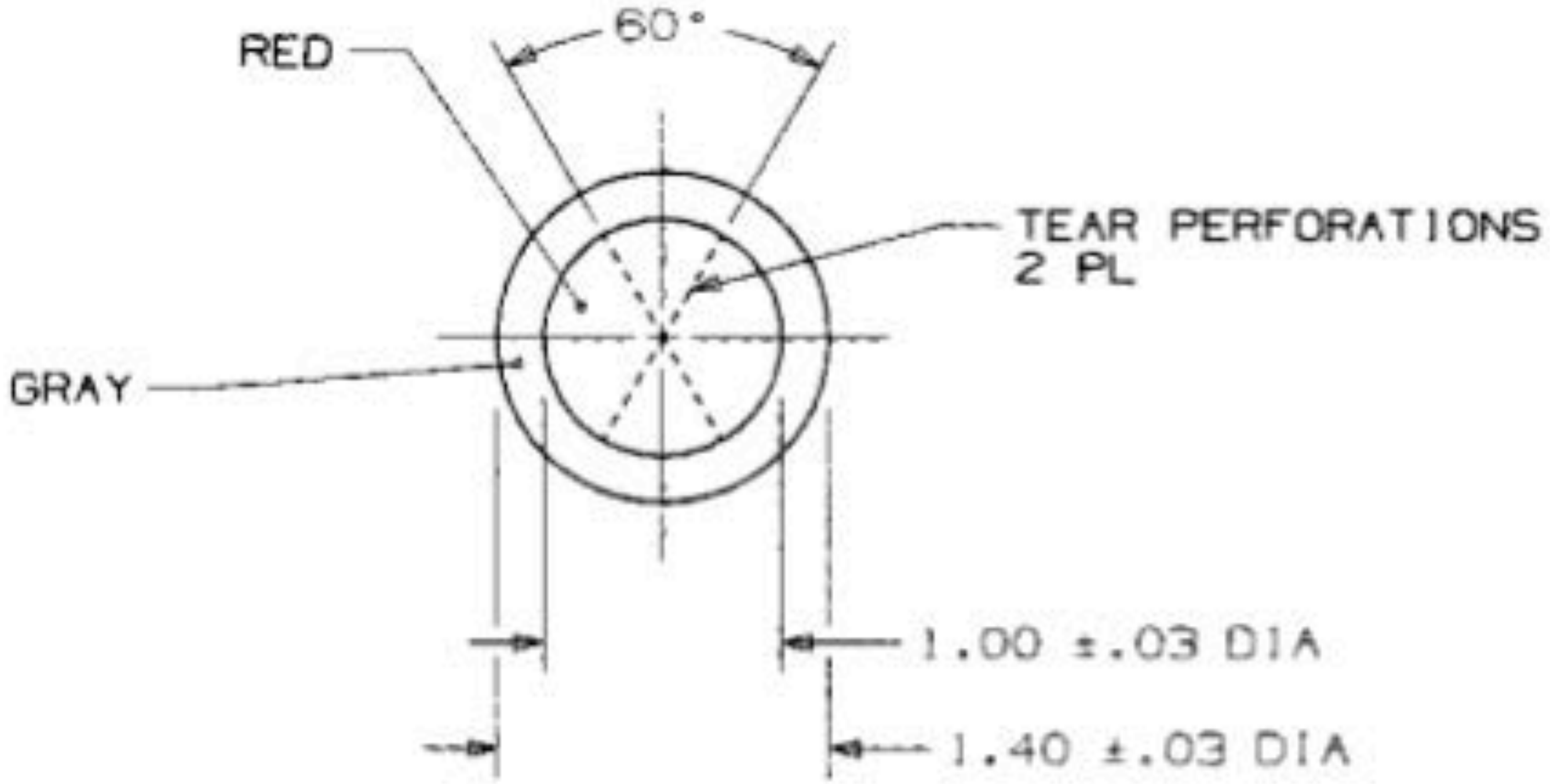
PFE Cover

- PFE Cover Characteristics
  - Made of Nomex
  - Fits snuggly to PFE
  - Keeps PFE within allowable touch temp. limits during discharge (w/o Cover, PFE reaches 0 deg. F and nozzle -32 deg. F)

