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

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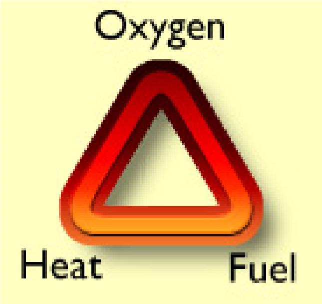
NASA's Risk Management for Spacecraft Fire Safety

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

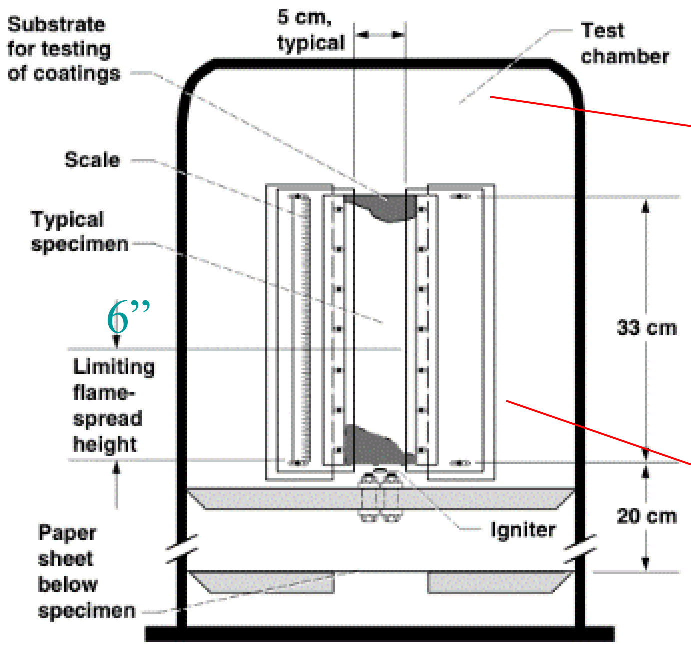
These are the focus of our fire safety activities!

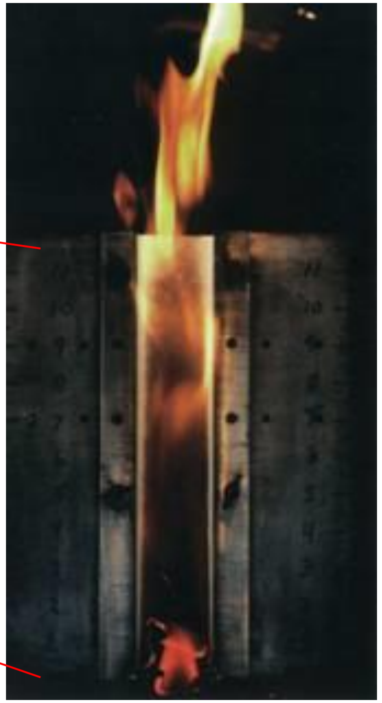
- Tasks "buy-down" the risk of fire for all manned exploration systems

What’s Different in Low-g and Exploration?

♦ 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).

