# Saffire: A Novel Approach to Study of Spacecraft Fire Safety Using Un-manned Spacecraft






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# Introduction

- Despite millennia of experience with fire, over 3,000 people die from fires each year in the U.S.
- Fire is a catastrophic hazard for spacecraft
- However, without any empirical results, it is impossible to be sure that our predictions of fire behavior in a spacecraft are realistic.
- What will kill you first?
  - CO buildup?
  - Other toxic products?
  - Heat?
  - Smoke?
  - Pressure Rise?
- How should the crew respond?

All inhabited types of structure, vehicle, or even open space on earth have been the subject of full scale fire studies and/or training.

## Air Force Fire Response Training

**FAA full scale aircraft test**

**Controlled burns of structures**

**Naval Research Laboratory - Ex-USS Shadwell**

Bureau of Mines explosion testing

Car Fire Training

**Forest Fire response**

# Benefit of experience

- From these tests we have a good understanding of
  - How fast a 1-g fire will grow
  - How to detect a 1-g fire
  - How to extinguish a 1-g fire
  - The probability of a 1-g fire

Having only burned samples up to 8 by 15 cm, we lack this understanding for low-g

Saffire was proposed to provide a means to address these questions for future spacecraft.

# Saffire Objectives

**To address these concerns, an experiment was defined to examine issues including**

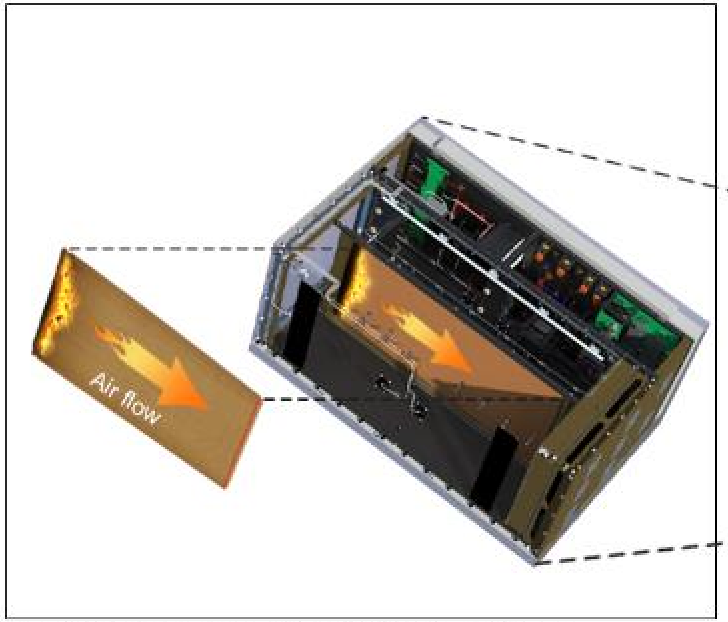
- *Low-g flammability limits for spacecraft materials*
- *Fate of a large-scale spacecraft fire and its interaction with the spacecraft*

**Objectives:**

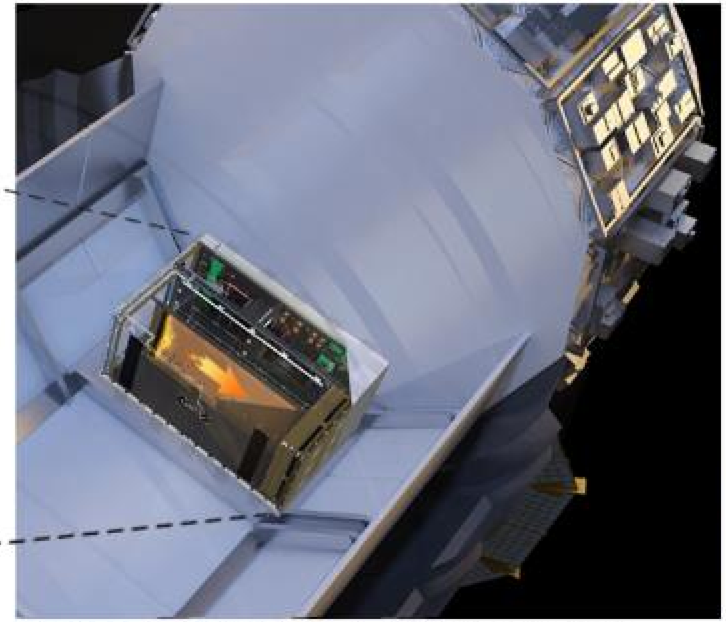
- *Saffire 1 & 3*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release)
- *Saffire 2*: Verify oxygen flammability limits in low gravity

- *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.*

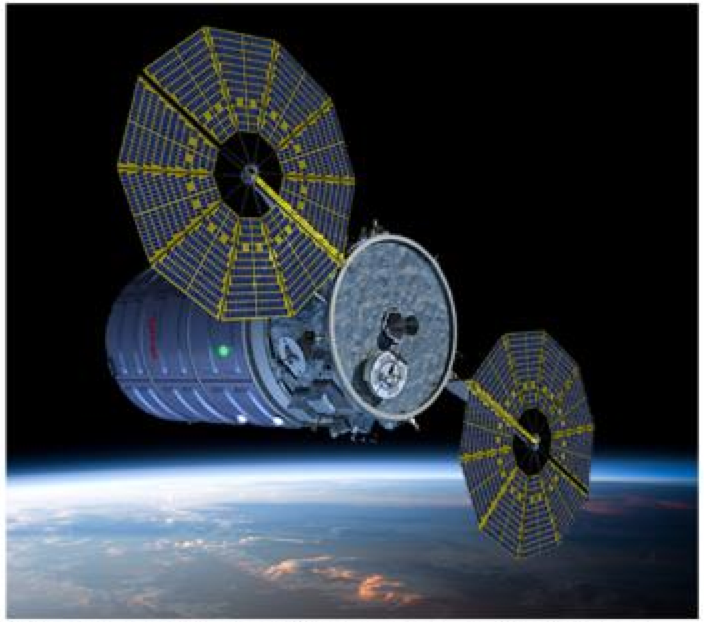
# Concept of Operations




Test sample inserted into hardware.

