



Results of Large-Scale Spacecraft Flammability Tests

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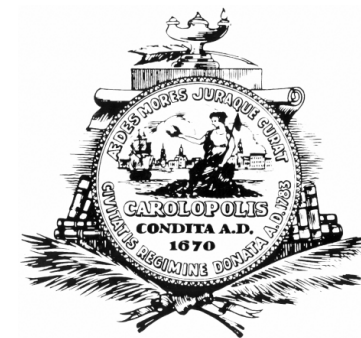
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Introduction

- Understanding ignition and flame growth → fire safety protocols for space
 - NASA relies on a test performed on Earth to rate materials for space use [NASA-STD-6001B]
 - If a material passes the test then it is assumed to be safe in the microgravity environment of space
 - Evidence that some materials which do not burn on Earth will burn in space in similar conditions
- An upward-spreading (concurrent-flow) flame on Earth is nearly always more hazardous than a downward-spreading (opposed-flow) flame.
 - Which configuration is more hazardous in reduced gravity?
 - Depends on flow speed, so extrapolating Earth-based test results to space is even further complicated.





Introduction

- Although large-scale fire tests on Earth are common, they had never been attempted in a space experiment for obvious reasons of practicality and safety.
- Fire remains a catastrophic hazard for spaceflight where the crew has very limited or no escape options.
- The spread and growth of a fire, combined with its interactions with the vehicle cannot be expected to scale linearly based on small-scale test data, and so there remains a substantial gap in our understanding of fire behavior in spacecraft.





Saffire Objectives

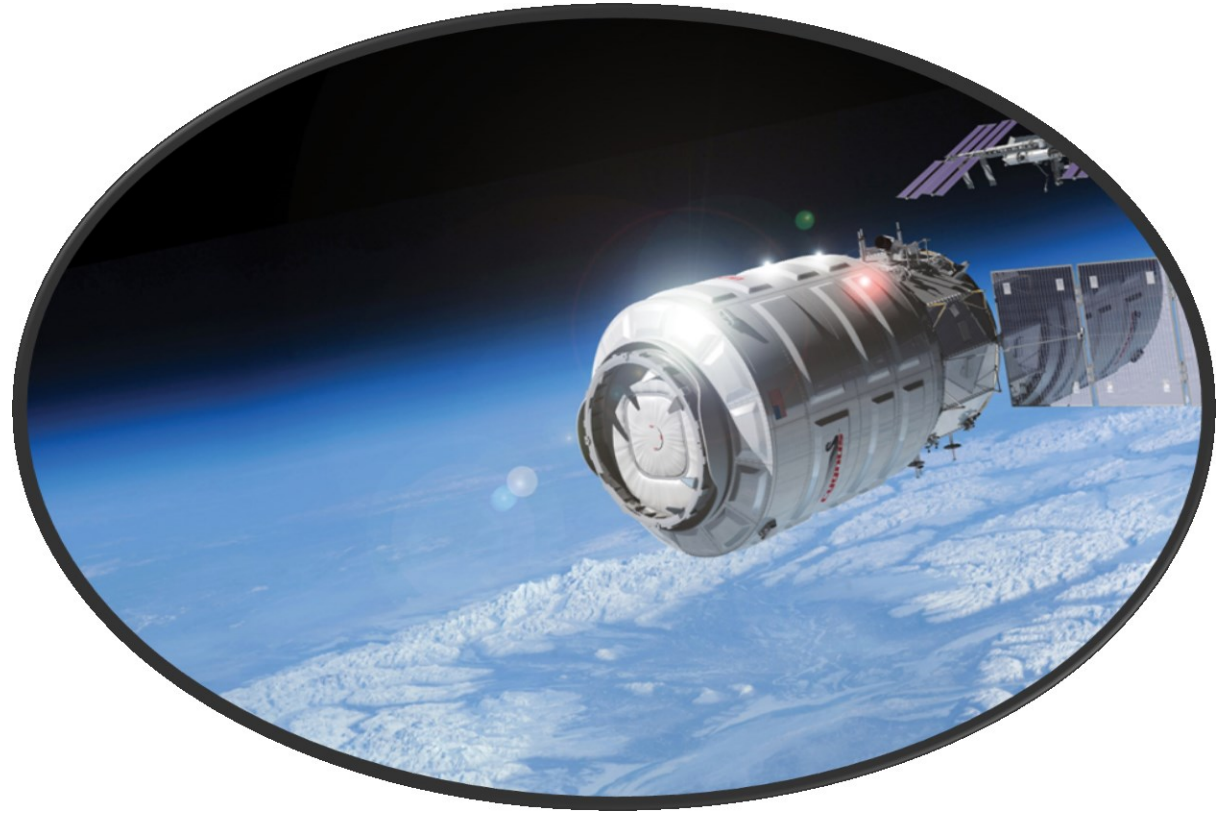
Needs:

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

Objectives:

- ◆ *Saffire 1: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release)*
- ◆ *Saffire 2: Verify oxygen flammability limits in low gravity*
- ◆ *Saffire 3: Same as Saffire 1 but at higher flow speed.*

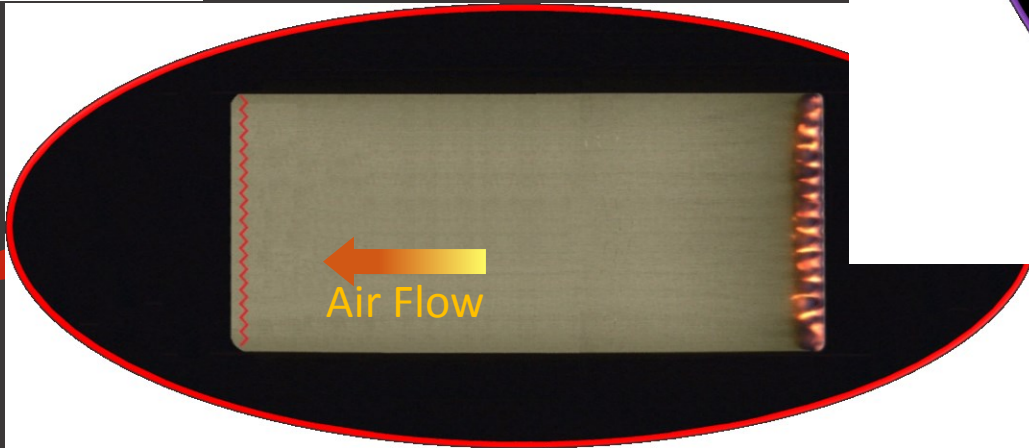
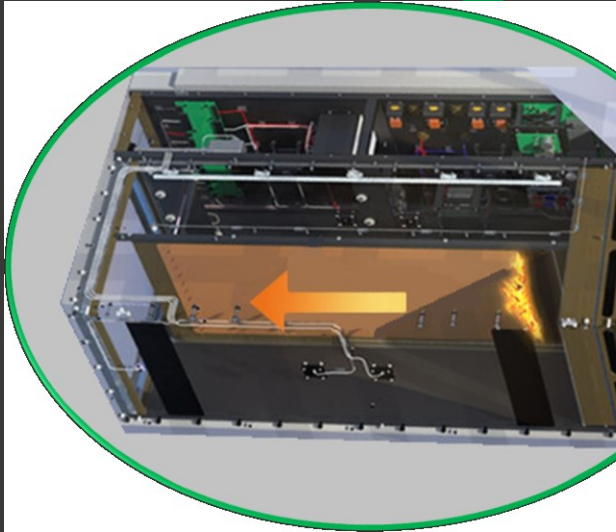
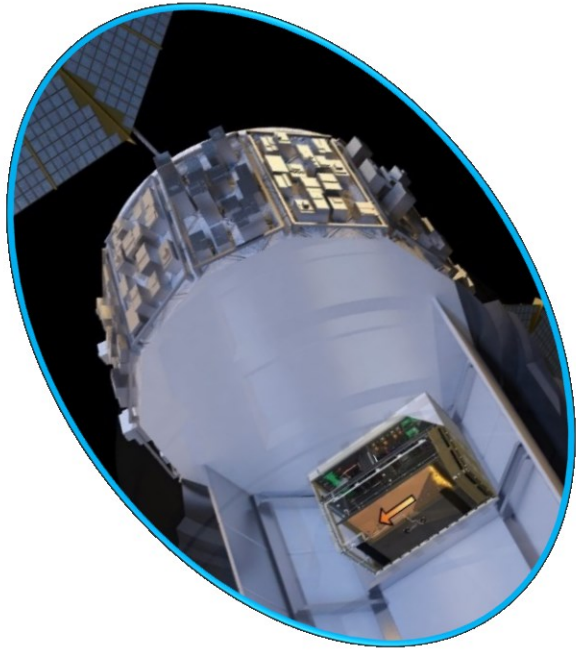
- *Data obtained from the experiment will be used to validate modeling of spacecraft fire response scenarios*
- *Evaluate NASA's normal-gravity material flammability screening test for low-gravity conditions.*