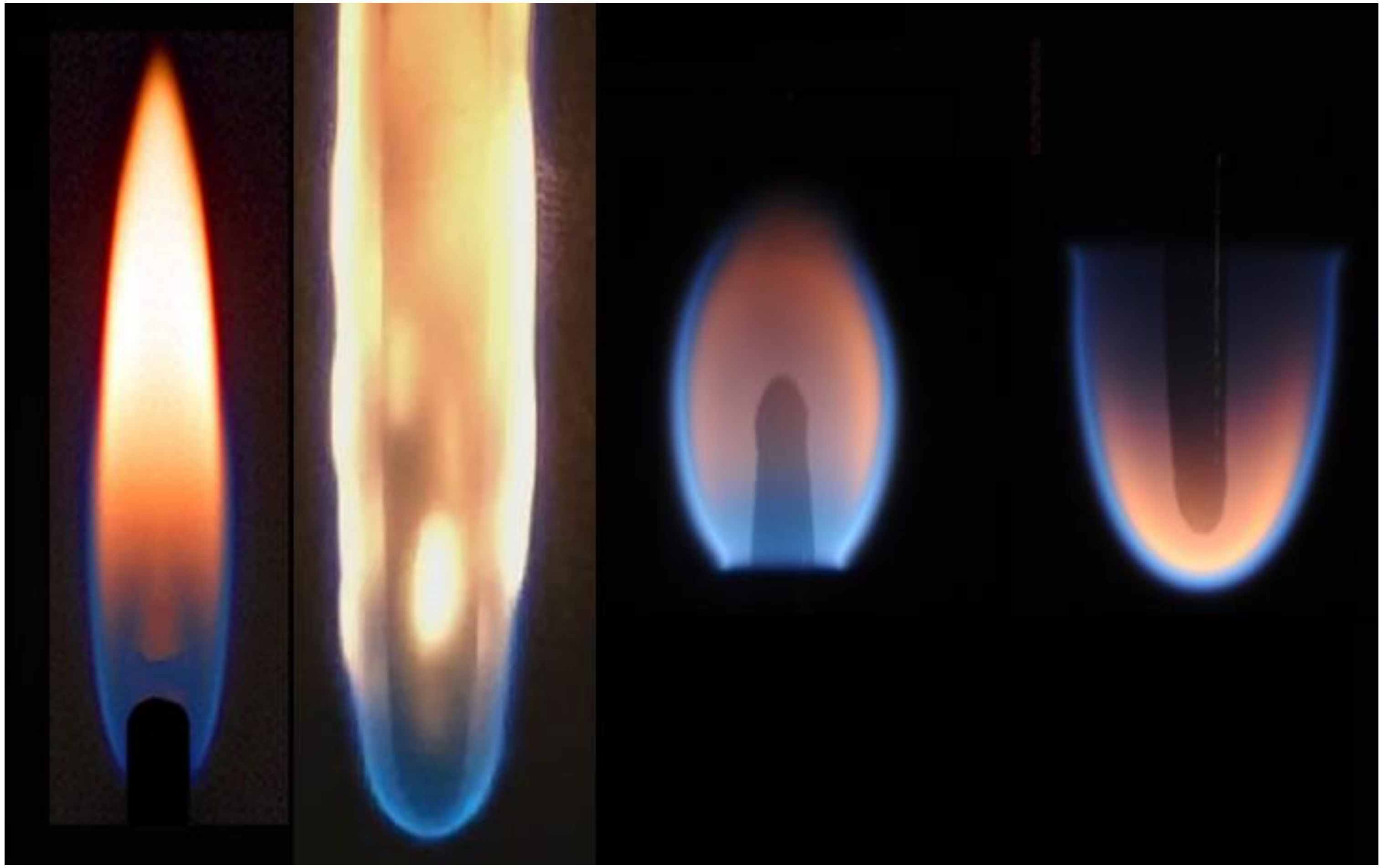




Sample failing NASA Test 1

Gravity

Air Flow is very Important to a Flame



Opposed *Concurrent* *Opposed* *Concurrent*

Normal Gravity (Buoyancy) **Microgravity**

Buoyant or Forced Flow Direction

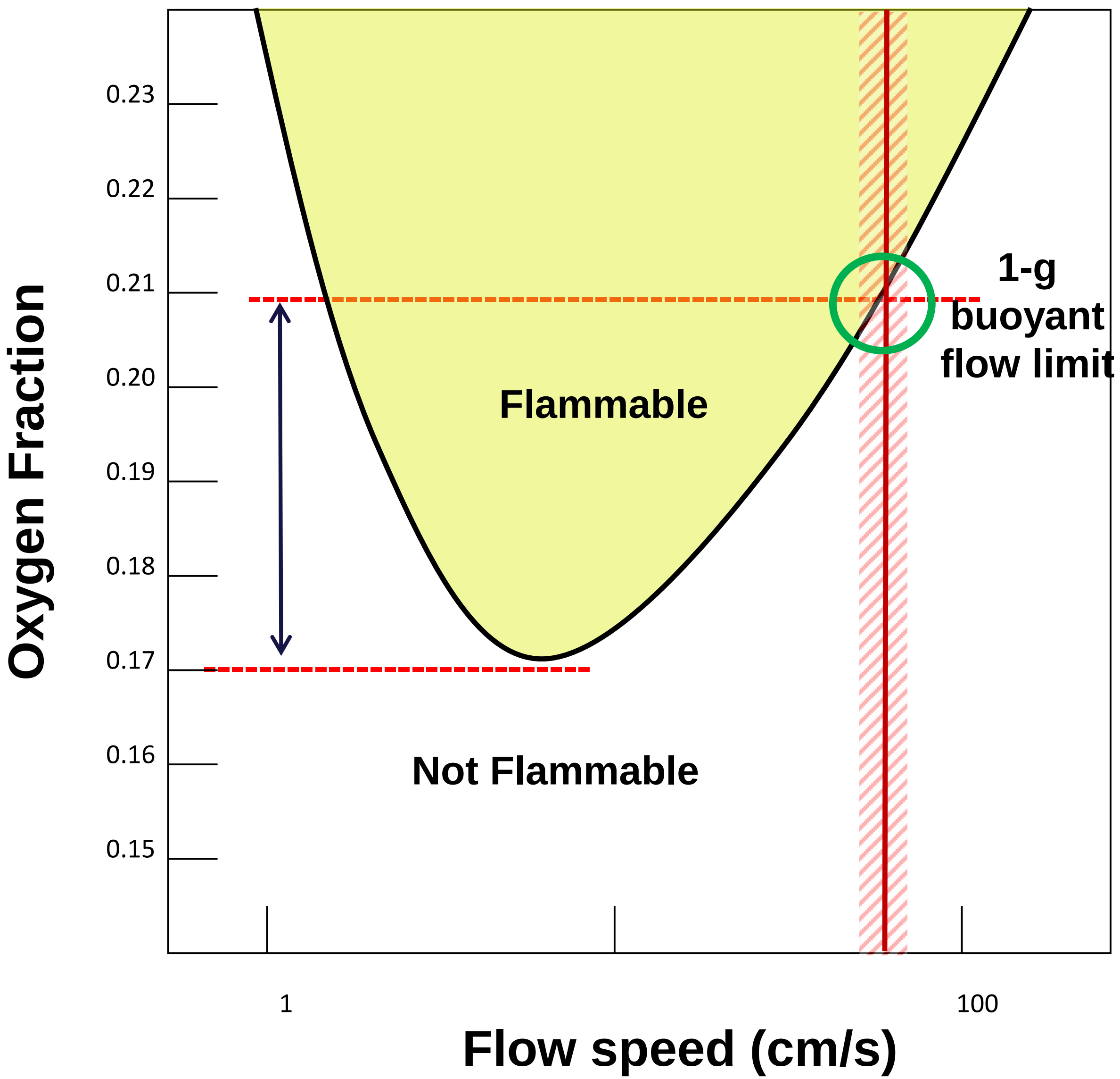
- **What does increasing flow do?**
  - Brings in oxygen
  - Removes heat faster
  - Reduces time for chemical reactions and heating
  - Makes flame closer to the surface (fuel)

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

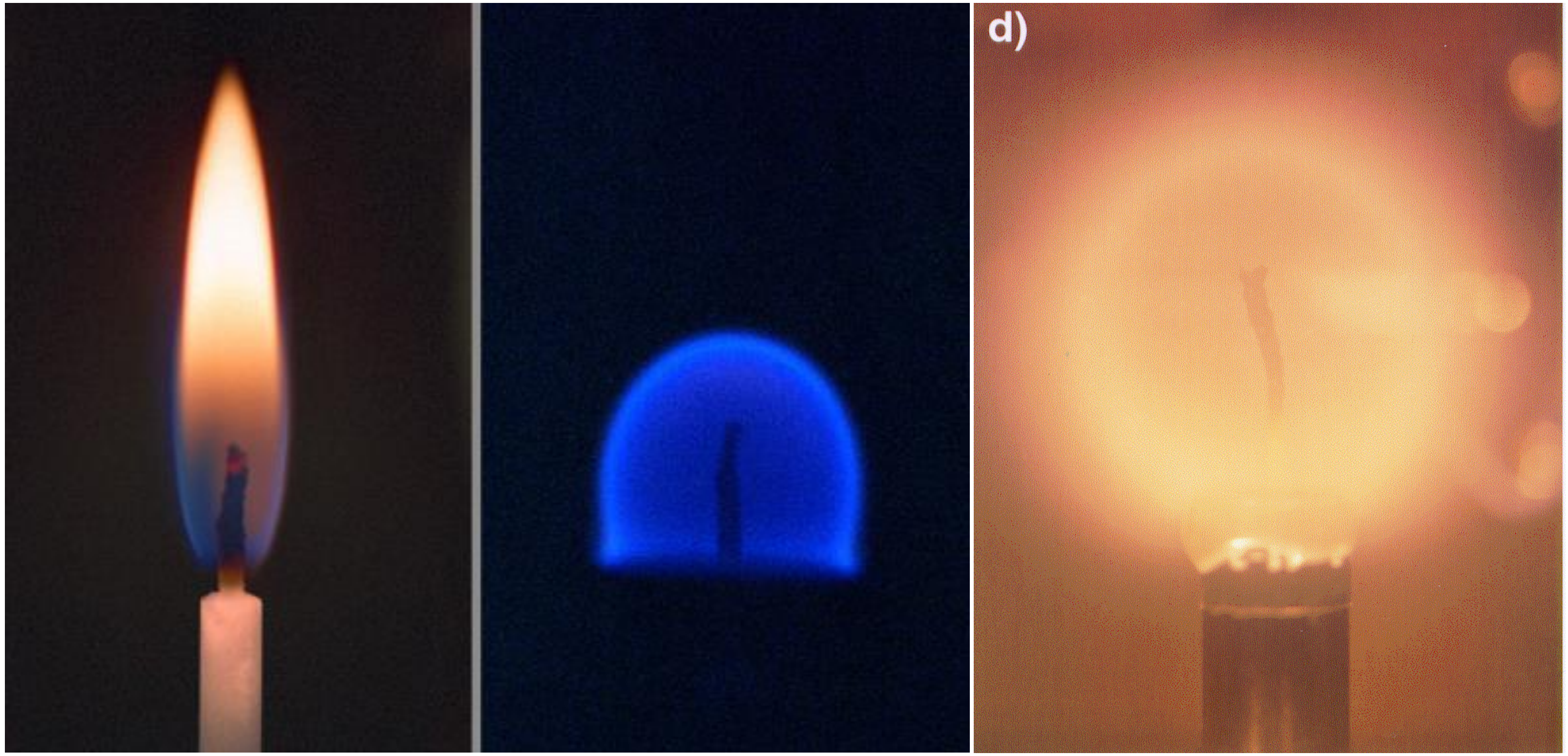
Typical Flammability Boundary for a Solid Fuel



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.