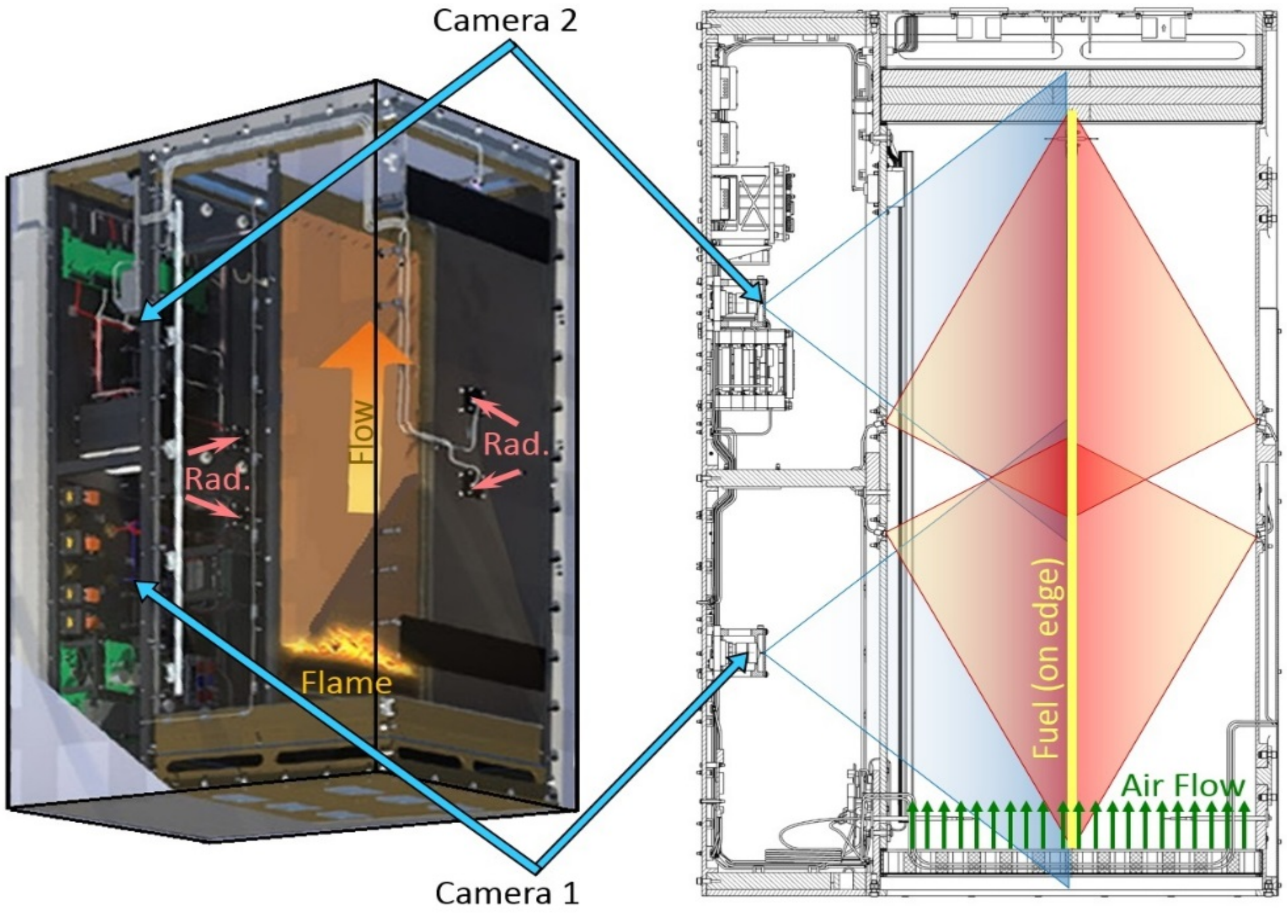


Hardware installed on Cygnus vehicle.

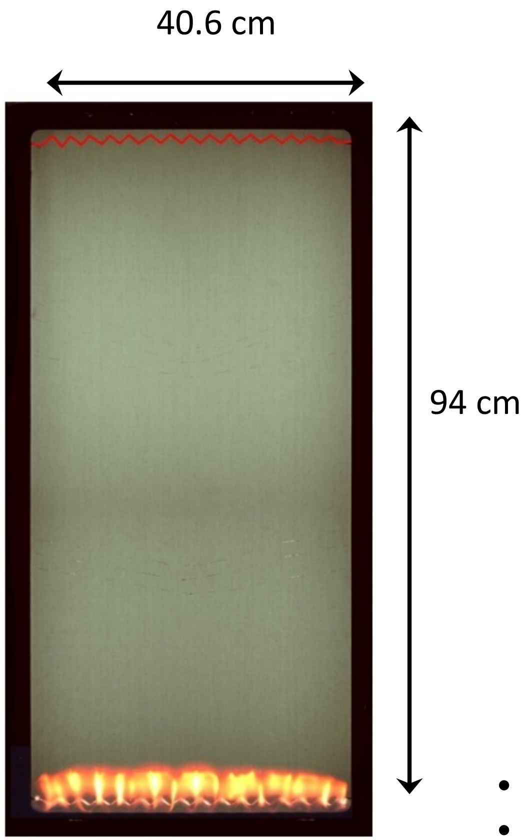


Cygnus vehicle with hardware installed.

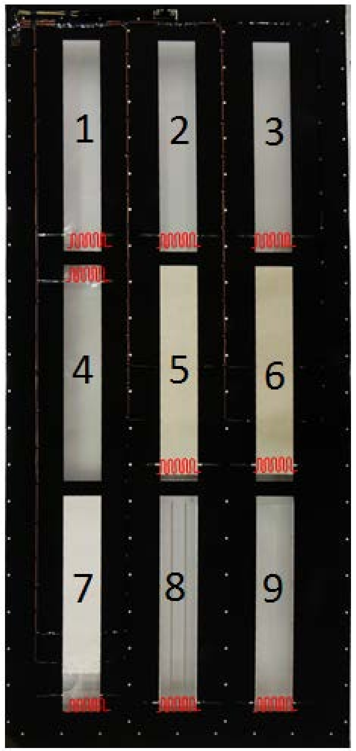
# Saffire Layout




The Saffire flow duct.




Saffire I and III

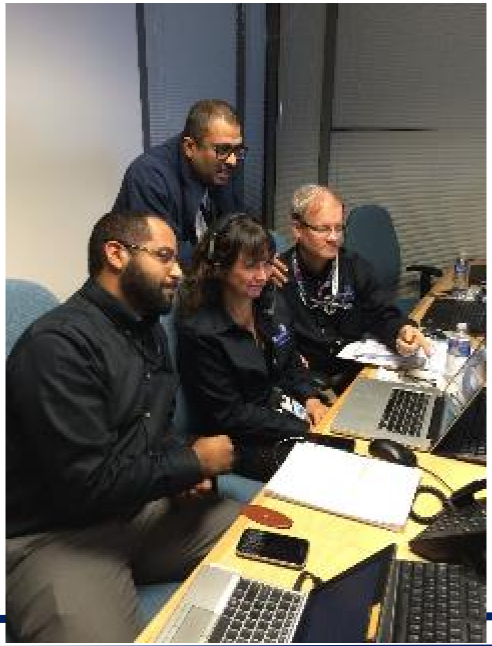



- Saffire II sample layout:
- Silicone) (1-4)
- SIBAL (5 & 6))
- Nomex (with PMMA ignition) (7)
- PMMA (flat and structured) (8 & 9)