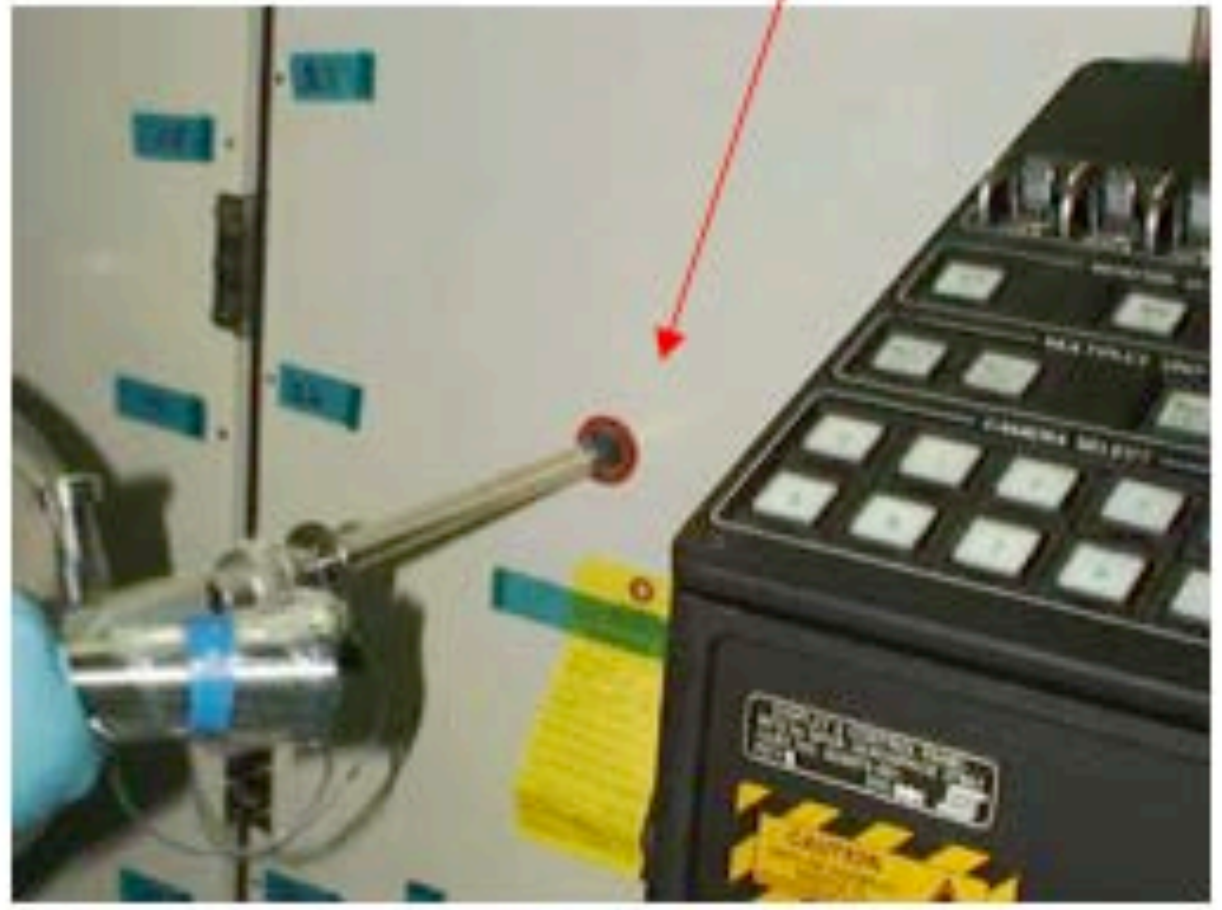


Fire Suppression Ports

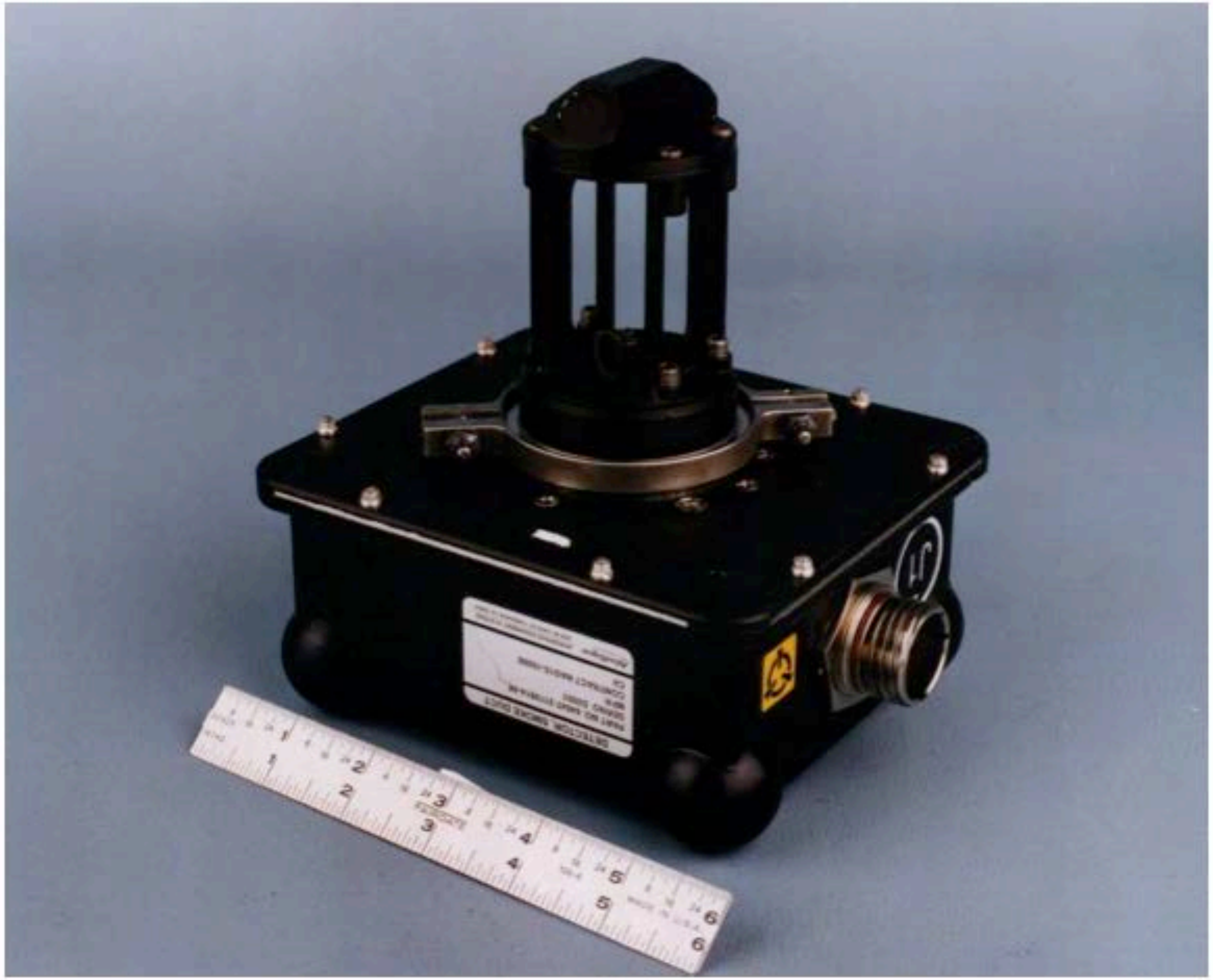
- 1” or 0.5” diameter perforated access ports in racks and standoffs for the cylindrical nozzle (enclosed area nozzle) to suppress fires
- O2 concentration in a rack is reduced to < 10.5% within 1 min of suppression.