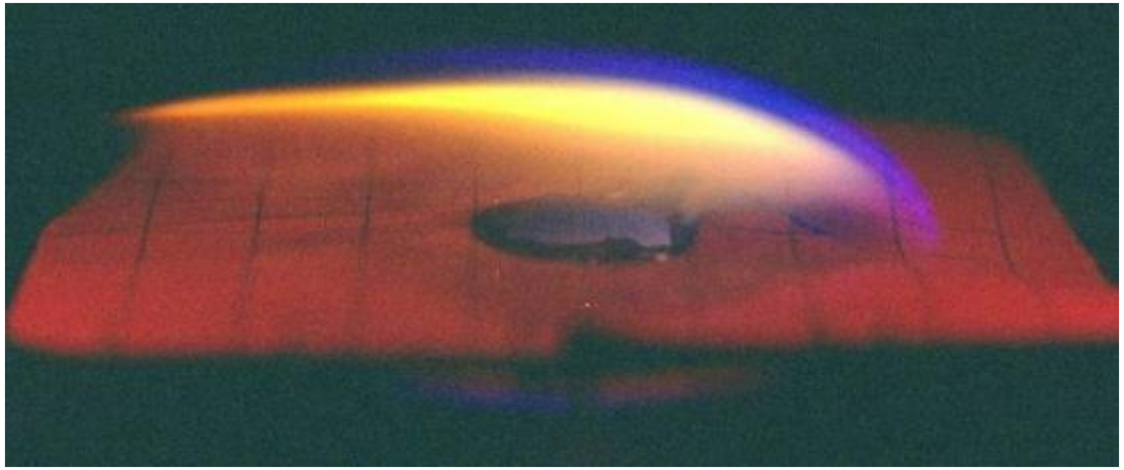


Cloud of condensed wax vapor after extinction of low-g flame

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

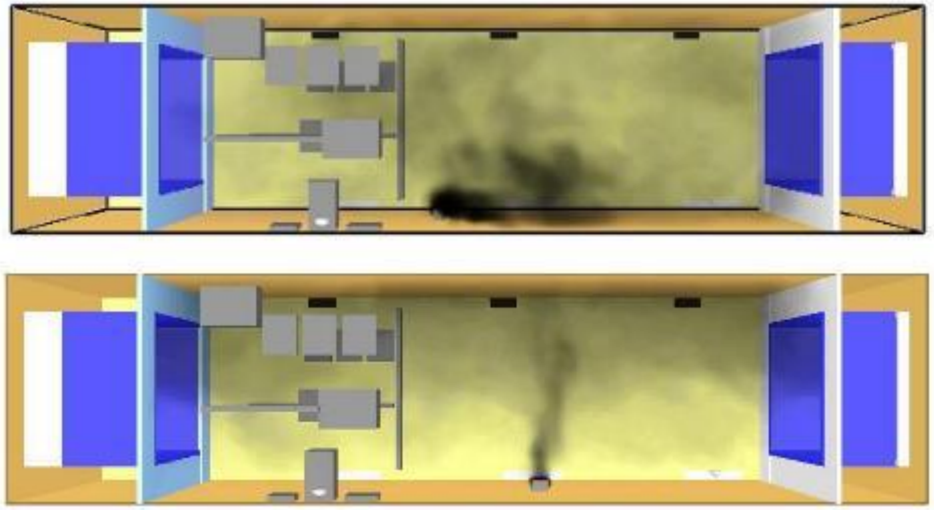
A Lot of Other Low-Gravity Implications!

- 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



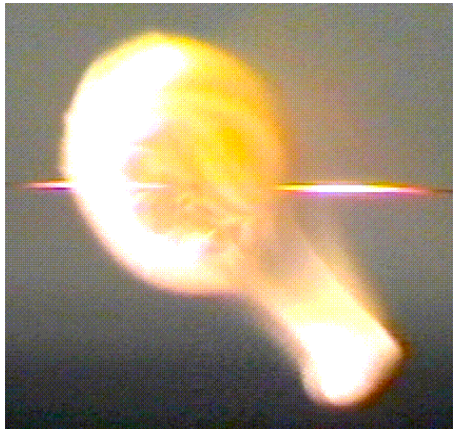
Flame spreads preferentially upstream, opposite that in 1g. Paper is centrally ignited in low-speed opposed-air flows (1 and 2 cm/s).

Low-gravity



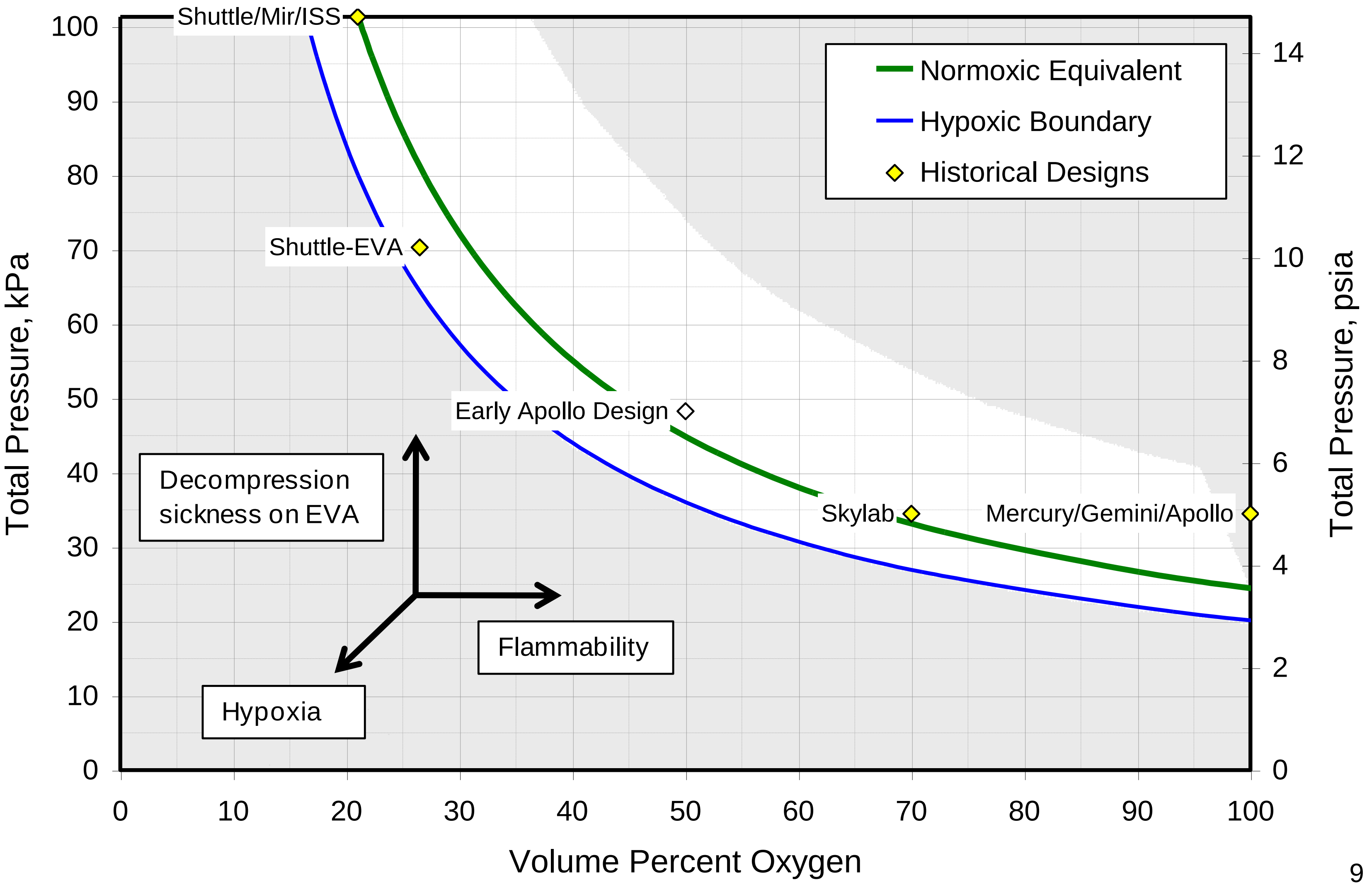
Normal-gravity

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

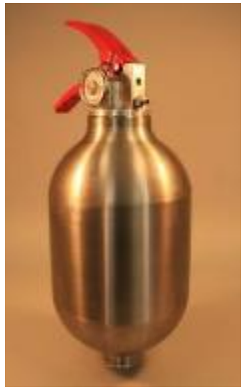
Sample failing NASA Test 1

US CO_2 fire extinguisher

FGB SD

US SD

SM SD



Engineering Development Unit of an Orion FWM PFE

Engineering Development Unit of an ISS 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