# 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 |

Orbital and Saffire team at Dulles



Saffire team at GRC

# Saffire-I and III Results

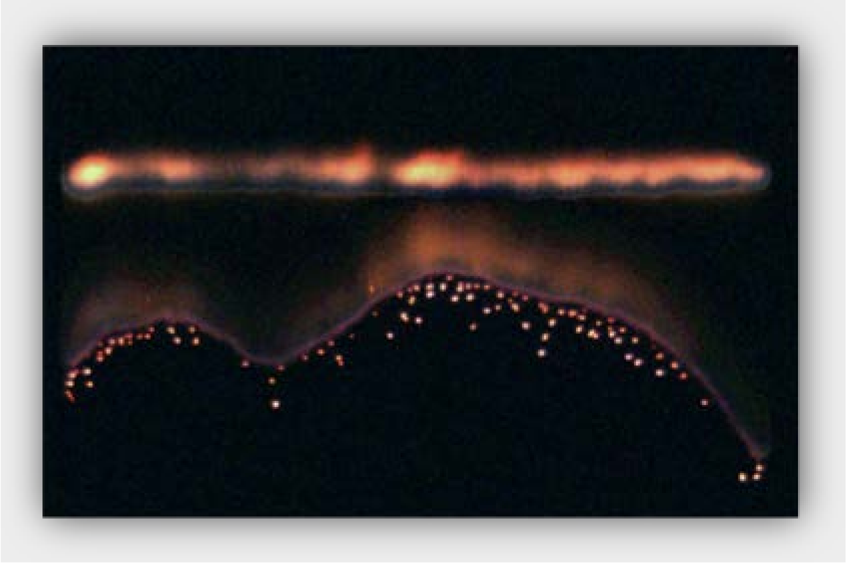
Saffire-I (20 cm/s)

Saffire-III (25 cm/s)

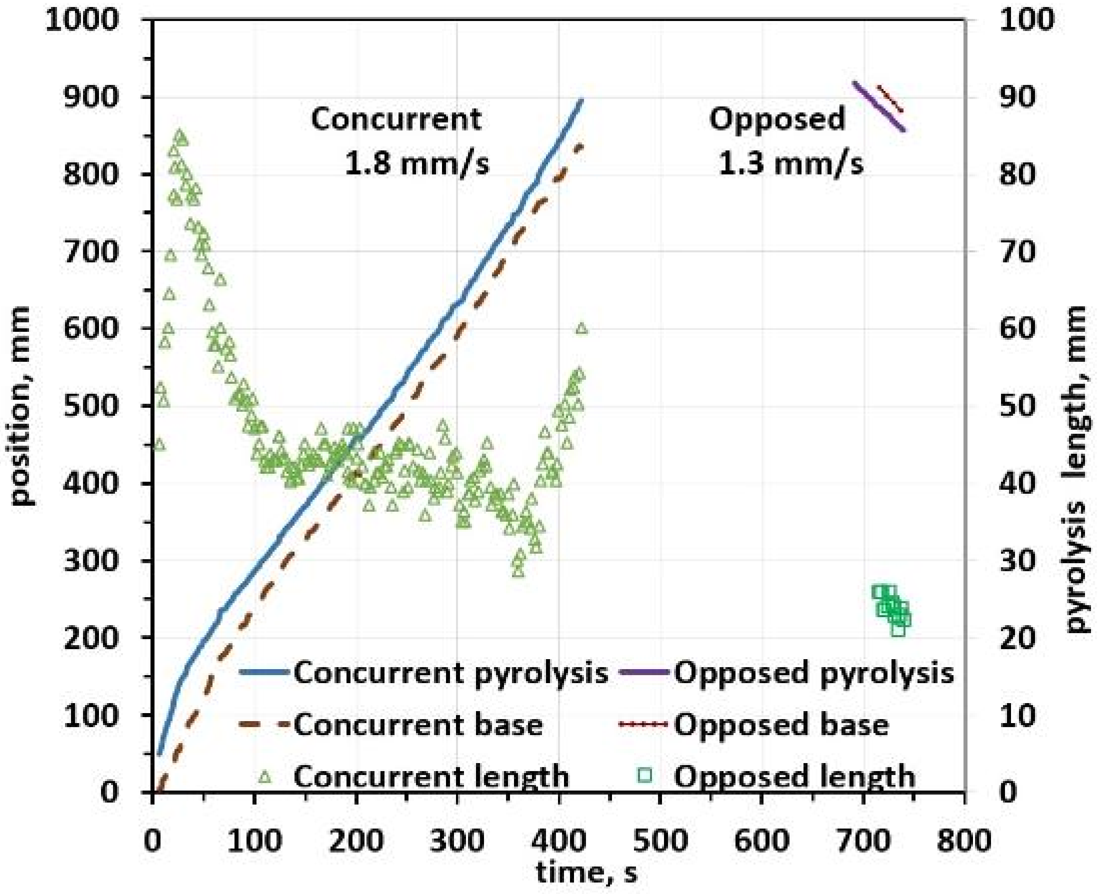
- **Sequence of concurrent flame images from Saffire-I and III.**
  - *Each image is 40-sec apart.*
  - *Saffire-I burned for 400 sec*
  - *Saffire-III burned for 320 sec.*

- **This is equal to the inverse ratio of the flame speed**
  - The flame speed is proportional to the air flow velocity