Suppression port nozzle inserted into suppression port



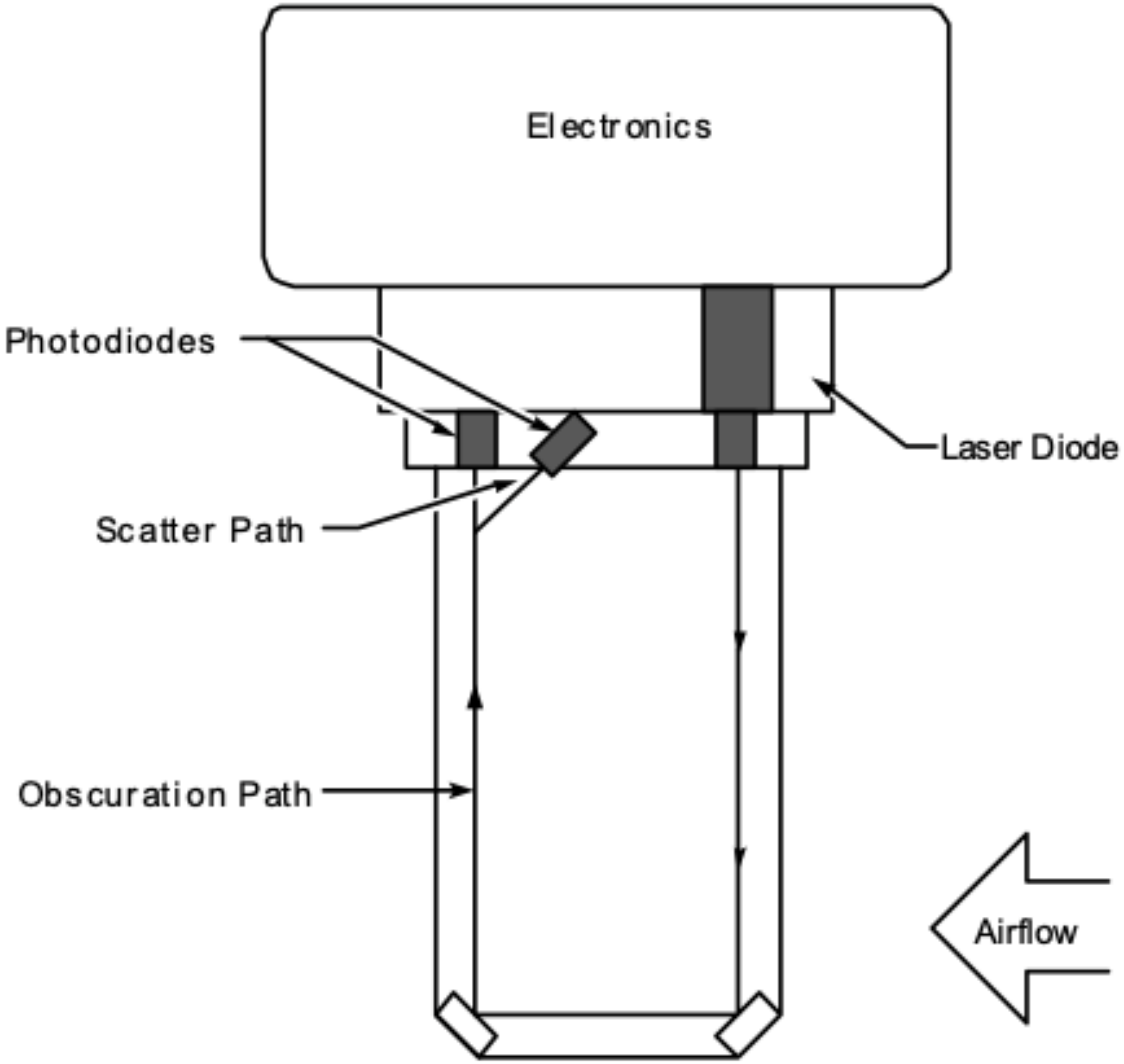
Smoke Detector



Smoke Detector

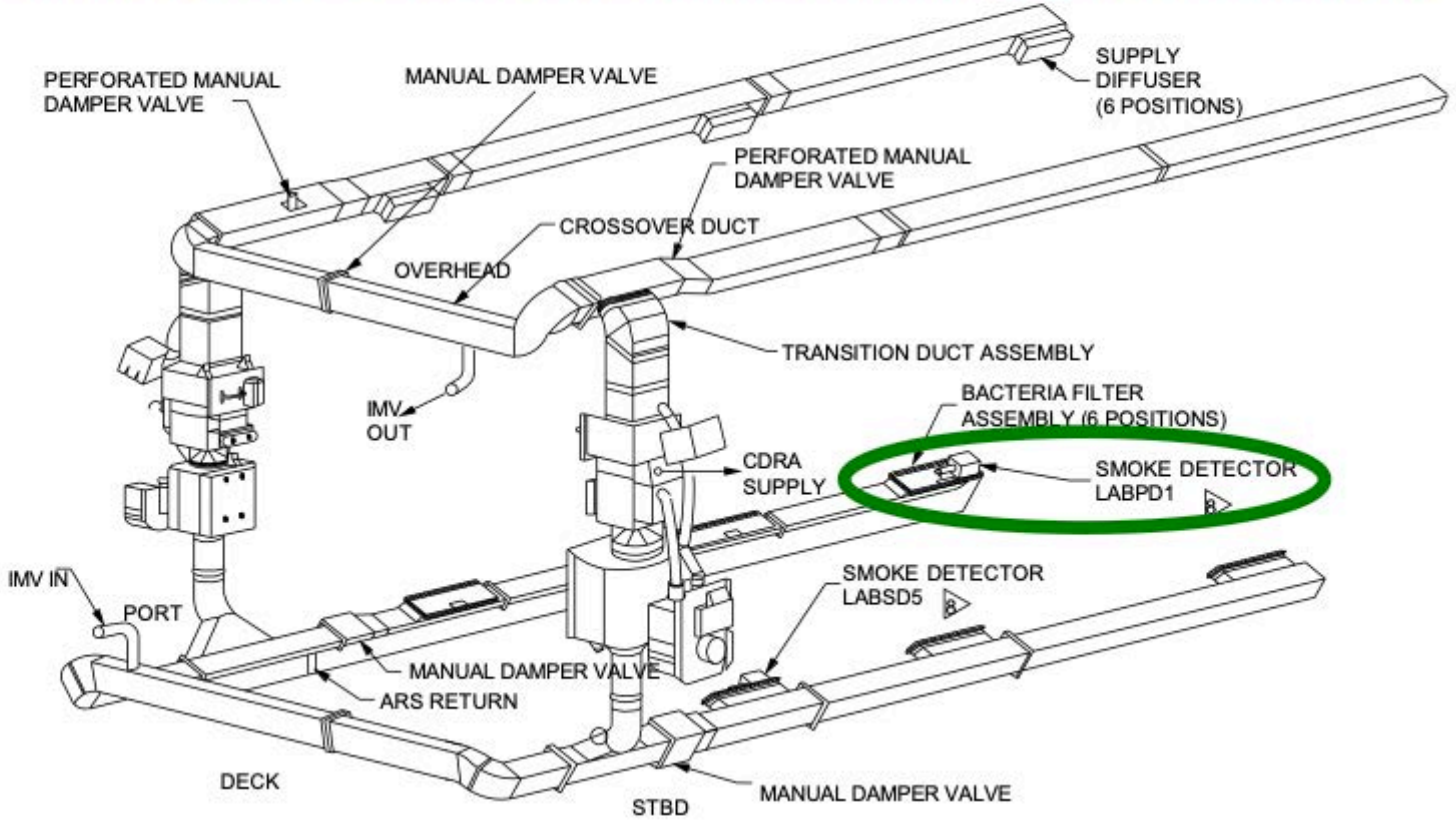
- Photoelectric Smoke Detector
  - Based on smoke particles scattering a light beam
  - Light from a laser source is reflected by mirrors back to a photodiode (obscuration).
  - Scattered light is measured by a second photodiode (scattering)
  - Alarms are based on the voltage level generated by the scattering photodiode.

Smoke Detector Principle



Smoke Detectors in Ventilation

- Smoke Detectors are located on the ventilation filter intake ducts.



Lab Cabin Air Temperature and Humidity Control Assembly with Smoke Detectors

Total and Oxygen Partial Pressure Control Not In Campout Mode

- Pressure control when Not in Campout Mode (nominal) is done with closed-loop control
  - Total Pressure
    - The PCPs will be taking constant (1 Hz) total pressures
    - If the total pressure drops below 14.25 psia the Nitrogen Isolation Valve in the primary PCP will open
    - When the total pressure >= 14.3 psia the Nitrogen Isolation Valve in the primary PCP will close
  - Oxygen Partial Pressure
    - The MCA will be making constant readings of the Station atmosphere
    - If the oxygen partial pressure drops below 3.00 psia the Oxygen Isolation Valve in the primary PCP will be opened
    - When the oxygen partial pressure >= 3.05 psia the Oxygen Isolation Valve in the primary PCP will close