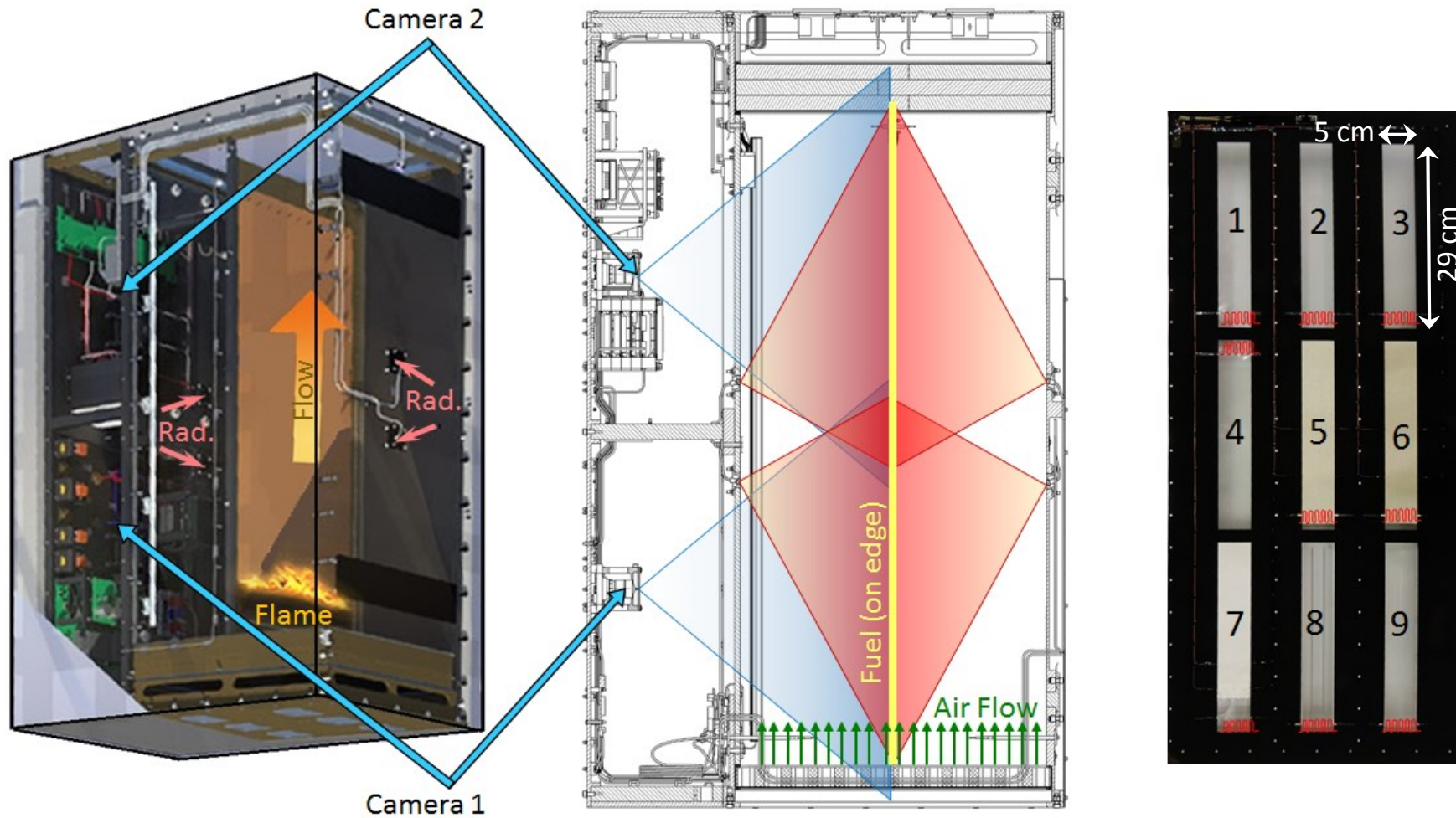




Experiment

- The Saffire experiments investigated intentionally-set, large-scale fires inside a spacecraft. For safety, they were conducted in unoccupied resupply vehicles for the International Space Station (ISS).
- The vehicles launched to the ISS with Saffire stowed onboard. Saffire stayed in the resupply vehicle and remained dormant while the vehicle was berthed with the ISS and its supplies were unloaded. After all supplies had been transferred, the crew carefully stowed ISS trash in the resupply vehicle, leaving adequate room for air circulation.
- Once the vehicle departed ISS, the Saffire tests were completed and all data was relayed to Earth. Finally, the vehicle was guided for destructive re-entry into the Earth's atmosphere.





The Saffire flow duct (18" x 20"). Two cameras and four radiometers are indicated. Camera and radiometer fields of view are shown by the cones, shaded blue and red, respectively.

Saffire-II sample card with the nine samples, and ignition locations are indicated in red.

There were six sample thermocouples per flight.

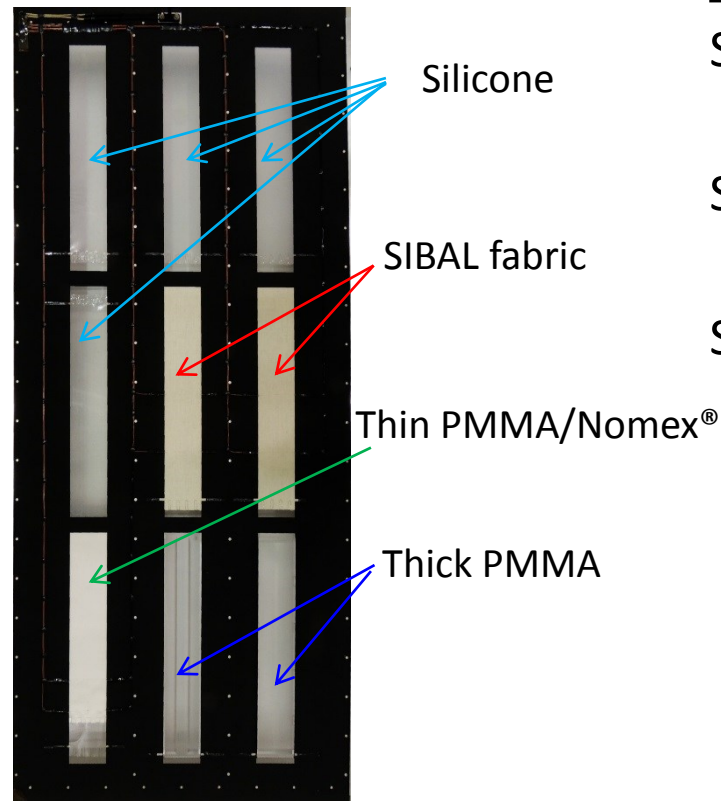


Configurations

Saffire 1



Saffire 2 (samples 5 cm wide)



Ignition power:

Saffire 1: 165 W (for 8 s); 4.1 W/cm (per unit fuel width)

Saffire 2, all samples except thick PMMA:

80 W (for 9.2 s); 16 W/cm (per unit fuel width)

Saffire 2, thick PMMA:

97 W (for 30 s); 19.5 W/cm (per unit fuel width)

Average flame power:

Saffire 1: 1200 +/- 300 W

Saffire 2: (SIBAL fabric) 200 +/- 50 W

Saffire 2: (Thick PMMA) 600 +/- 100 W

Saffire-2 Description

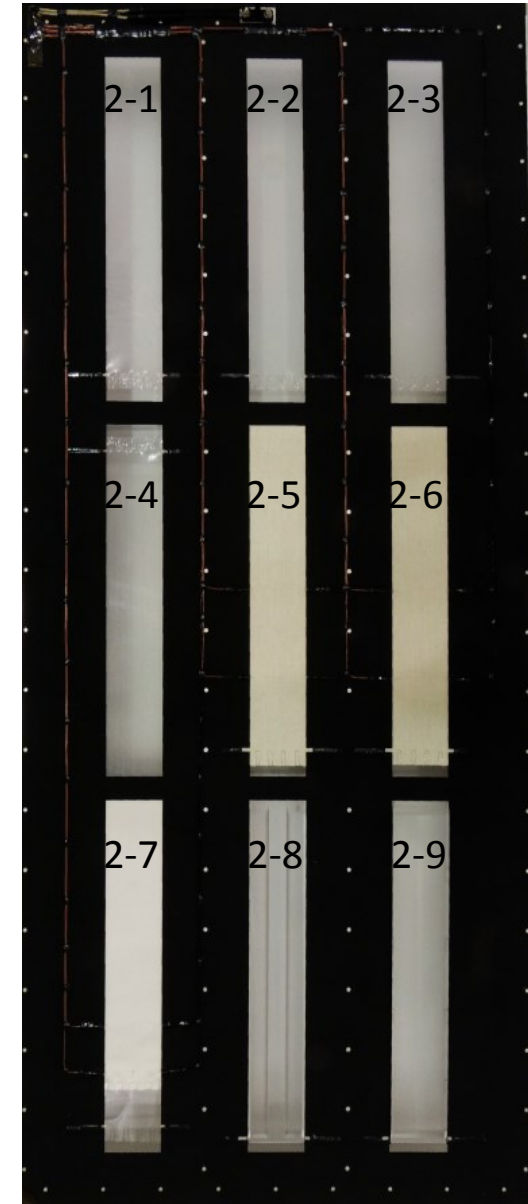
Nine samples; 5 cm wide by 29 cm long
20 cm/s flow for all tests except for Sample 2-6 (25 cm/s)
All upward burns except Sample 2-4 was downward
Initial oxygen concentration 22.1% (ISS reading,
slightly higher than Saffire-1's 21.7%)

Samples 2-1 to 2-4 were silicone sheets 0.27, 0.61, 1.03, and 0.37 mm thick.