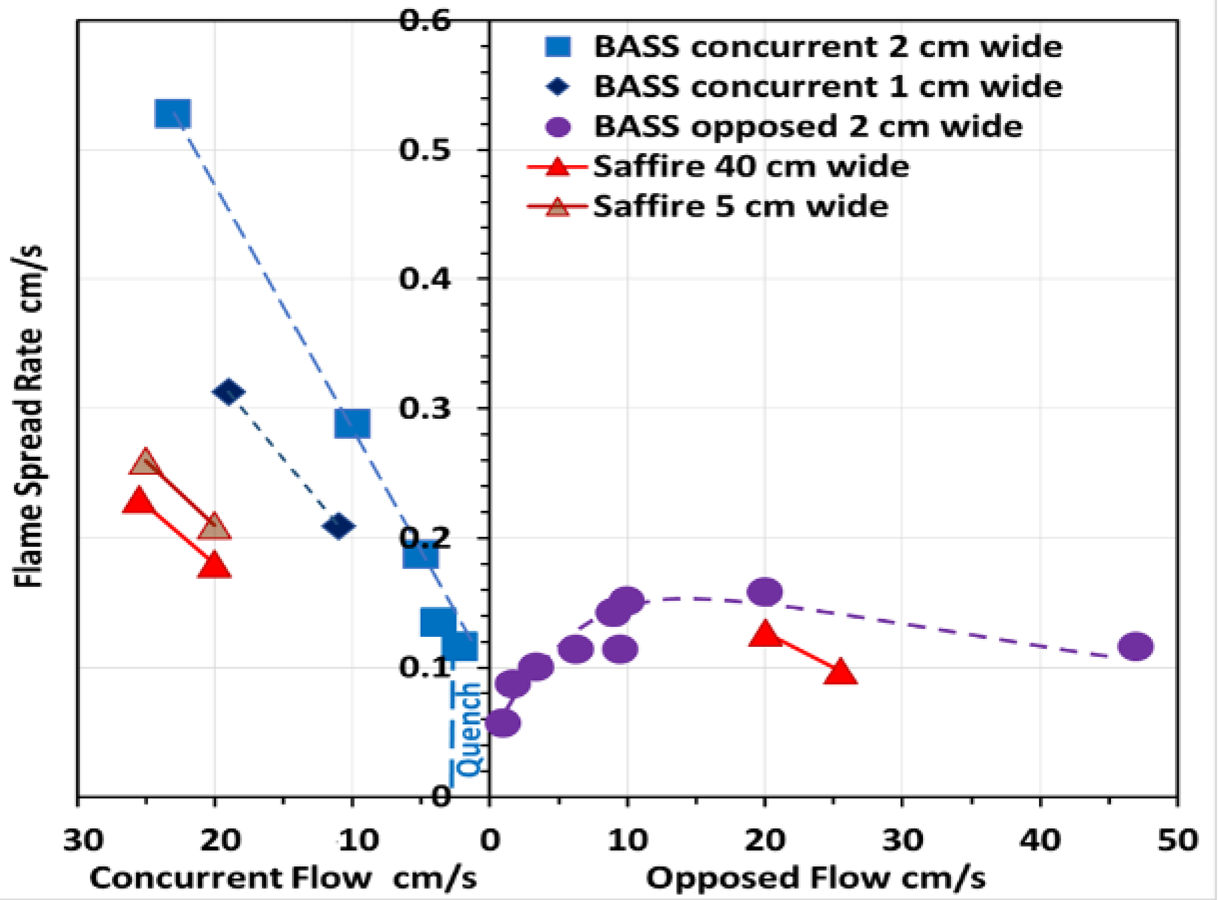
- **Comparison of the opposed (upper) and concurrent (lower) flames from Saffire-III.**
  - *The flame images were taken at different times (near the end of each burn and superimposed.*



# Saffire-I-III Results




Measurements of flame base (up stream), pyrolysis tip (downstream), and pyrolysis length from concurrent and opposed burns from Saffire-I.




Spread rate summary for Cotton/Fiberglass fabric burning in microgravity

# Saffire-I-III Results

- Flame spread over a large thin charring surface in low-gravity showed that steady flame spread was possible (unlike normal gravity).
- Concurrent flame spread (with the wind) was shown to be more sensitive to the flow duct dimension than previously anticipated.
- Large scale experiments could be safely conducted in an un-manned spacecraft.

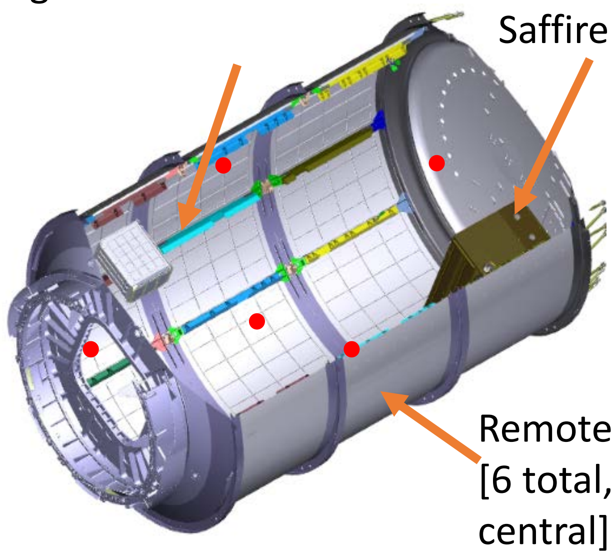
*A new series of experiments was proposed to extend the impact to the vehicle, examine thick materials and consider detection and post-fire cleanup*

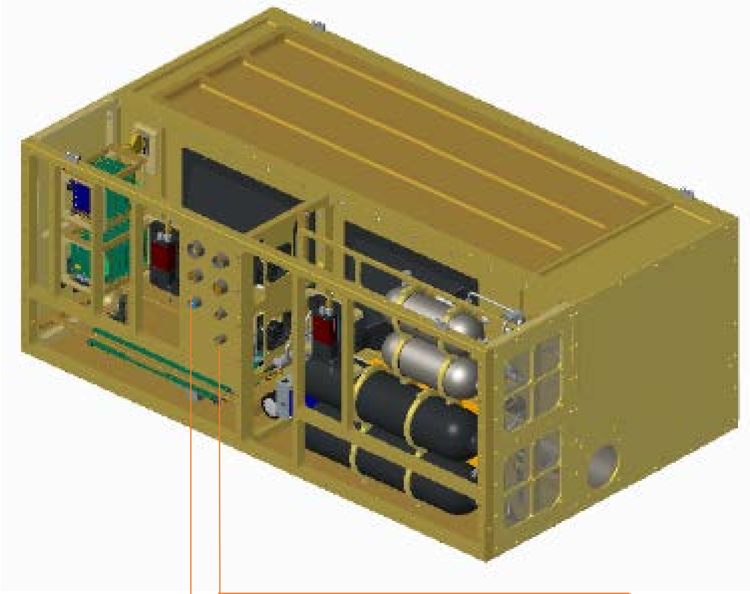
# Saffire-IV, V, and VI Concept

## Objectives:

- 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 prediction of the impact of a fire on vehicle habitability

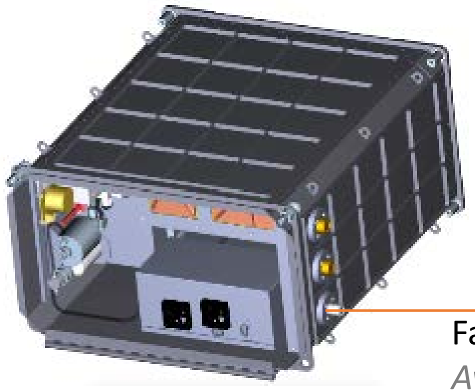
Far Field Diagnostics

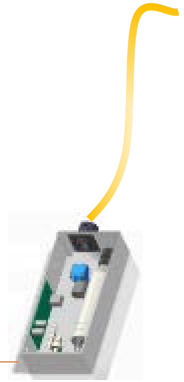


Saffire Flow Unit

*Approx. 53x90x133cm. New features include 2 side view cameras, acid gas, $O_2$, heat and byproduct release to cabi*





Remote Sensors (6)

*Measure temp & $CO_2$ in standoffs, hatch and end cone*

Far Field Diagnostics (in Mid Deck Locker)

*Avionics, $CO_2$ scrubber, Smoke Eater, combustion product and smoke sensors*

# Forward Steps

- The Saffire experiments were the first practical-scale spacecraft fire safety investigations.