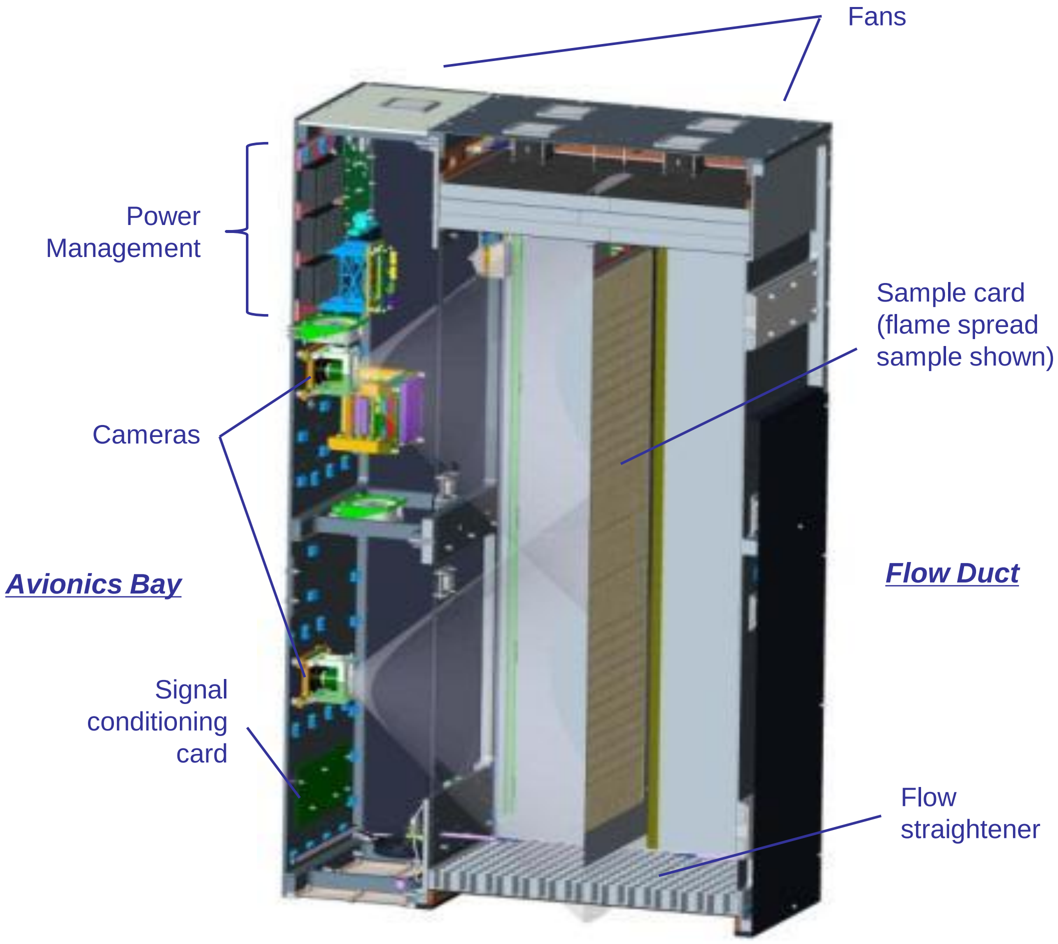
Needs:

- *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

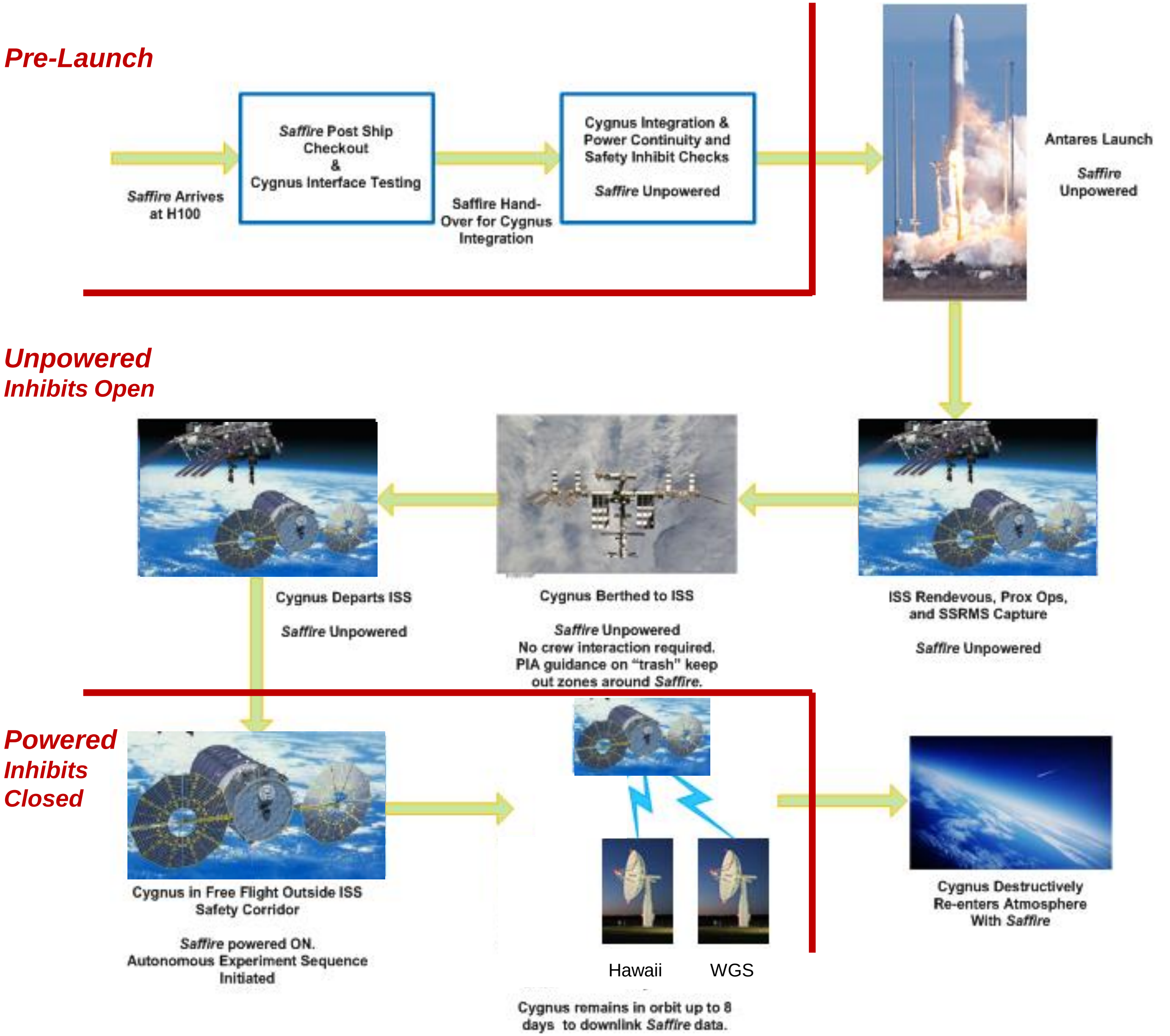
Composite fabric (SIBAL cloth)
(75% cotton – 25% fiberglass by mass)
(0.4 m x 0.95 m)

Saffire-II Sample Card

Saffire-II Samples (5 cm x 29 cm)