Samples 2-5 and 2-6 were cotton-fiberglass fabric identical to that used in Saffire-1.

Sample 2-7 had a composite construction, the first 5 cm of which was a thin (0.8 mm) sheet of PMMA and the remainder Nomex[®] fabric (HT 90-40).

Samples 2-8* and 2-9* were PMMA slabs with a nominal thickness of 1 cm. Sample 2-8 had some surface features, including a groove down the center (in the flow direction) on both sides, while Sample 2-9 was flat.

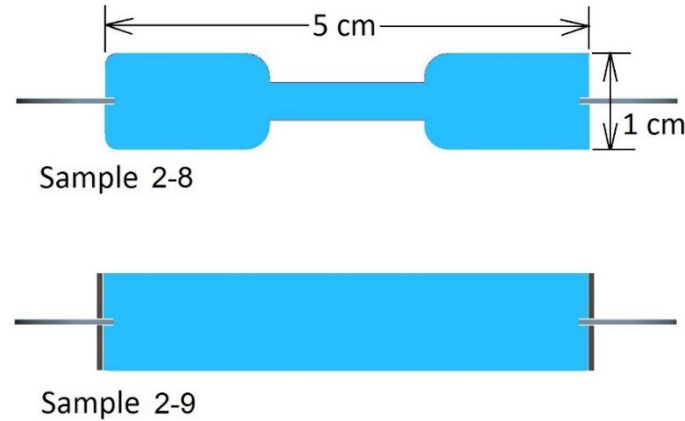


* Results from these samples are described in another paper at this conference.

Saffire-2 Description (con't)

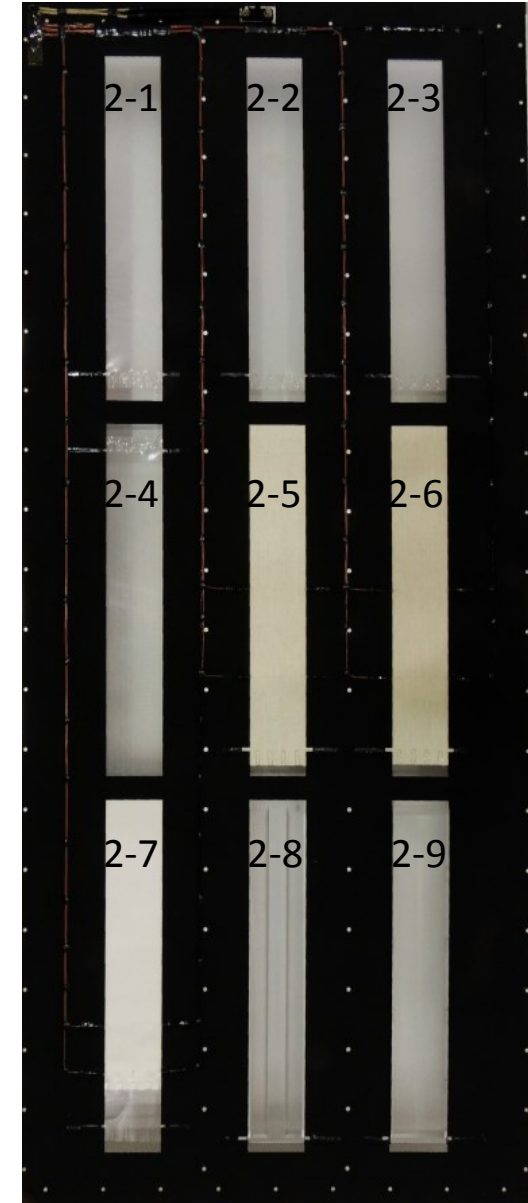
Thick PMMA Sample cross sections:

The middle 1.8-cm-wide portion of Sample 2-8 is only 0.4 cm thick.



The ignition energy and time for samples 2-1 through 2-7 were chosen to mimic the NASA 6001 Test 1 ignition, 736 J applied uniformly for 9.2 s.

Samples 2-8 and 2-9 had slightly more powerful igniters (97 W instead of 80 W) and were left on longer (30 s instead of 9.2 s) to assure ignition of these thick fuels.



Saffire-2; Why Silicone?

Upward burning silicone samples (2-1 to 2-3) were 0.27, 0.61, and 1.03 mm thick.

In upward-burning, normal-gravity tests, these three thicknesses spanned the flammability limits from significant burn, to partial burn, to no burn.

- The 0.27-mm thick samples were almost always completely consumed
- The 0.61-mm thickness burned on average 7.6 cm of the available 30 cm before extinguishing
- The 1.03-mm thickness would not burn at all.

Downward burning silicone sample (2-4) was 0.37 mm thick.

In downward burning, normal gravity tests, this thickness was completely consumed. The next higher thickness tested (0.61 mm) would not burn.

Microgravity behavior was sought:

- How much of the available fuel would be burned?
- Would microgravity prove more or less favorable to flame spread?

Saffire-2; Silicone Results

Results were convincing although rather anticlimactic as none of the silicone samples burned.

When the igniter was powered off, a tiny gas phase flame remained but did not spread and quickly extinguished. The igniters all appeared to function normally and the materials were clearly damaged in the vicinities of the igniters.

It was surprising that not even the thin sample could permit any flame spread, given that it was entirely consumed in normal gravity. Previous experience with cellulosic fuels (paper and fabric) and even PMMA suggested that if a flame could persist in upward 1-g tests then it would also burn in microgravity at a moderate flow speed which was less than that typical in buoyant flow.

Saffire-2; Silicone Results (con't)

The behavior of silicone in microgravity is perplexing perhaps due to its complex burning:

- Silicone produces fine silica powder as it burns, which could be deposited on the fuel and impede pyrolysis.
- The relatively-larger buoyant flow speeds could sweep out the silica at a high enough rate so that it does not hamper combustion.
- Silicone fuel becomes quite irregular as it burns, cracking and flaking off in complex ways. The surface reaction details and geometrical effects could significantly impact the observed results. Buoyant flow might aid the cracking and flaking processes which in turn could promote combustion as fresh fuel is exposed.

More work is needed to understand the differences between the normal and micro-g flammability of silicone.

- It would be interesting to repeat these tests in microgravity but at a much higher flow speed of around 60 to 80 cm/s, which is more typical of the level in 1-g.
- Perhaps the nature of the buoyant boundary layer compared to the forced convection boundary layer is contributing to the flammability differences.

Saffire-I Description

Large sample (40.6 cm x 94 cm)

Flow speed of 20 cm/s

Initial oxygen concentration 21.7% (ISS reading)

- Only concurrent-flow test was planned; opposed-flow test was a contingency.
- Everything performed nominally for the first test which was allotted 420 s before the air flow turned off.
- About 90% of the fuel burned in the first test leaving 10% unburned, allowing a meaningful opposed-flow test to be completed.





Fuel characteristics (“SIBAL” fabric)

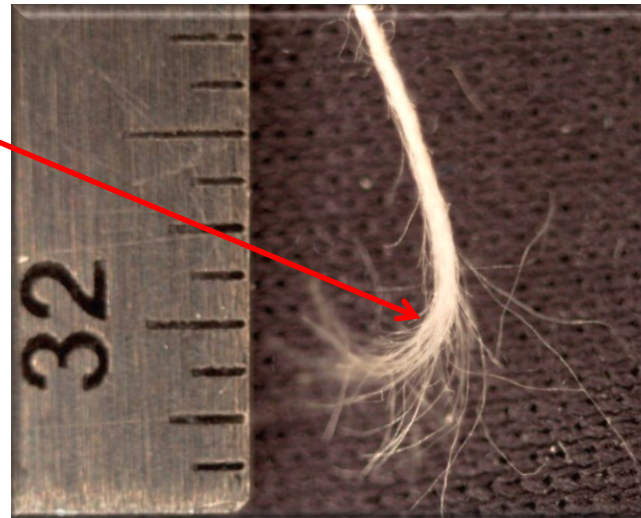
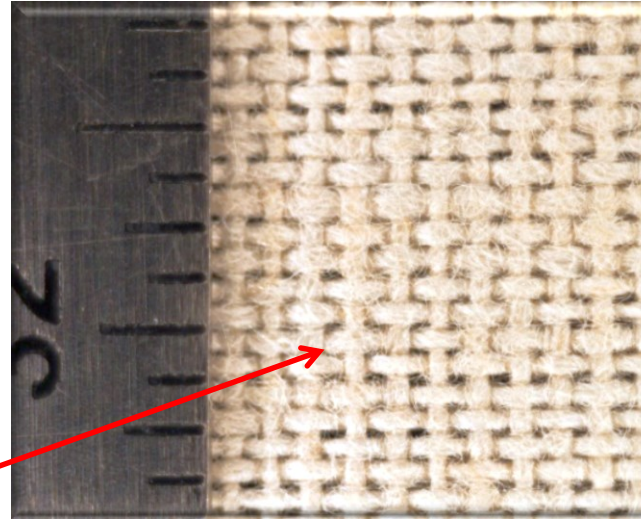
75% cotton, 25% fiberglass blend