- In addition to pioneering a new research capability, they determined that concurrent flames can achieve a steady spread rate and that overall the concurrent spread rates are strongly influenced the the flow duct size.

- The next Saffire series will examine larger fires of longer duration to examine the impact of a fire on the vehicle habitability .


Spacecraft Fire Safety Demonstration
Saffire
NASA GRC
Orbital Sciences Corporation
ISS

# Backup

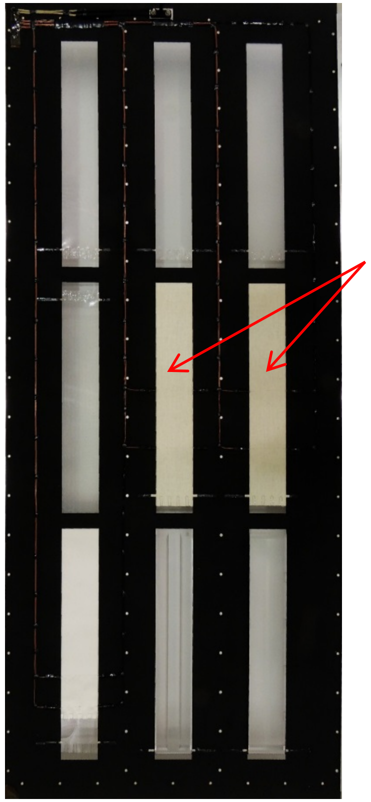
Four tests:

40.6-cm-wide SIBAL fabric (cotton-fiberglass); concurrent and opposed-flow in 20 cm/s air flow

5-cm-wide SIBAL fabric; concurrent-flow in air at 20 and 25 cm/s

Saffire 1


Saffire 2



SIBAL fabric
5 cm wide

Ignition power:

Saffire 1: 165 W (for 8 s)

4.1 W/cm (per unit fuel width)

Saffire 2: 80 W (for 9.2 s)

16 W/cm (per unit fuel width)

Average flame power:

Saffire 1: 1200 +/- 300 W

Saffire 2: 200 +/- 50 W

Fuel characteristics (“SIBAL” fabric)

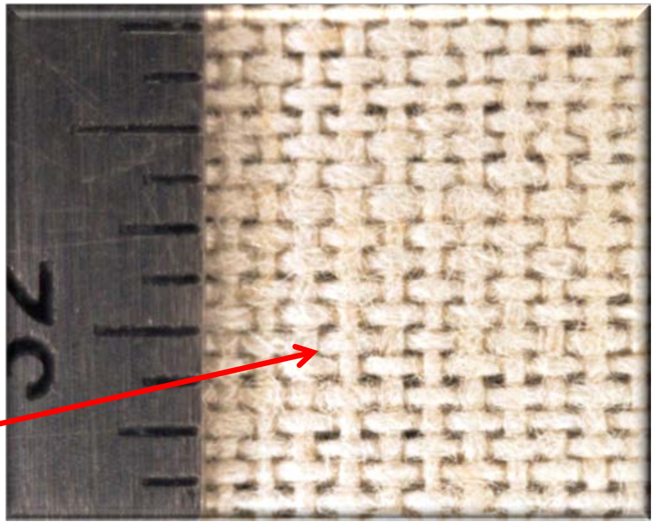
75% cotton, 25% fiberglass blend

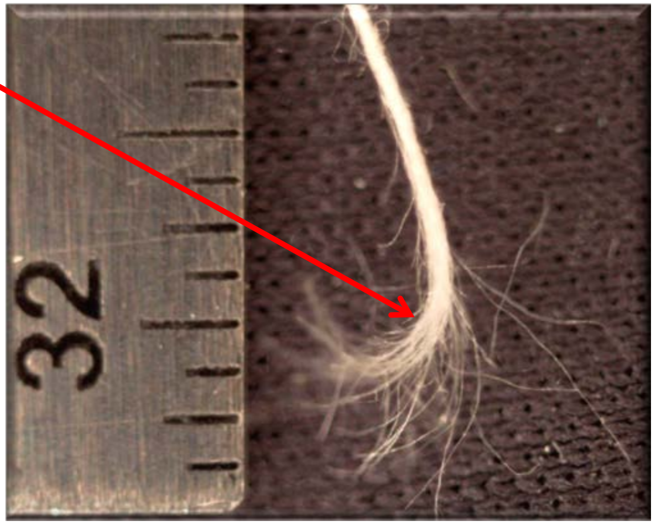
Simple weave pattern (60 x 40 threads per inch)