Total and Oxygen Partial Pressure Control In Campout Mode

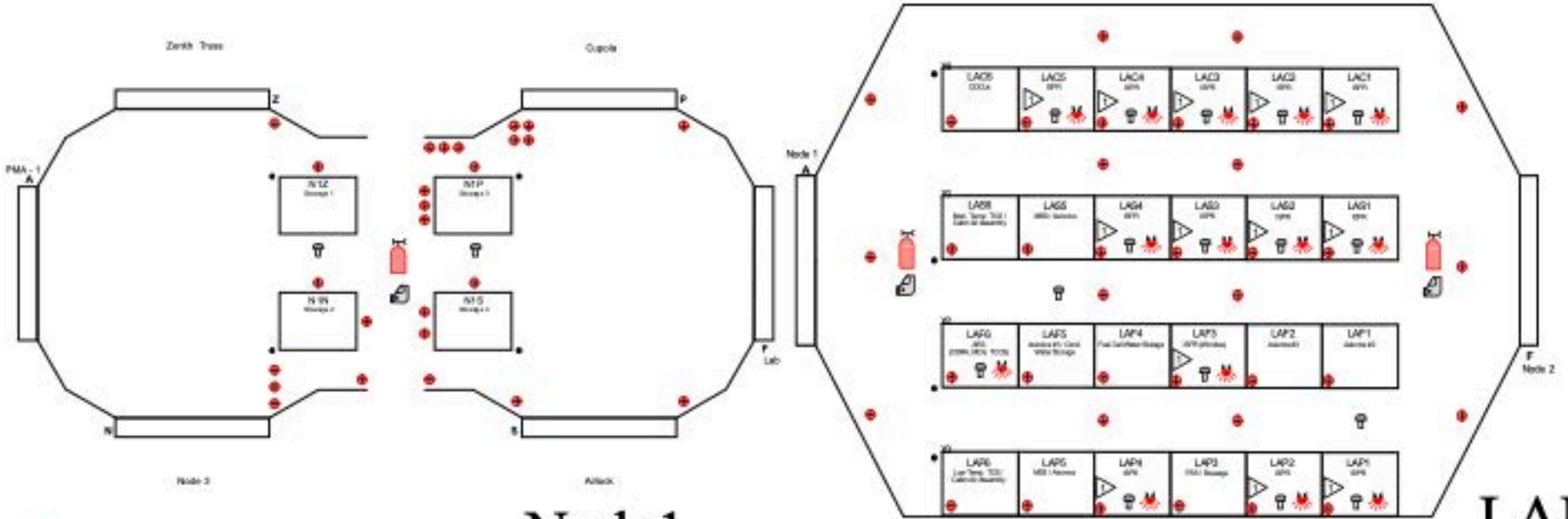
- While in Campout Mode, the ppO2 in the Airlock will be controlled by the following:
  - If ppO2 < 2.7 psia in the Airlock, the Airlock PCA will open the PCP OIV for 4 minutes +/- 10 seconds
  - If the ppO2 > 2.85 psia in the Airlock, the Airlock PCA will open the PCP NIV for 2 minutes +/- 2 seconds
  - If either the PCP NIV or OIV was opened, wait 11 minutes after the valve closes
  - Repeat
- Total pressure control is via manual operation of the Depress Pump
- The rest of Station will continue to control total and oxygen partial pressures in the standard method

Portable Breathing Apparatus (PBA)

Portable Breathing Apparatus (PBA)