Simple weave pattern (60 x 40 threads per inch)

Cotton and fiberglass fibers intermingled

Overall area density: 18 mg/cm²

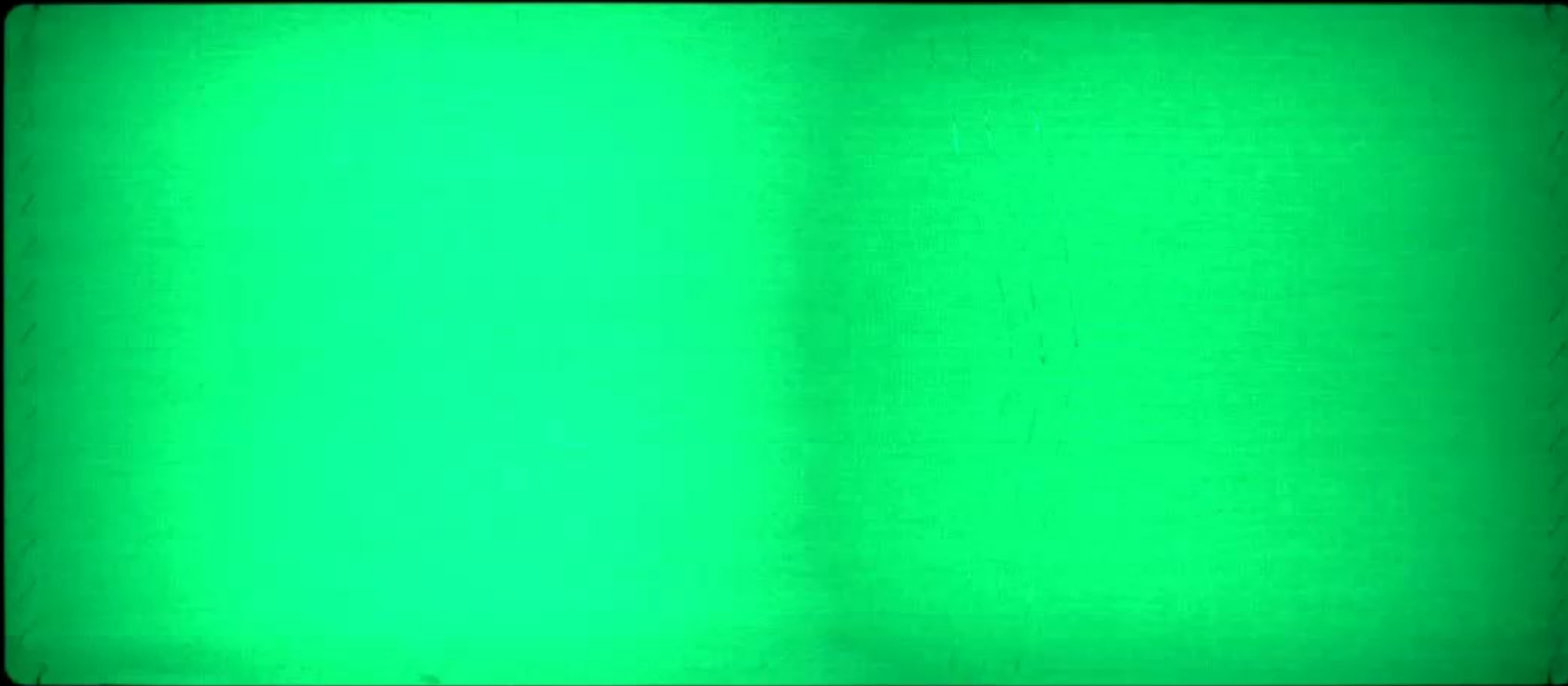
Fuel sizes (W x L): 40.6 x 94 cm and 5 x 29 cm





SIBAL Fabric Results

- 40.6-cm-wide concurrent-flow test: flame ignited across the bottom of the fuel
 - At ignition, the flame was mostly bright yellow and relatively vigorous but it soon developed a blue base and a pattern of orange radiation coming from incandescent soot
 - Initially the flame length fluctuated at about 1.4 Hz before finally becoming more stable at about 90 s
 - After the flame had passed, exothermic surface smolder spots burning some of the leftover fuel were visible
 - The flame burned the entire allotted test time of about 7 min. at which point the air flow was shut off and the flame immediately extinguished
- 40.6-cm-wide opposed-flow test: flame ignited across the top of the fuel
 - There was a small but sufficient amount of fuel remaining after the concurrent-flow test of the first experiment to permit an opposed-flow test
 - Only about 10% of the fuel remained after the concurrent test, but that was enough to make conclusions about the opposed-flow flame spread and development
- 5-cm-wide concurrent-flow tests: flame ignited across the bottom of the fuel
 - Two flow speeds tested; 20 and 25 cm/s



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



Flame Fluctuations

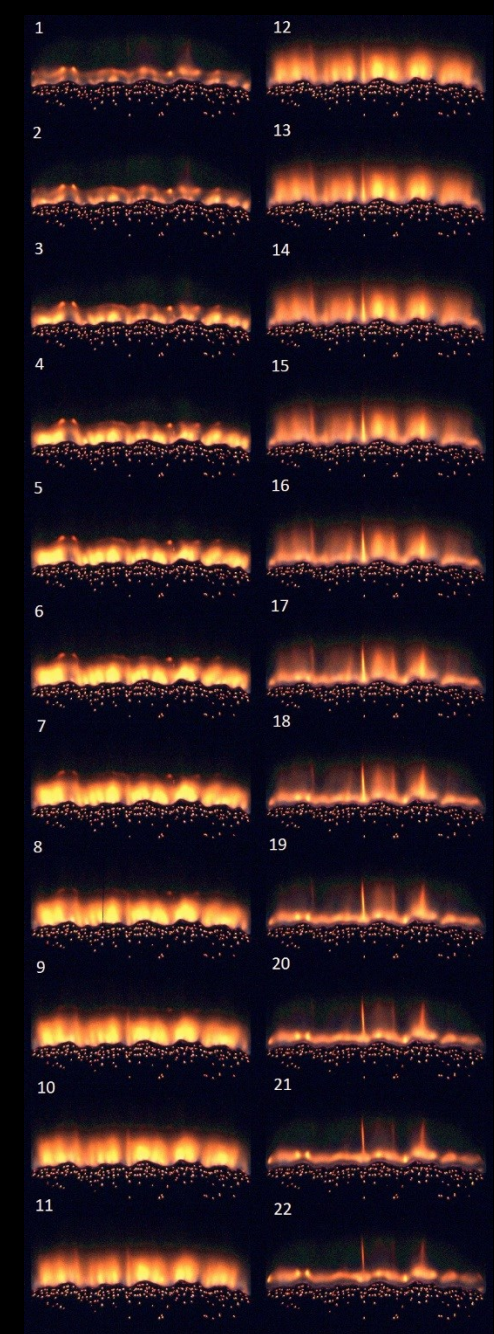
Microgravity image sequence (30 Hz) of 40.6-cm-wide fabric burning in air at 20 cm/s concurrent-flow speed.

Images start 24 s after the igniter is turned off.

At first, the flame length and brightness varied significantly at a periodic frequency of about 1.4 Hz before finally becoming more stable at about 90 s into the test.

However, subtle fluctuations in flame length and brightness persisted for the duration of the test albeit at a slightly slower frequency of around 0.75 Hz.

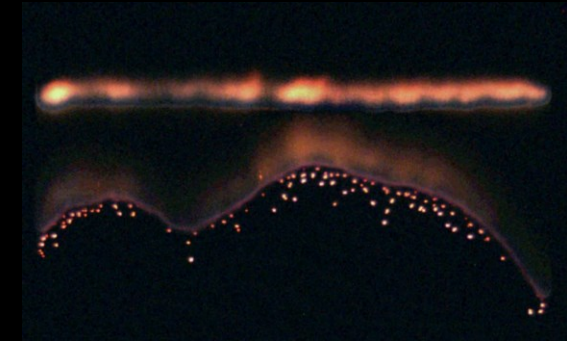
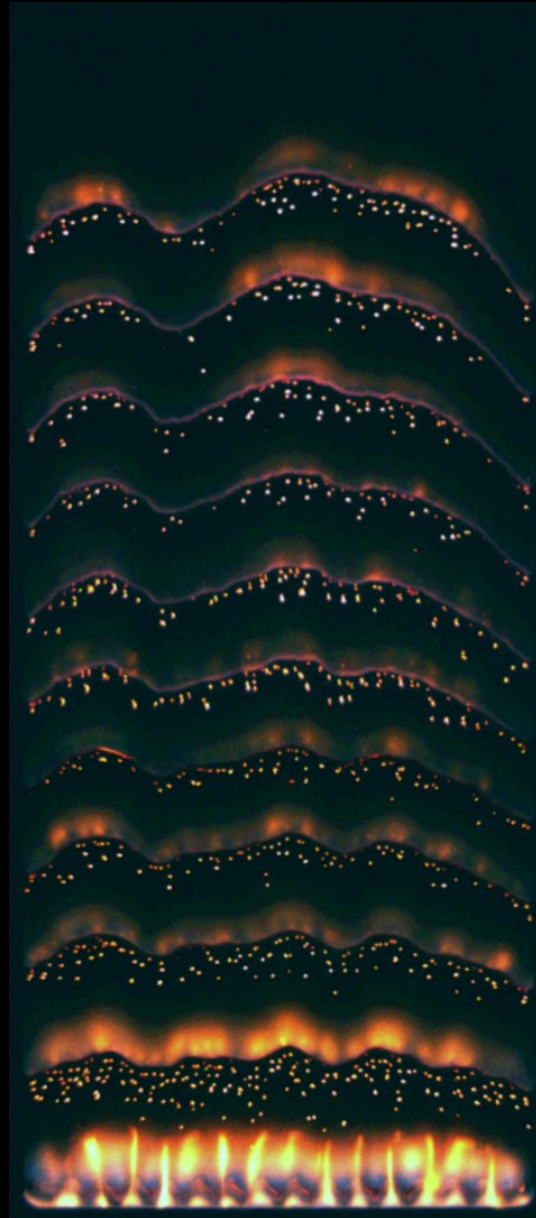
The reason for the fluctuation is unclear. It may be due to a flow oscillation which is present even in the cold flow, or it may be the result of the flame interacting with the flow field in the first part of the flow duct