Cotton and fiberglass fibers intermingled

Overall area density: 18 mg/cm$^2$

Fuel sizes (W x L): 40.6 x 94 cm and 5 x 29 cm



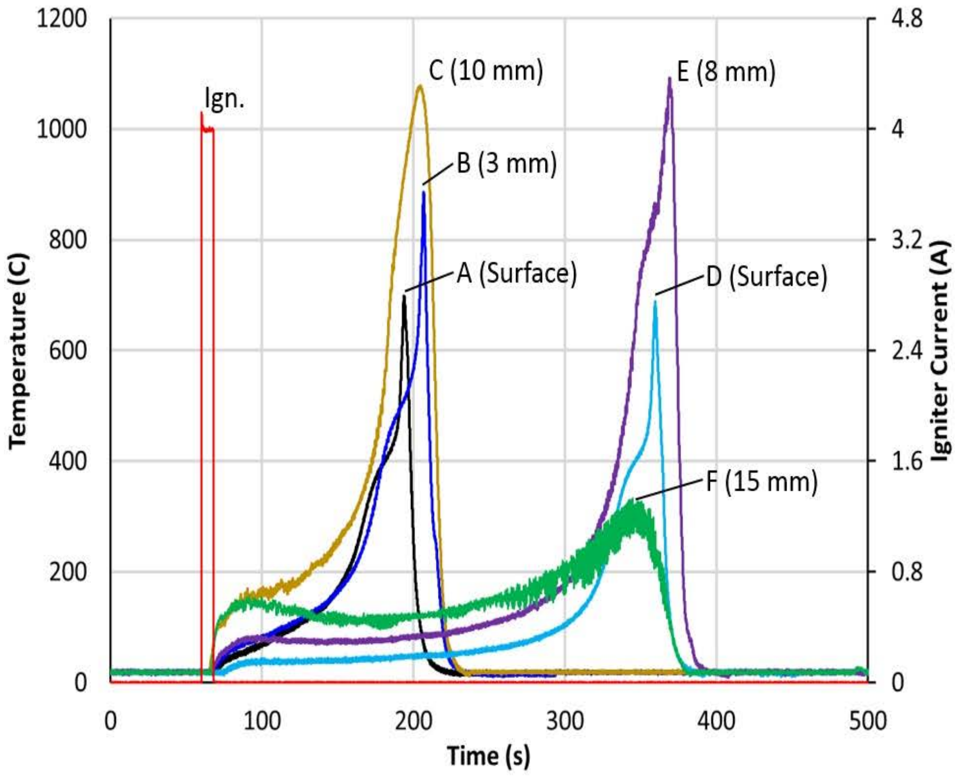



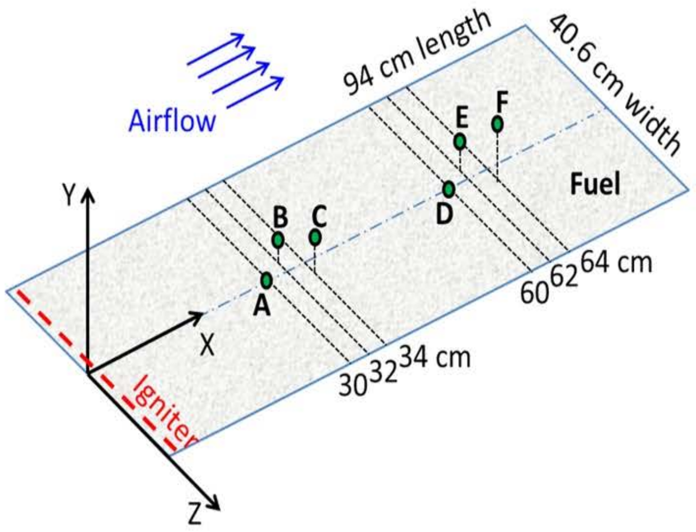
Saffire 1 video

SIBAL fabric (40.6 cm x 94 cm) burning in air at 20 cm/s concurrent flow

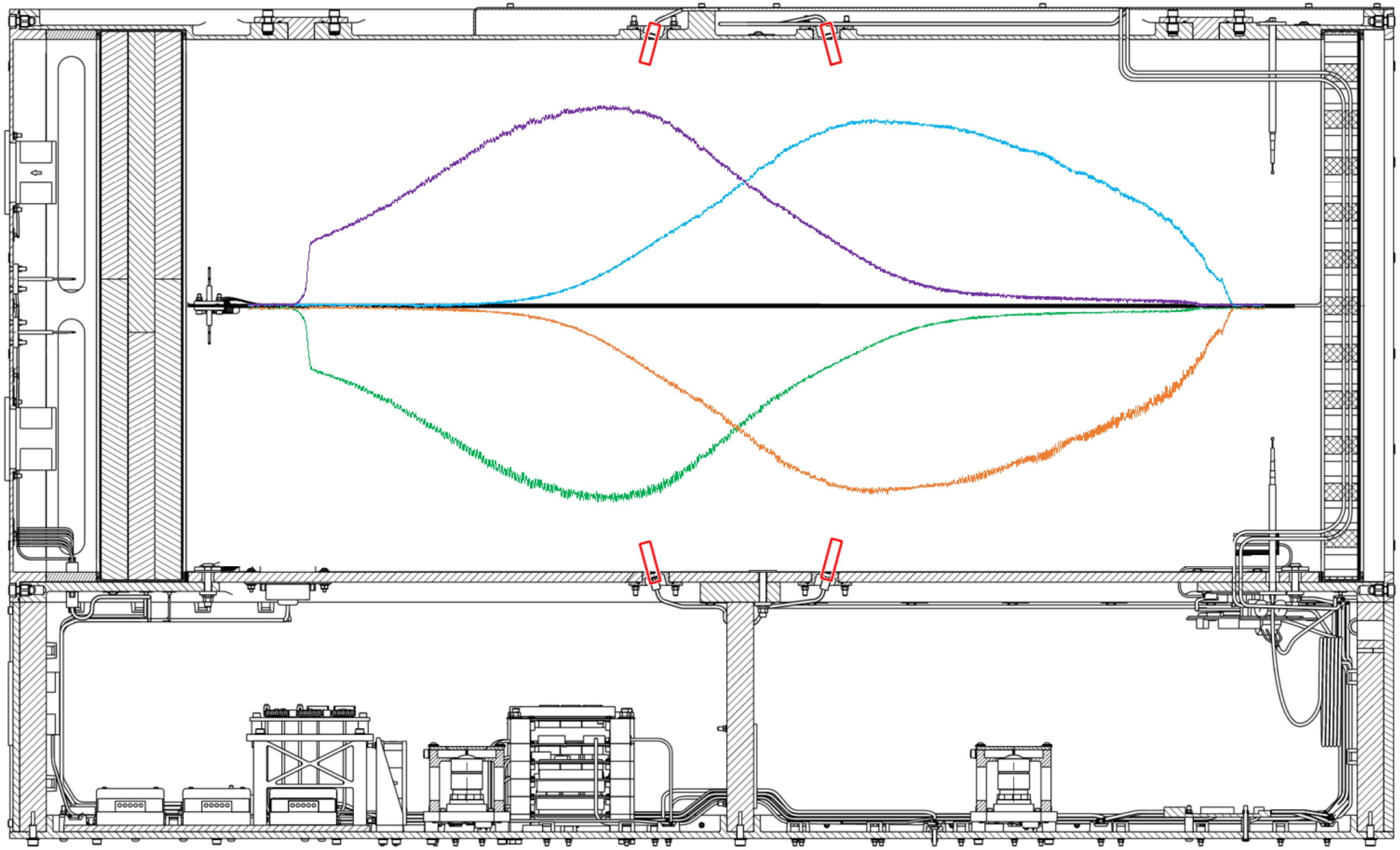
Average flame spread rate is 1.8 mm/s; estimated average flame power is 1200 +/- 300 W