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

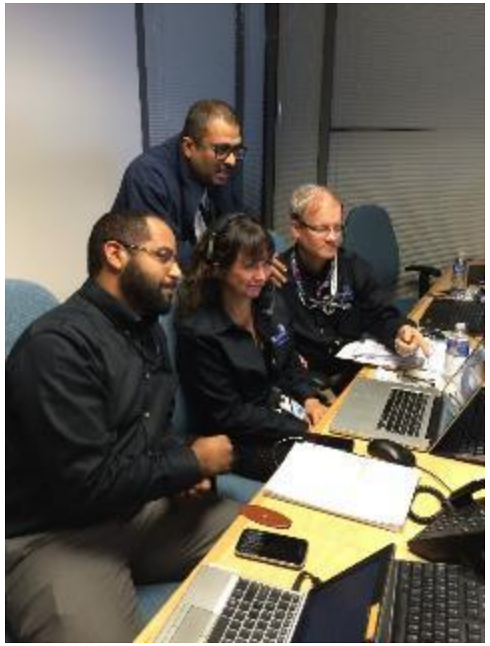
Operations Concept



Saffire Operations

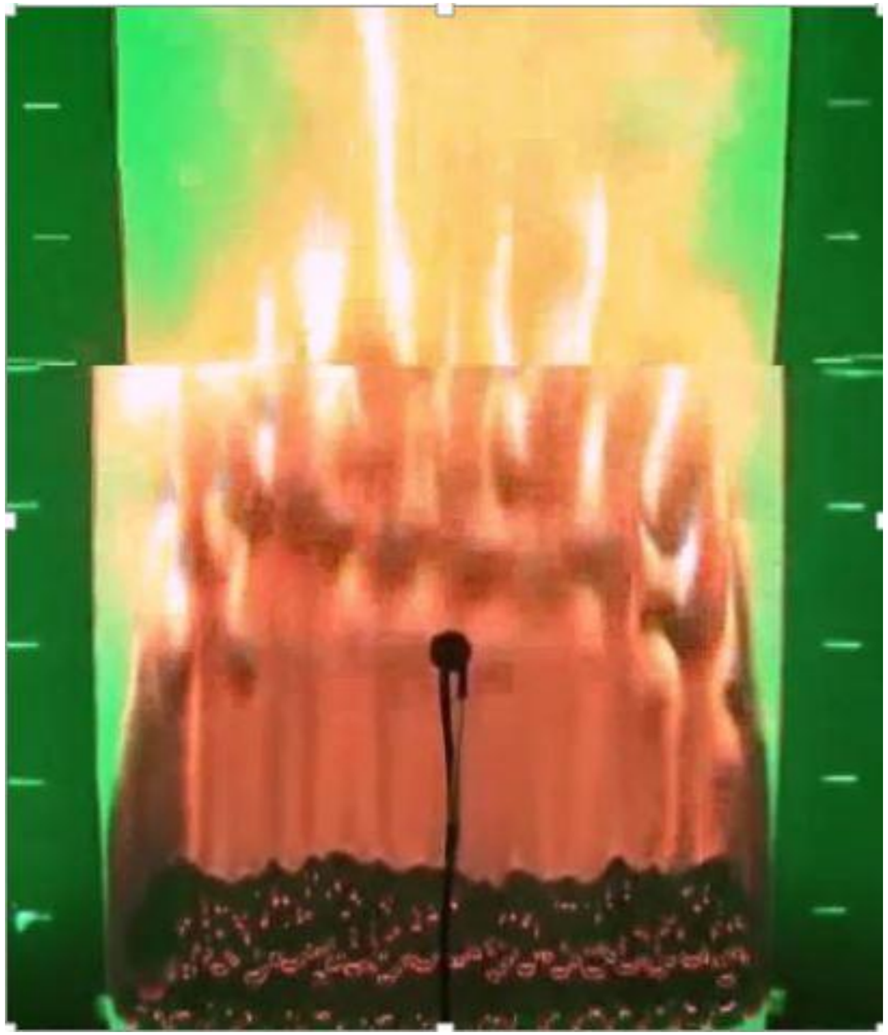
	Mission	Launch Site	Launch Vehicle	Integration	Launch	Mission Ops
Saffire-I	OA-6	KSC	Atlas	Jan 25, 2016	Mar 22, 2016	June 14, 2016
Saffire-II	OA-5	WFF	Antares	May 12, 2016	Oct 17, 2016	Nov 21, 2016
Saffire-III	OA-7	KSC	Atlas	Feb 3, 2017	April 18, 2017	June 4, 2017

- **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

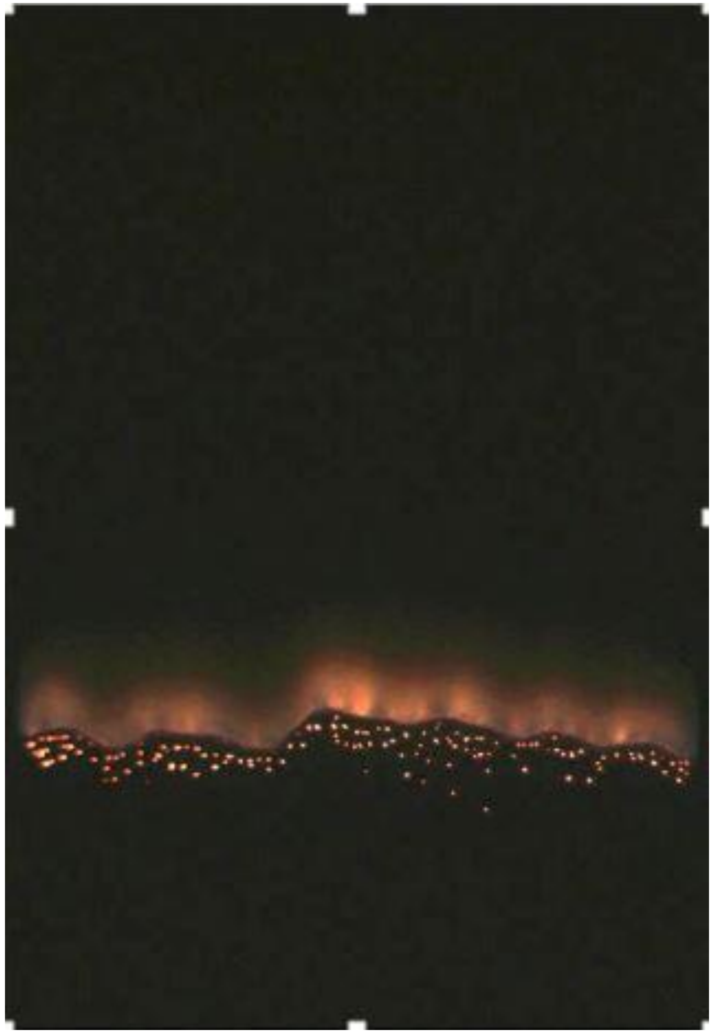


Still image of the Saffire-I material burning in normal gravity.