40.6-cm-wide concurrent-flow flame montage

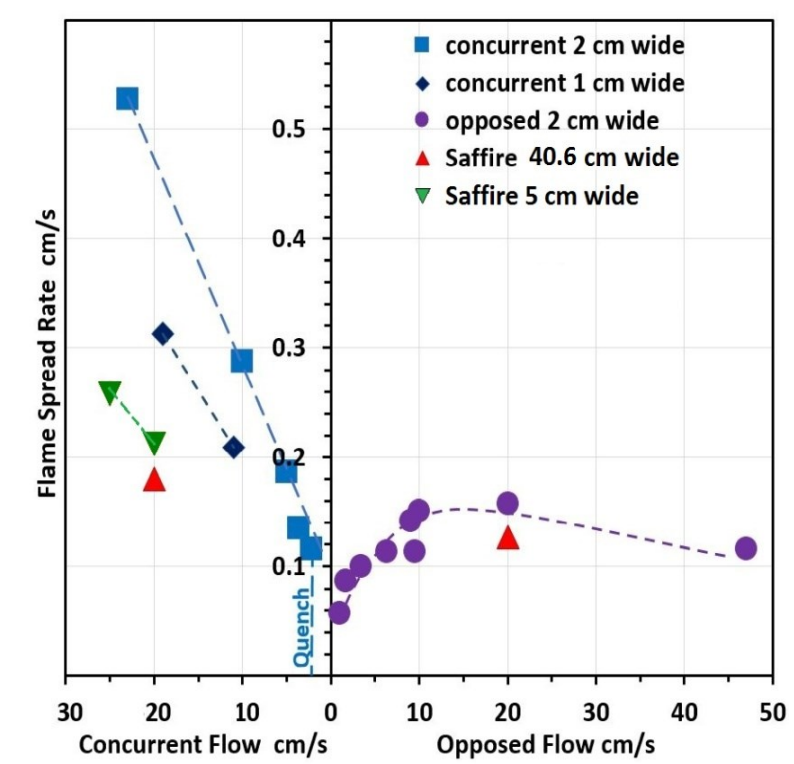
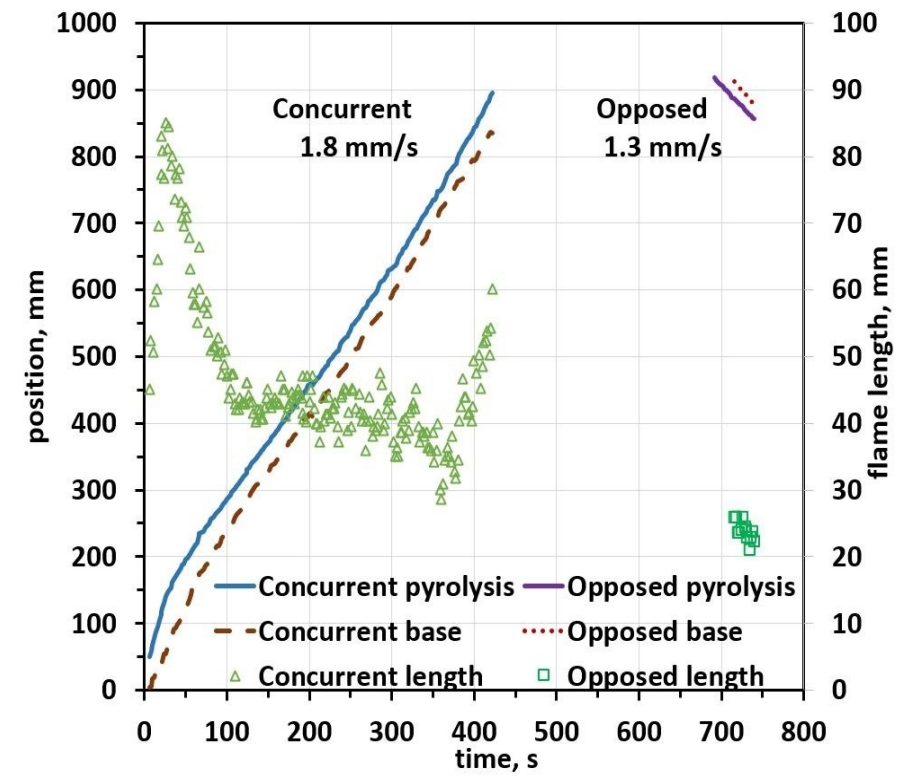
(Each image is 40 s apart)



Comparison of concurrent and opposed-flow images



SIBAL Fabric Results (con't)



Left: Flame base and pyrolysis position for concurrent and opposed-flow test in Saffire-1. Air flow speed was 20 cm/s.

Right: Spread rate summary for cotton/fiberglass fabric burning in microgravity. Concurrent flames are shown to the left of the origin, and opposed to the right.

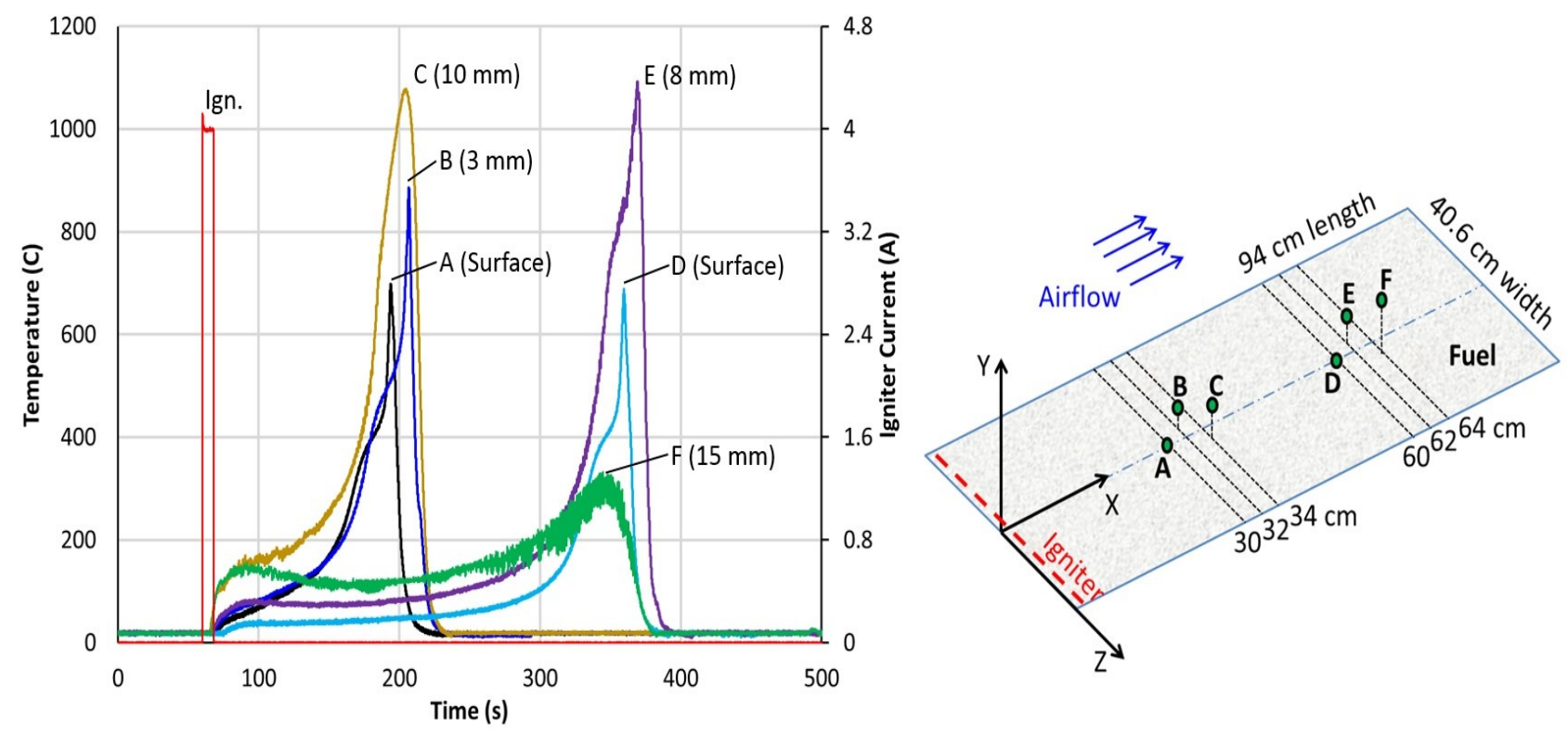


SIBAL Fabric Results (con't)