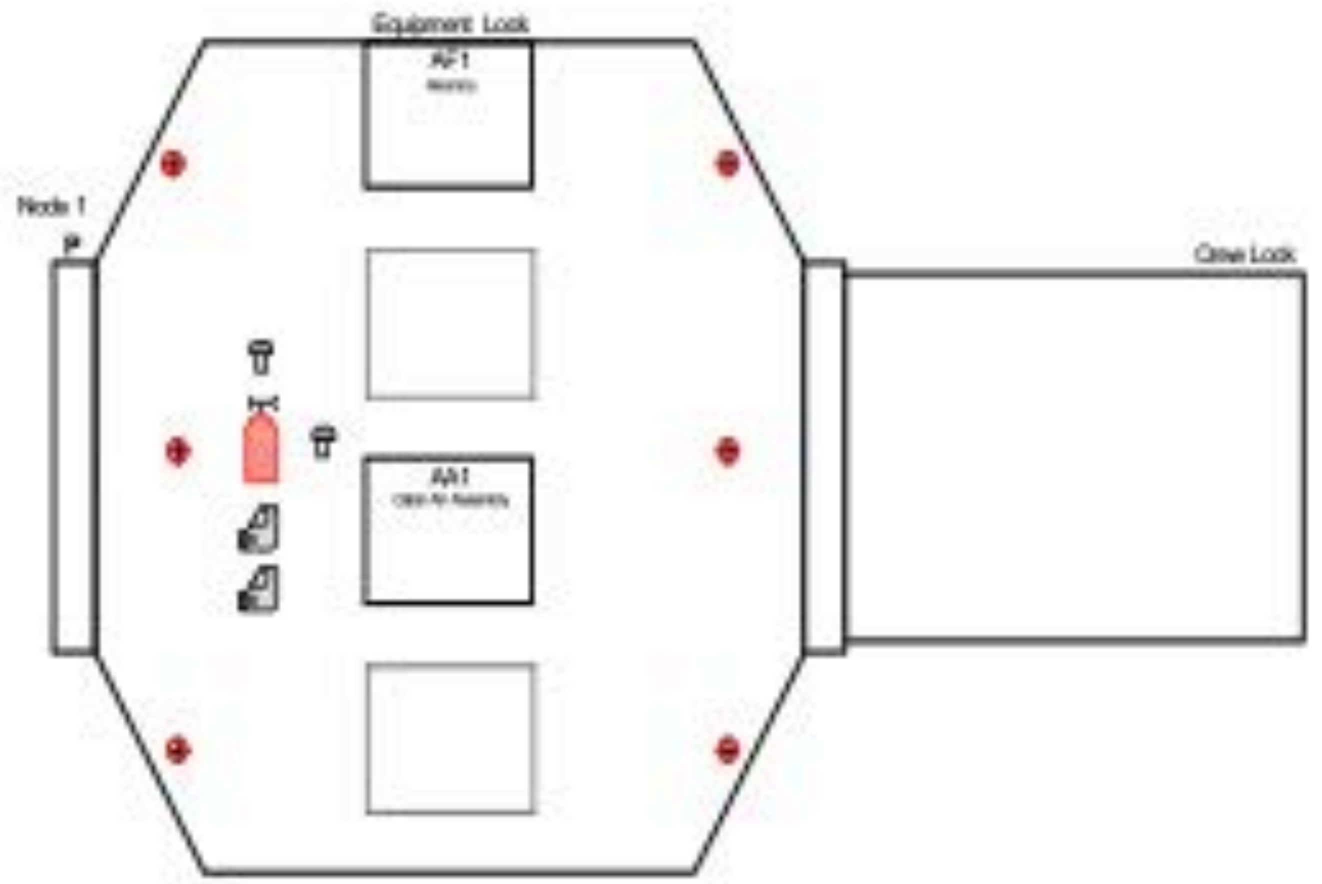
- PBA is composed of:
  - Mask
  - 15 minute O_2 bottle
  - 30’ hose
- Provides O_2 to crew in emergency situations
  - Post-fire clean-up
  - Environmental contamination
  - Depressurization

FDS System Component Location



Node1

LAB



Airlock

- Suppression Port
- Portable Fire Extinguisher
- Smoke Detector
- Portable Breathing Apparatus
- Visual Indicator (LED)
- ISPR FDS equipment required depends on payload and payload rack integration. These schematics show worst case scenario until payload rack designs are finalized.

FDS Automatic and Manual Response

(Overview)

- In case of fire or smoke
  - The crew can manually push the fire alarm or the Smoke Detectors can automatically initiate the fire alarm to perform the following functions:

    1) Remove power to racks-to isolate ignition sources

    2) Isolate module by shutting off ventilation (close IMVvalves, sample delivery systems, cabin fans)-to stop air flow within module and exchange between modules

    3) Inhibit introduction of O_2 and N_2 into module (inhibit pressure control assembly in LAB)

Crew can use PFE at their discretion

Post Fire Atmosphere Restoration

- Gaseous Contaminants removed by the following:
  - **SM - Micropurification Unit(БМП)**
    - Removes 19 different gaseous contaminants using a catalytic oxidizer (ambient) and expendable & regenerative charcoal beds.
  - **FGB - Harmful Impurities Filter (ФВП)**
    - Removes gaseous trace impurities (particles of 0.5 to 300μm to a level of 0.15 mg/m^3).
  - **Lab - Trace Contaminant Control Subsystem (TCCS)**
    - Removes gaseous contaminants using a catalytic oxidizer (400ºC) and expendable sorbent and charcoal beds. Sorbent contains LiOH which can remove acid gases.

Post Fire Atmosphere Restoration

- **Carbon Dioxide Removal Assembly (CDRA)**
  - Removes CO_2 from the atmosphere that was discharged from the PFE
- **Extra charcoal air filters**
  - Scrub the environment and contain 2% Pt for CO removal.
- **CO_2 Removal Kit (CRK)**
  - Consists of a portable fan assembly with a LiOH cartridge adapter.
  - Can be used with LiOH or ATCO catalyst canister for CO_2 or CO removal
- **Venting module to space**
  - Only in worst case scenario