- 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)

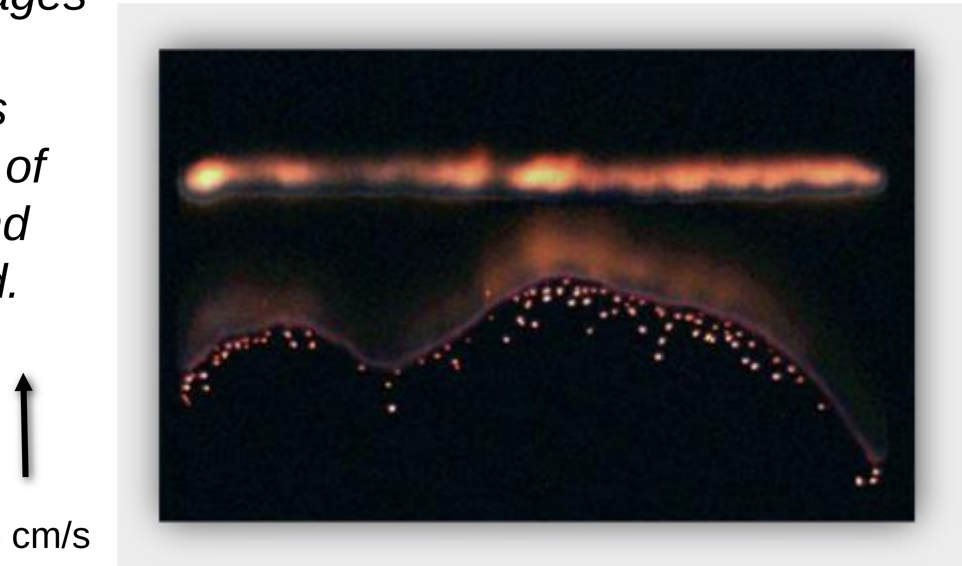
Image of the Saffire-III concurrent (upstream) burn.

Saffire-I and III Results

Saffire-I (20 cm/s)

Saffire-III (25 cm/s)

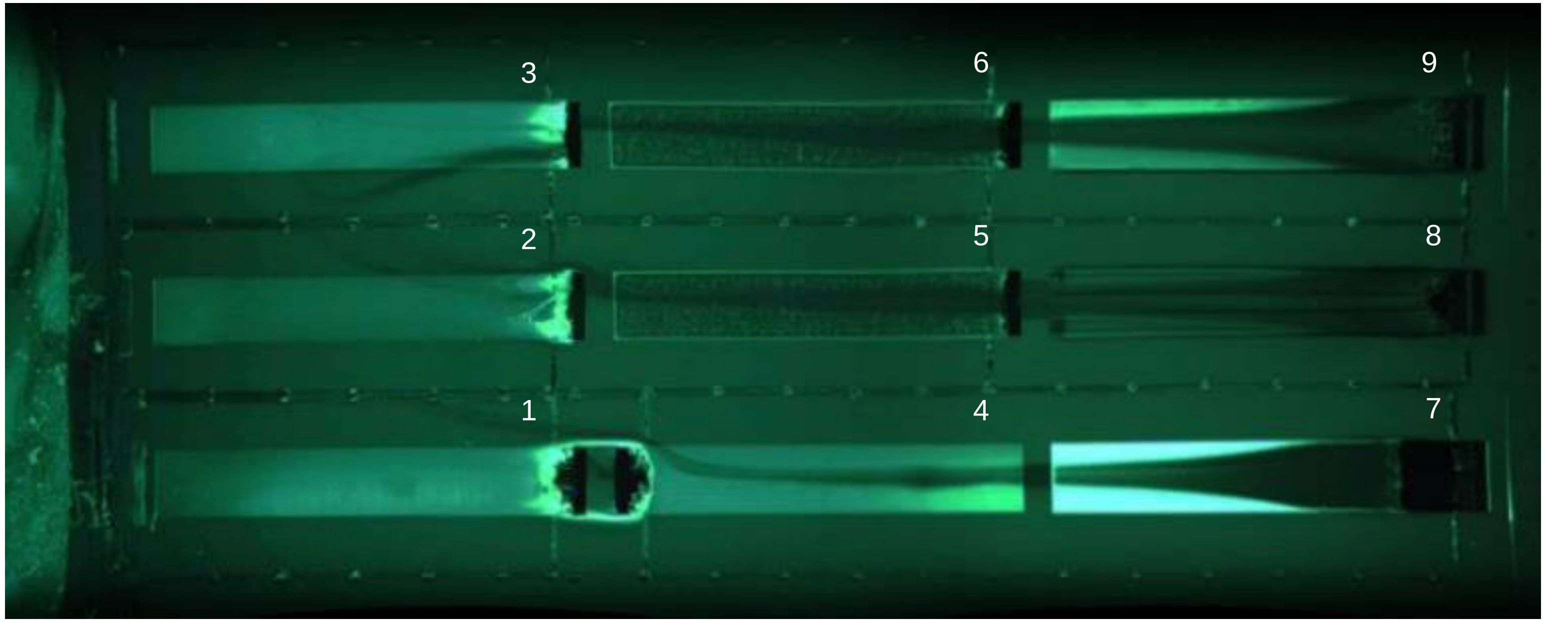
- **Left: Sequence of concurrent flame images from Saffire-I and III.**
  - *Each image is 40-sec apart.*
  - *Saffire-I burned for 400 sec*
  - *Saffire-III burned for 320 sec*
    - The flame speed is proportional to the air flow velocity
- **Below: Comparison of the opposed (upper) and concurrent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



Saffire-II Summary

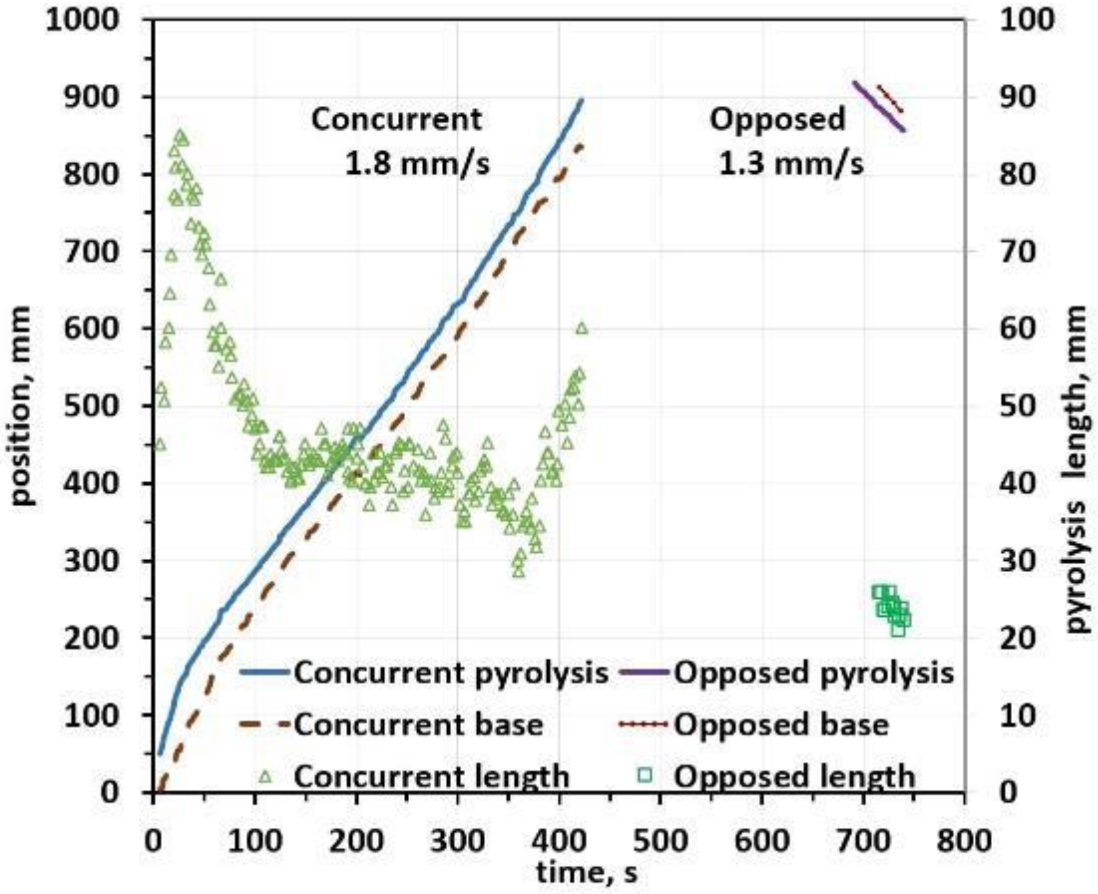
- Samples 1-4: Silicone sheets of varying thickness *(0.25 mm, 0.61 mm, 1.03 mm, 0.36 mm respectively)*
  - Samples ignited but flame did not propagate
- Samples 5-6: SIBAL cloth *(20 cm/s and 25 cm/s - same as Saffire-I and III)*
  - Burned to completion
- Sample 7: Nomex with PMMA igniter *(1 mm thick 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