- The flame position curves show that spread rate is steady for most of the tests.
- 40.6-cm wide sample
 - For the concurrent flame, the length reaches a plateau value of around 40 mm, while the opposed-flow flame is a bit shorter at 24 mm.
 - The average concurrent-flow flame spread rate is 1.8 mm/s. The opposed-flow flame average spread rate 1.3 mm/s.
- The flame spread rate for the 5-cm-wide sample is marginally faster compared to the spread rate for the 40.6-cm-wide sample for the same flow speed of 20 cm/s (2.1 compared to 1.8 mm/s).
 - This is partly due to the slightly higher starting oxygen percentage (22.1% vs. 21.7%).
 - However, the 5-cm-wide sample might have spread faster because of larger side entrainment effects compared to the wide sample.



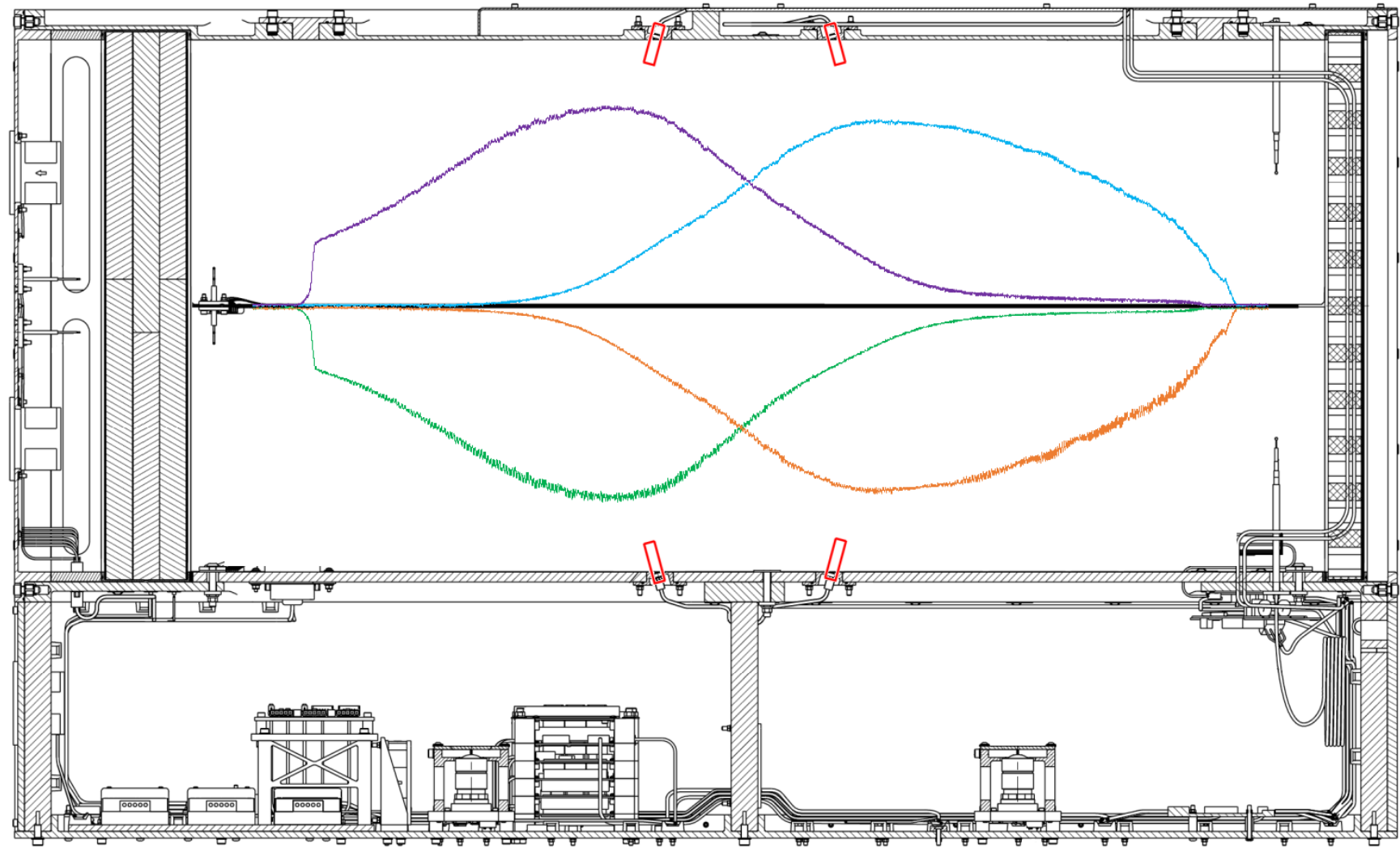
SIBAL Fabric Results (con't)



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.



SIBAL Fabric Results (con't)



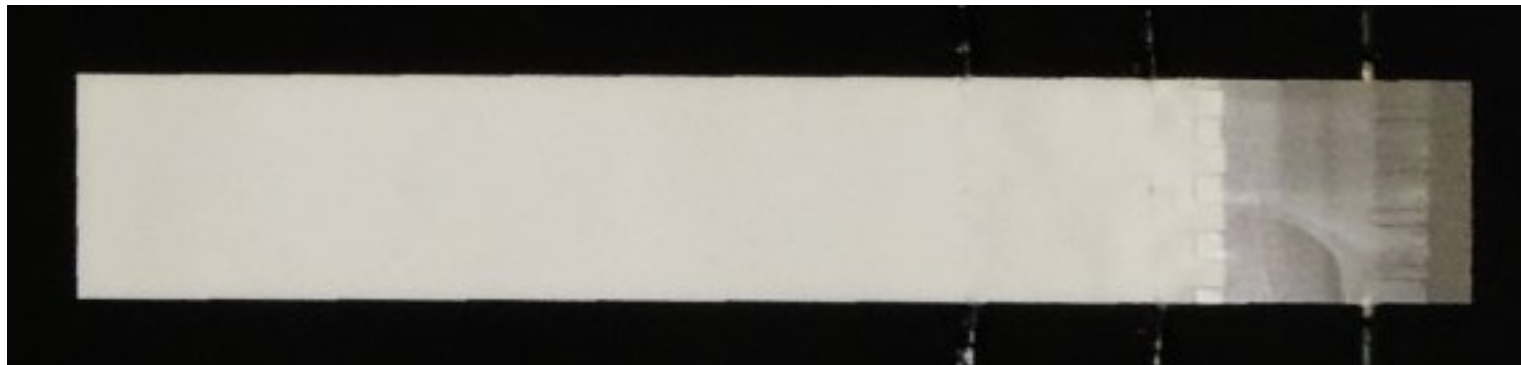


Composite PMMA-Nomex[®] Results (Saffire-2, Sample 2-7)

Purpose: see how a material rated “safe” by the NASA 6001 Test 1 standard test reacted during extended exposure to a flame in microgravity.

The material is a meta-aramid fabric commonly used on the ISS called Nomex[®] HT90-40. On Earth, it will only burn if the oxygen concentration is increased to around 24 to 25%.

A thin sheet of PMMA (0.8 mm thick) comprised the first 5 cm of the length. Then there was an overlap area about 7 mm long where the PMMA and the fabric were in intimate physical contact. The remainder of the sample was Nomex fabric.



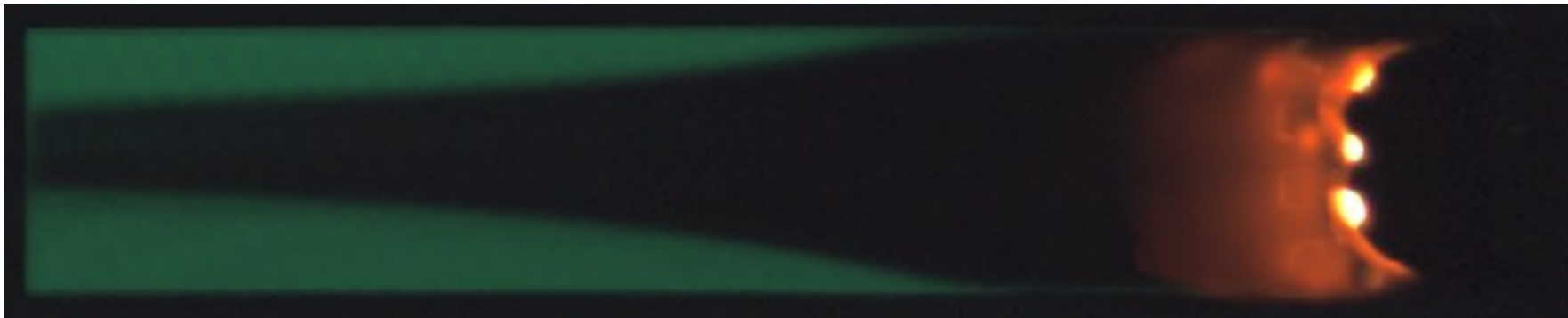


Composite PMMA-Nomex[®] Results (Saffire-2, Sample 2-7) (con't)

It took about two minutes for the PMMA to be consumed, all the while the flame plume was extending over and heating the base of the Nomex[®] fabric.