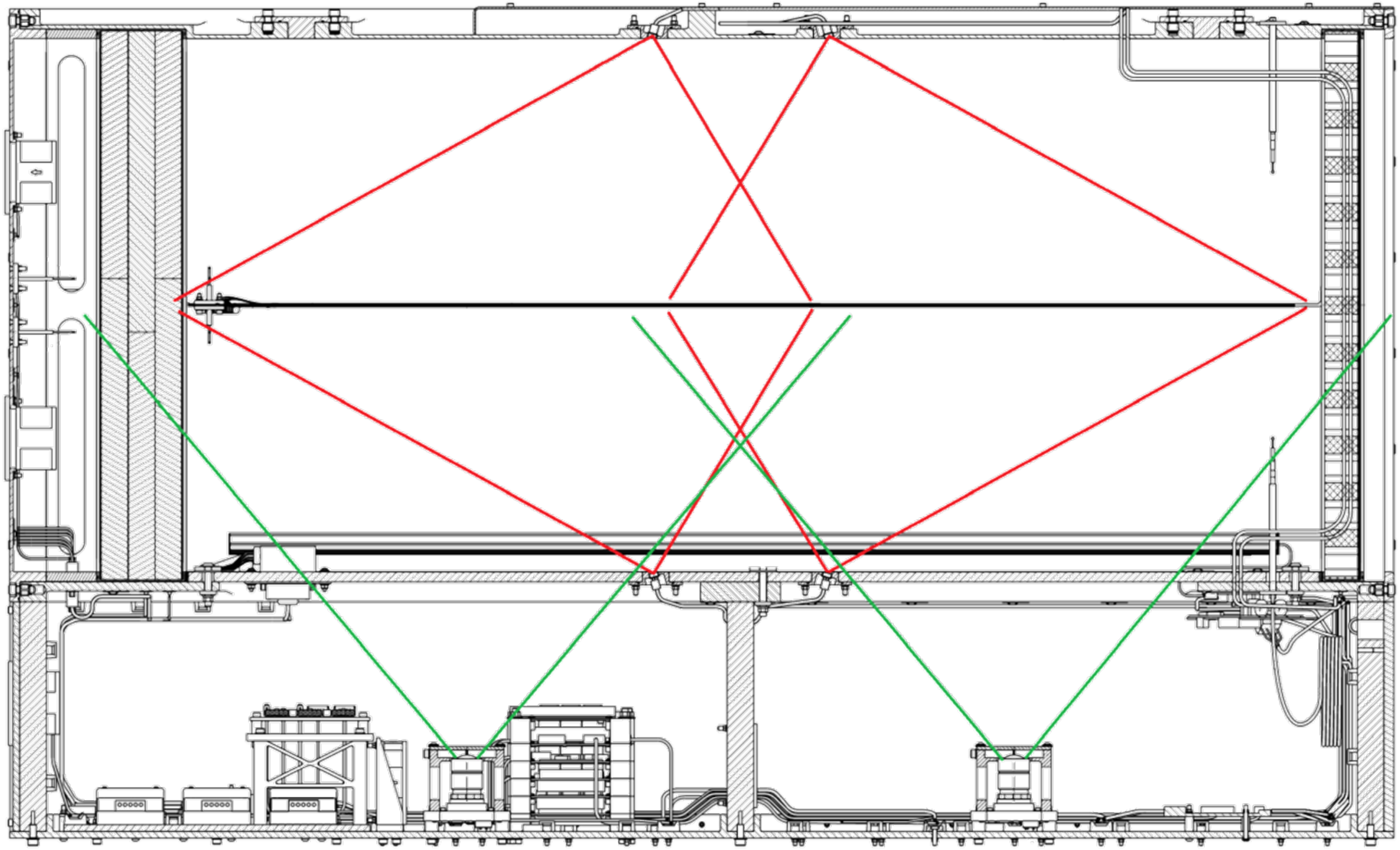
Total burn time is 420 s

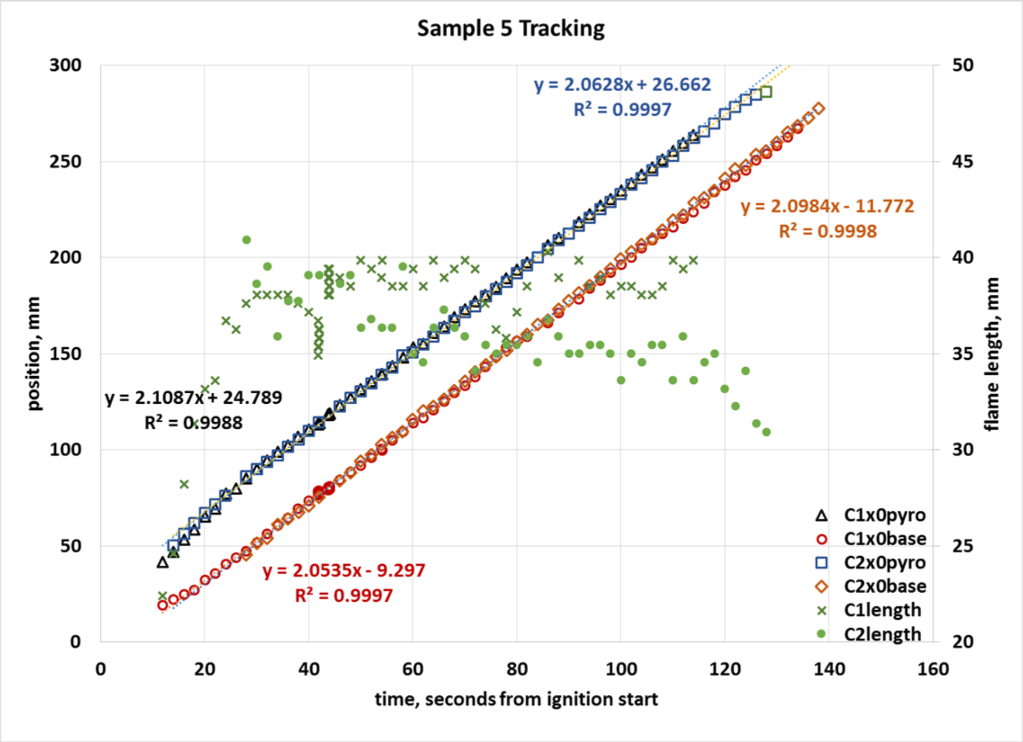


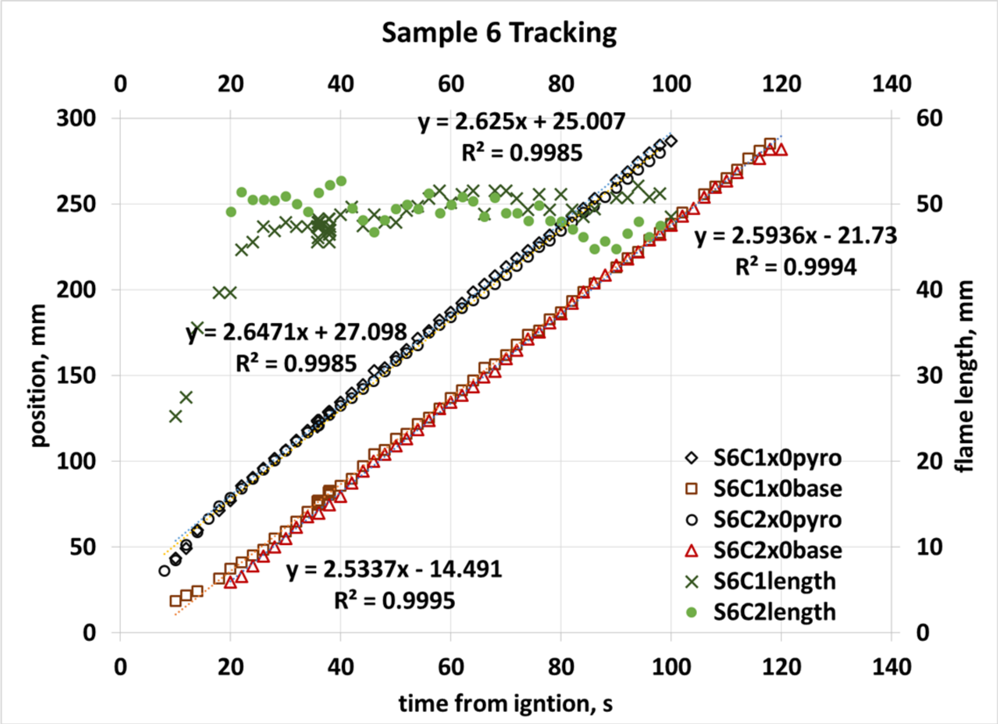




Plots of igniter current and thermocouple temperatures. X-distance along the sample for each thermocouple is shown on the diagram. Heights above the surface are indicated on the plot.