Flow

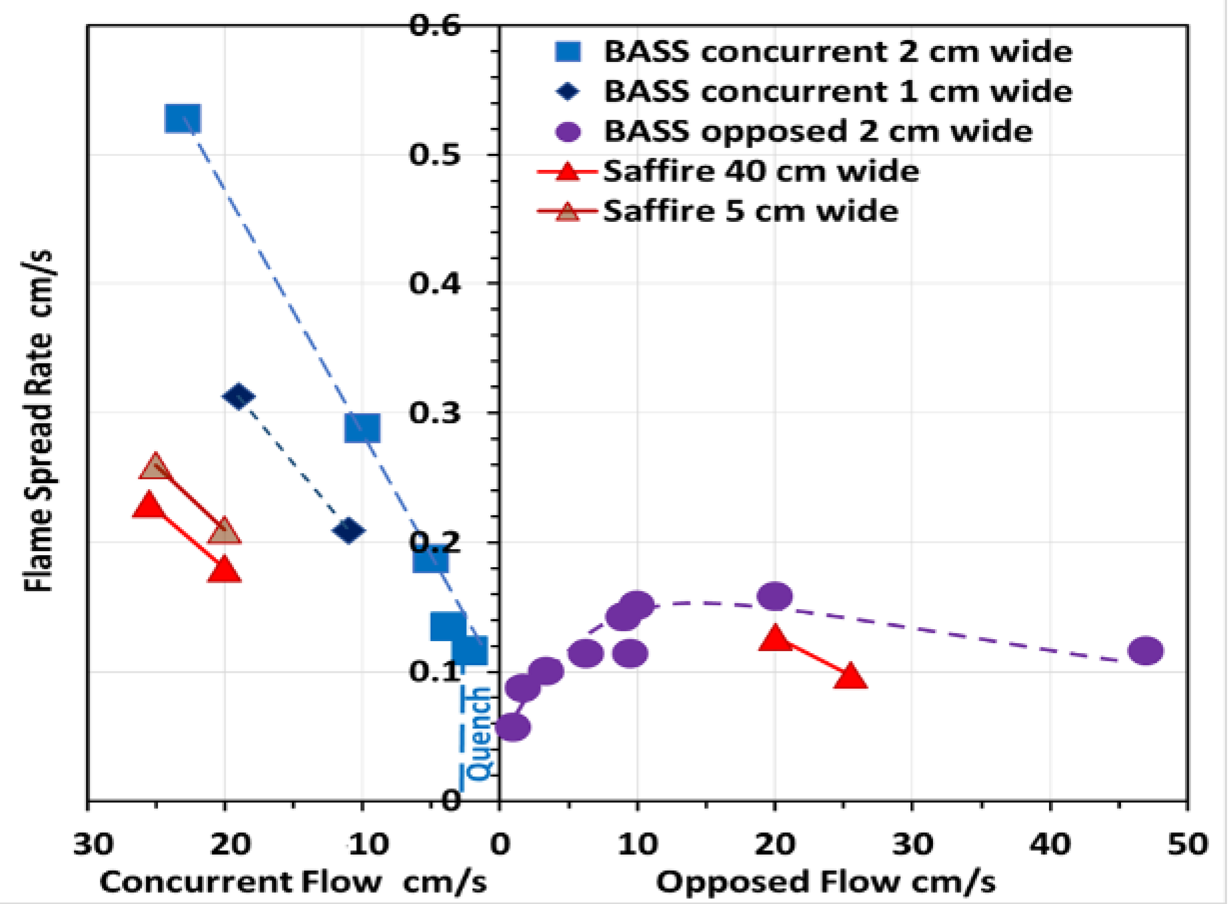


Composite picture of samples 1-9 at end of experiment. *Streaks are soot from Samples 7-9 deposited on card.*