The average flame power from the PMMA (assuming complete conversion of the fuel) was 460 ± 50 W. Despite this significant heating load, the fabric was not ignited.

The first 1-cm of the fabric was significantly damaged, the first 5-cm was completely blackened, and the remainder had a black streak down its center. However, some of this discoloration may have been caused by deposition of soot from the PMMA flame on the fabric, and not necessarily pyrolysis of the fabric itself.





Summary and Conclusions

- For the first time, a large-scale fire was intentionally set inside a spacecraft while in orbit.
- In addition, smaller samples of various materials were burned in a subsequent spaceflight.
- Unlike 1-g, the results revealed that a steady flame could be achieved even for a wide sample burning in concurrent-flow.
- The flames spread more slowly than prior tests in smaller ducts. This behavior of the flame demonstrated the importance of confined spaces for potential spacecraft fires.
- Flammability of silicone in microgravity appears to be reduced compared to normal gravity, at least for the flow speeds tested.
- Nomex[®], a common material used on the ISS and rated “safe,” could not be ignited even when bathed by a pilot flame.

There are plans for the Saffire project to continue with additional experiments examining the effects of enhanced oxygen at reduced pressure.

Results will increase our knowledge of how a fire spreads in a large enclosure, and what effects the fire has on the spacecraft. This understanding will influence vehicle design and materials screening, ultimately increasing the safety of the crew.



Acknowledgements



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Backup slides



Table I. Summary of Samples, Test Conditions, and Selected Results

Sample	Material	Width	Thickness	Length	Flow	Direction	$\Delta \%O_2$ ⁱ
1-1	Cotton-Fiberglass	40.6 cm	0.37 mm	94 cm	20 cm/s	Concurrent	21.7 to 21.5
1-2	Cotton-Fiberglass	40.6 cm	0.37 mm	~ 10 cm	20 cm/s	Opposed	~ 21.5
2-1	Silicone	5 cm	0.27 mm	29 cm	20 cm/s	Concurrent	~ 22.1
2-2	Silicone	5 cm	0.61 mm	29 cm	20 cm/s	Concurrent	~ 22.1
2-3	Silicone	5 cm	1.03 mm	29 cm	20 cm/s	Concurrent	~ 22.1
2-4	Silicone	5 cm	0.37 mm	29 cm	20 cm/s	Opposed	~ 22.1
2-5	Cotton-Fiberglass	5 cm	0.37 mm	29 cm	20 cm/s	Concurrent	~ 22.1
2-6	Cotton-Fiberglass	5 cm	0.37 mm	29 cm	25 cm/s	Concurrent	~ 22.1
2-7	PMMA & Nomex	5 cm	0.85 & 0.37 mm	5 & 24 cm	20 cm/s	Concurrent	~ 22.1
2-8	PMMA	5 cm	See Fig. 5	29 cm	20 cm/s	Concurrent	22.1 to 22.0
2-9	PMMA	5 cm	1 cm	29 cm	20 cm/s	Concurrent	22.0 to 21.9

... Table I (continued)

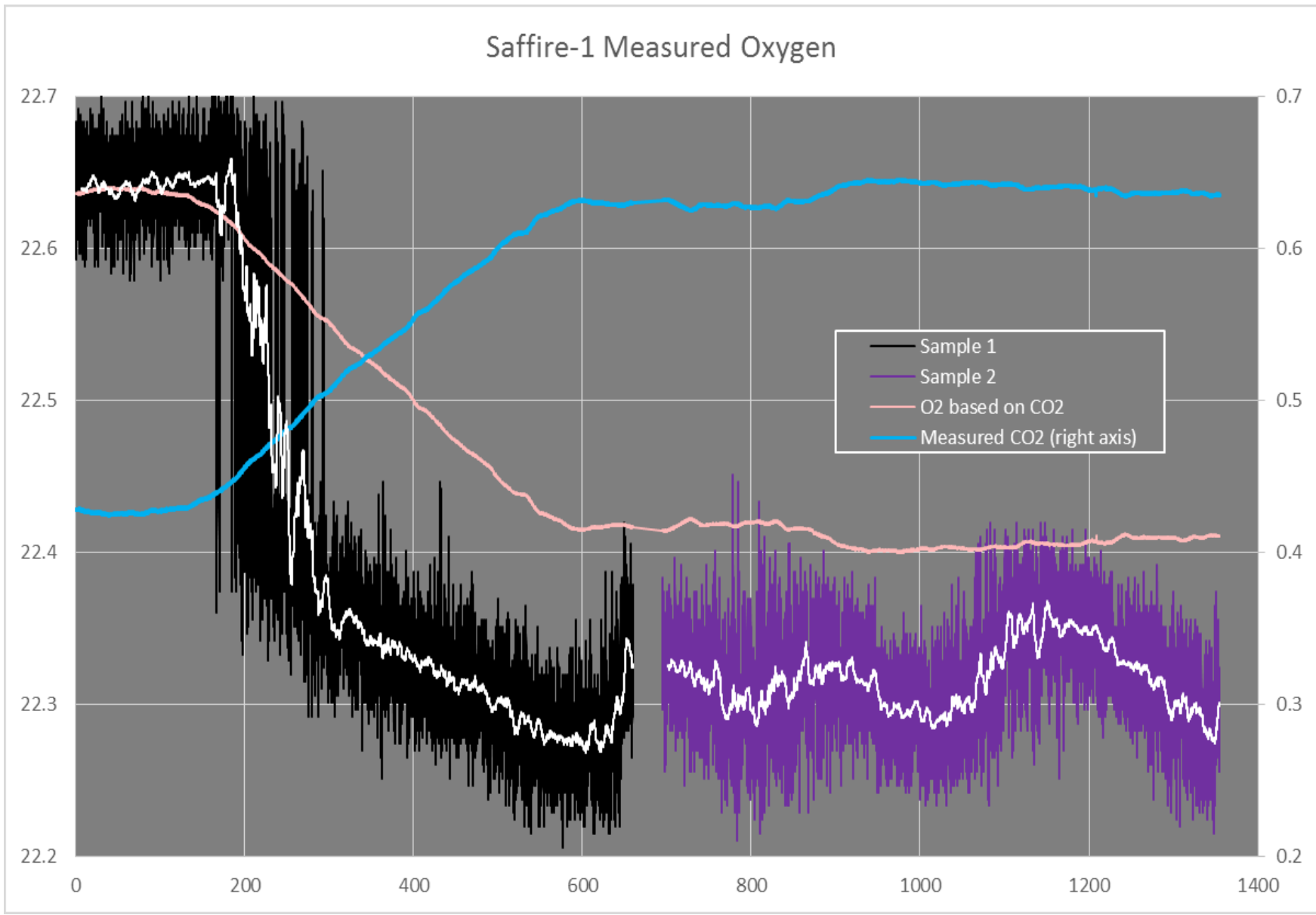
Sample	Ignition Power	Ignition Time	Burn Duration	μ -g Burn Length	μ -g Spread Rate	1-g Burn Length	1-g Spread Rate
1-1	182 W	8 s	420 s	~ 84 cm	1.8 mm/s	Complete	Acceleratory
1-2	182 W	8 s	70 s	~ 10 cm	1.3 mm/s	~ 0	n/a
2-1	80 W	9.2 s	Insignificant	~ 0	n/a	~ Complete	Acceleratory
2-2	80 W	9.2 s	Insignificant	~ 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