Sample 5 Tracking
y = 2.0628x + 26.662
R² = 0.9997
y = 2.0984x - 11.772
R² = 0.9998
y = 2.1087x + 24.789
R² = 0.9988
y = 2.0535x - 9.297
R² = 0.9997
position, mm
flame length, mm
time, seconds from ignition start
C1x0pyro
C1x0base
C2x0pyro
C2x0base
C1length
C2length


Sample 6 Tracking
y = 2.625x + 25.007
R² = 0.9985
y = 2.5936x - 21.73
R² = 0.9994
y = 2.6471x + 27.098
R² = 0.9985
y = 2.5337x - 14.491
R² = 0.9995
position, mm
flame length, mm
time from igntion, s
S6C1x0pyro
S6C1x0base
S6C2x0pyro
S6C2x0base
S6C1length
S6C2length

| Table 1. Summary of Samples, Test Conditions, and Selected Results | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sample | Material | Width | Thickness | Length | Flow | Direction | Δ %$O_2$ [i] |
| I-1 | Cotton-Fiberglass | 40.6 cm | 0.37 mm | 94 cm | 20 cm/s | Concurrent | 21.7 to 21.5 |
| I-2 | Cotton-Fiberglass | 40.6 cm | 0.37 mm | ~ 10 cm | 20 cm/s | Opposed | ~ 21.5 |
| II-1 | Silicone | 5 cm | 0.27 mm | 29 cm | 20 cm/s | Concurrent | ~ 22.1 |
| II-2 | Silicone | 5 cm | 0.61 mm | 29 cm | 20 cm/s | Concurrent | ~ 22.1 |
| II-3 | Silicone | 5 cm | 1.03 mm | 29 cm | 20 cm/s | Concurrent | ~ 22.1 |
| II-4 | Silicone | 5 cm | 0.37 mm | 29 cm | 20 cm/s | Opposed | ~ 22.1 |
| II-5 | Cotton-Fiberglass | 5 cm | 0.37 mm | 29 cm | 20 cm/s | Concurrent | ~ 22.1 |
| II-6 | Cotton-Fiberglass | 5 cm | 0.37 mm | 29 cm | 25 cm/s | Concurrent | ~ 22.1 |
| II-7 | PMMA & Nomex | 5 cm | 0.85 & 0.37 mm | 5 & 24 cm | 20 cm/s | Concurrent | ~ 22.1 |
| II-8 | PMMA | 5 cm | See Fig. 5 | 29 cm | 20 cm/s | Concurrent | 22.1 to 22.0 |
| II-9 | PMMA | 5 cm | 1 cm | 29 cm | 20 cm/s | Concurrent | 22.0 to 21.9 |
| III-1 | Cotton-Fiberglass | 40.6 cm | 0.37 mm | 94 cm | 25 cm/s | Concurrent | 21.2 to 21.0 |
| III-2 | Cotton-Fiberglass | 40.6 cm | 0.37 mm | ~ 10 cm | 25 cm/s | Opposed | 21.2 to 21.0 |

| Table 1. Summary of Samples, Test Conditions, and Selected Results (continued) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sample** | Ignition Power | Ignition Time | Burn Duration | μ-g Burn Length | μ-g Spread Rate | 1-g Burn Length | 1-g Spread Rate |
| **1-1** | 182 W | 8 s | 420 s | ~ 84 cm | 1.8 mm/s | Complete | Acceleratory |
| **1-2** | 182 W | 8 s | 70 s | ~ 10 cm | 1.3 mm/s | ~ 0 | n/a |
| **2-1** | 80 W | 9.2 s | Insignificant | ~ 0 | n/a | ~ Complete | Acceleratory |
| **2-2** | 80 W | 9.2 s | Insignificant | ~ 0 | n/a | 7.6 cm | 1.2 mm/s |
| **2-3** | 80 W | 9.2 s | Insignificant | ~ 0 | n/a | ~ 0 | n/a |
| **2-4** | 80 W | 9.2 s | Insignificant | ~ 0 | n/a | Complete | 0.6 mm/s |
| **2-5** | 80 W | 9.2 s | 145 s | 29 cm | 2.1 mm/s | Complete | Acceleratory |
| **2-6** | 80 W | 9.2 s | 115 s | 29 cm | 2.6 mm/s | Complete | Acceleratory |
| **2-7** | 80 W | 9.2 s | 140 s | 5 cm & 0 [ii] | n/a (Nomex) | ~ 0 (Nomex) | n/a (Nomex) |
| **2-8** | 97 W | 30 s | 600 s | ~ 10 cm [iii] | Note (iv) | Complete | Acceleratory |
| **2-9** | 97 W | 30 s | 900 s | ~ 10 cm [iii] | Note (iv) | Complete | Acceleratory |
| **3-1** | 182 W | 8 s | 300 s | ~ 84 cm | 2.3 mm/s | Complete | Acceleratory |
| **3-2** | 182 W | 8 s | 60 s | ~ 10 cm | 0.98 mm/s | ~ 0 | n/a |

## Cygnus

The Enhanced variant of Cygnus is seen approaching the ISS

| | |
|---|---|
| **Manufacturer** | Orbital ATK |
| **Country of origin** | United States |
| **Operator** | NASA |
| **Applications** | ISS resupply |

| **Specifications** | |
|---|---|
| **Spacecraft type** | Unmanned cargo vehicle |
| **Design life** | 1 week to 2 years[1] |
| **Dry mass** | 1,500 kg (3,300 lb) (Std)<br>1,800 kg (4,000 lb) (Enh) |
| **Payload capacity** | 2,000 kg (4,400 lb) (Std)<br>3,200 kg (7,100 lb) (Enh on Antares 230)[2][3]<br>3,500 kg (7,700 lb) (Enh on Atlas V 401)[2][4] |
| **Dimensions** | 5.1 m × 3.07 m (16.7 ft × 10.1 ft) (Std)<br>6.3 m × 3.07 m (20.7 ft × 10.1 ft) (Enh)[5][6] |
| **Volume** | 18.9 $m^3$ (670 cu ft) (Std)<br>27.0 $m^3$ (950 cu ft) (Enh)[3] |
| **Power** | 3.5 kW |