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

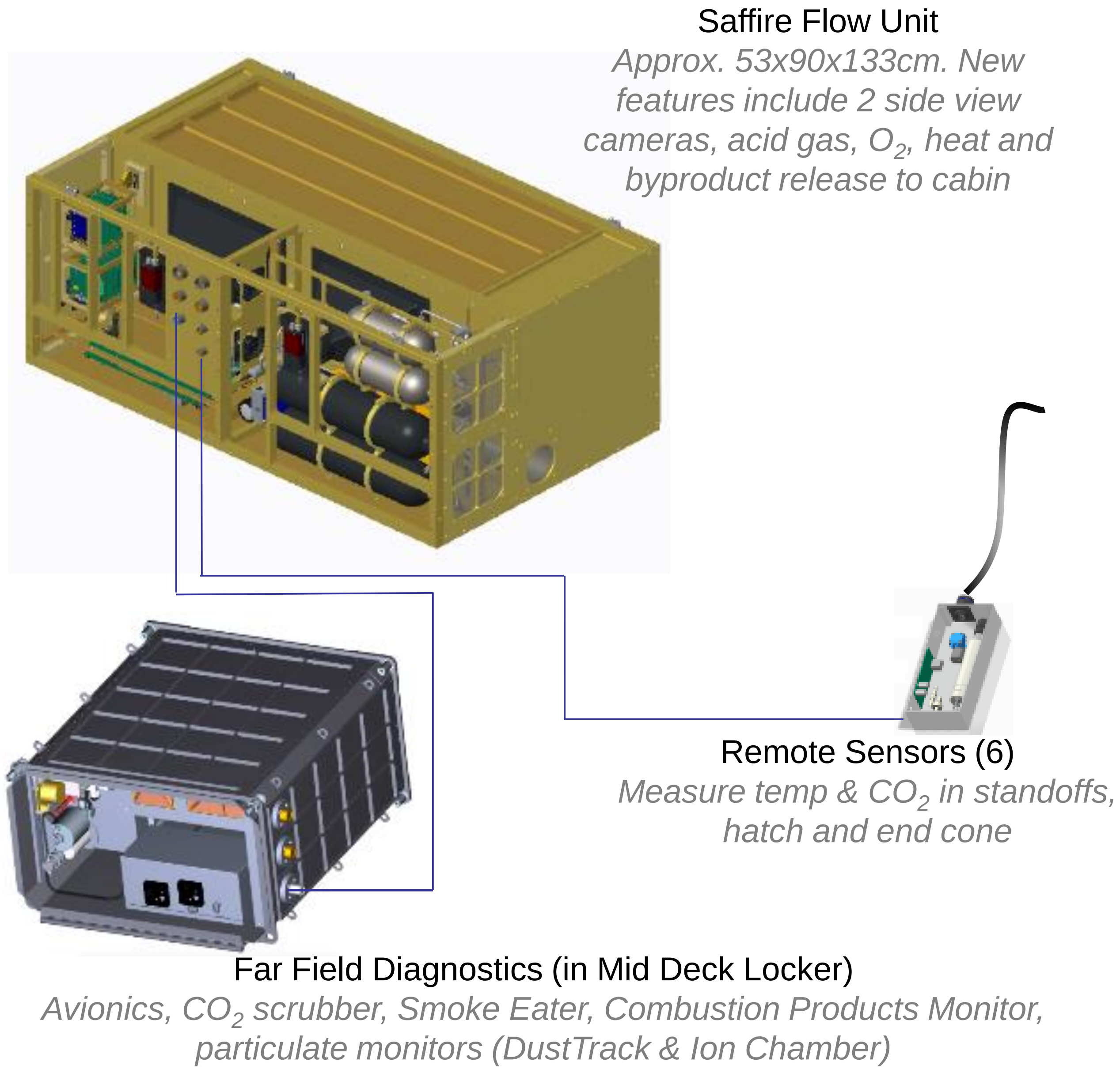
Saffire-IV, V, and VI Summary

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

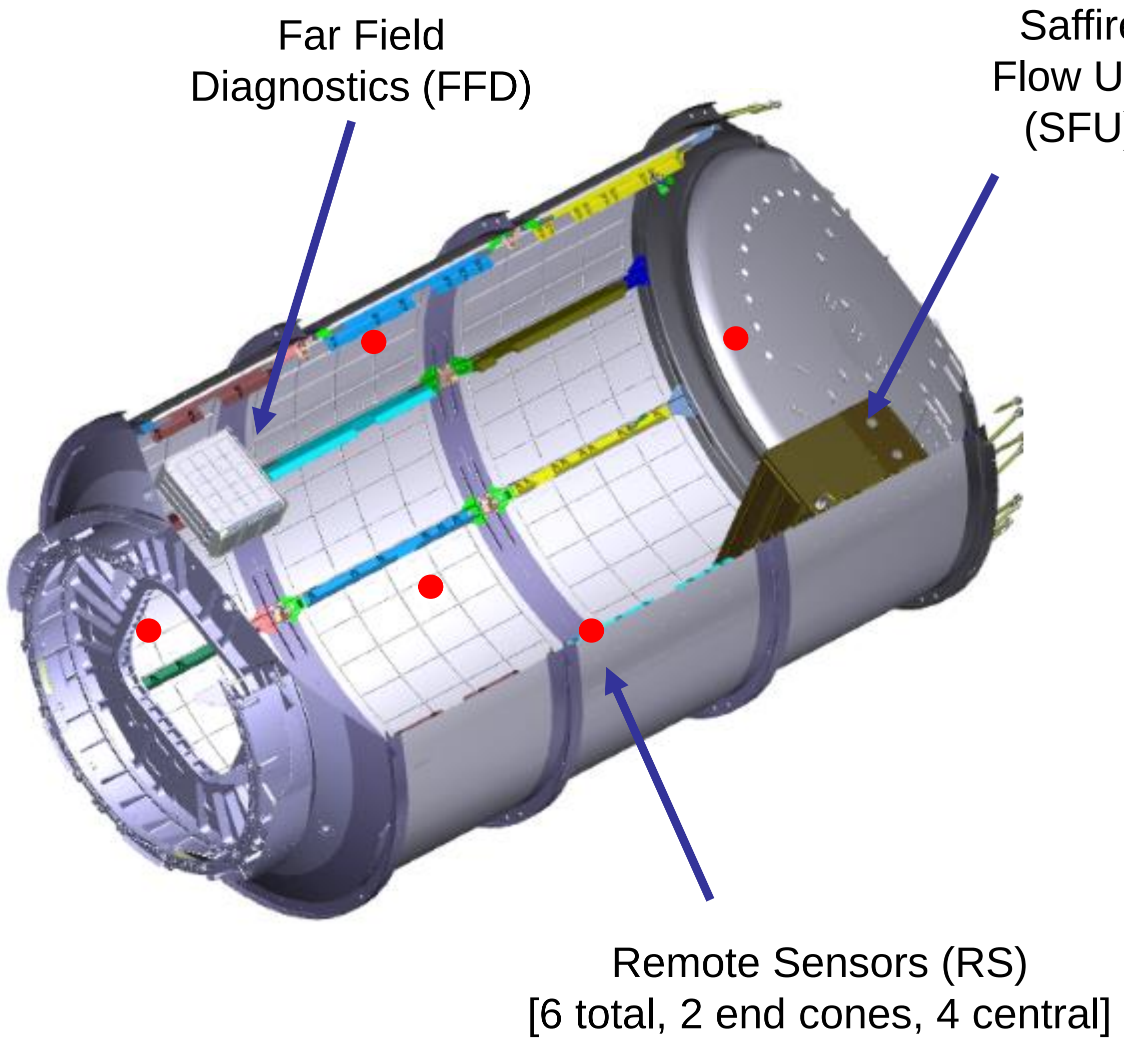
Objectives:

- *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

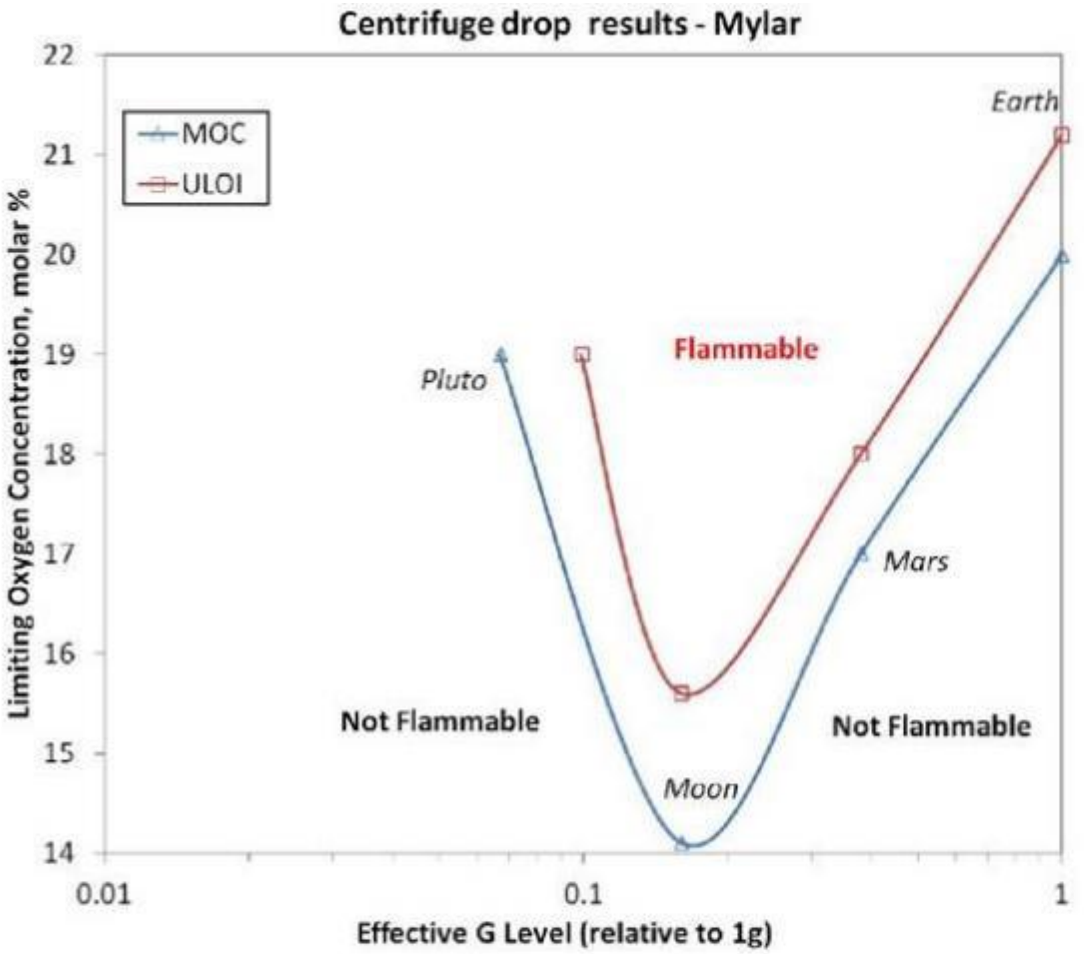


Expected Results of the Saffire-IV, V, and VI Experiments

- 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

NASA