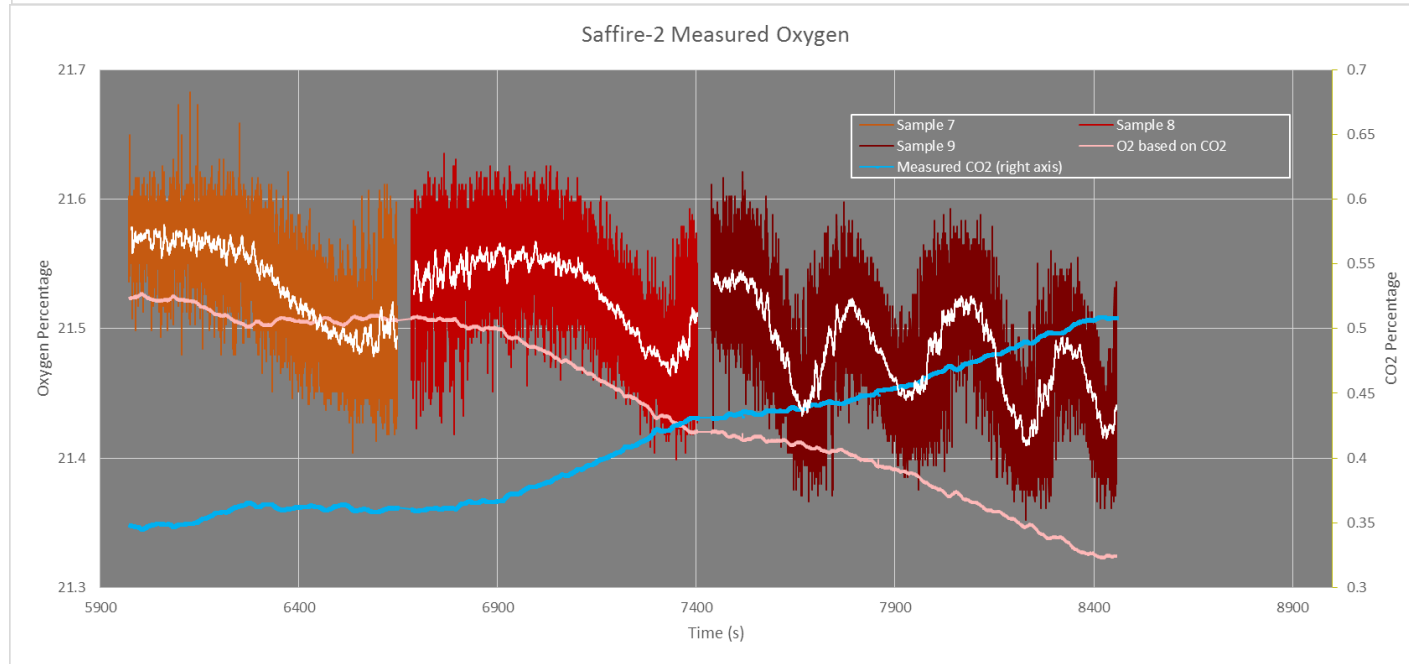
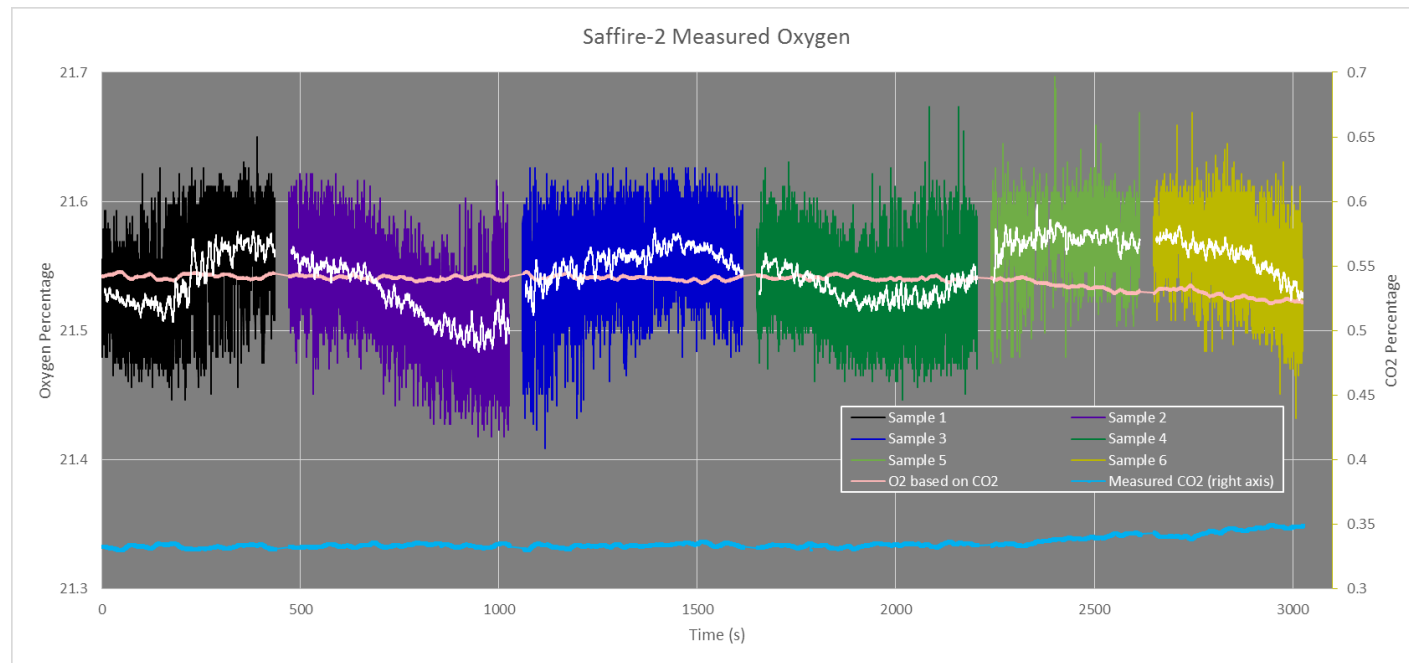
ⁱ Derived from measured CO₂ production and referenced to initial O₂ concentration reported by ISS.

ⁱⁱ The PMMA portion was completely consumed but the Nomex was not ignited.

ⁱⁱⁱ This is the length of fuel with significant visible damage.

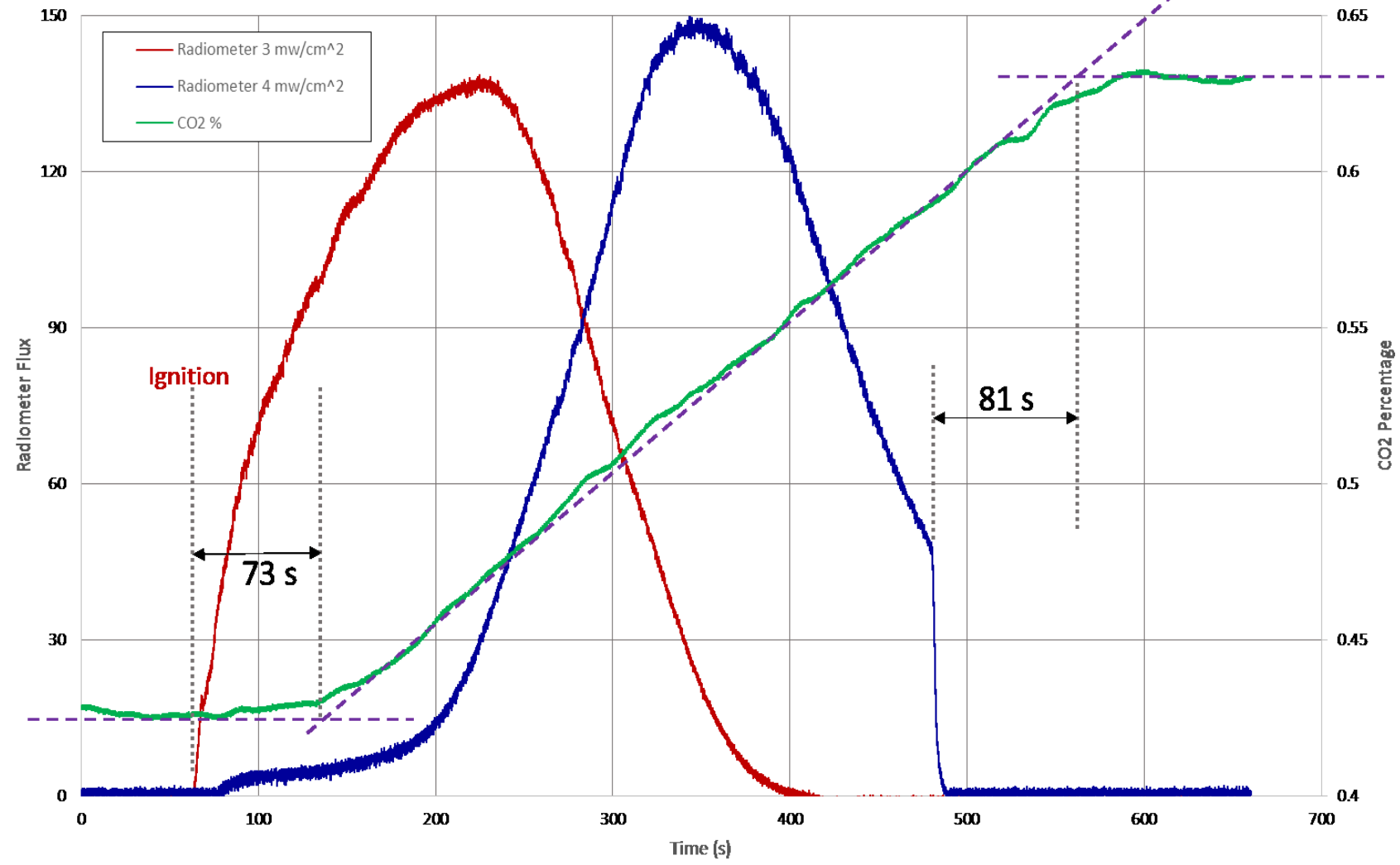
^{iv} The flames remain anchored at the base of the sample which has a very slow regression rate (0.01 to 0.04 mm/s).





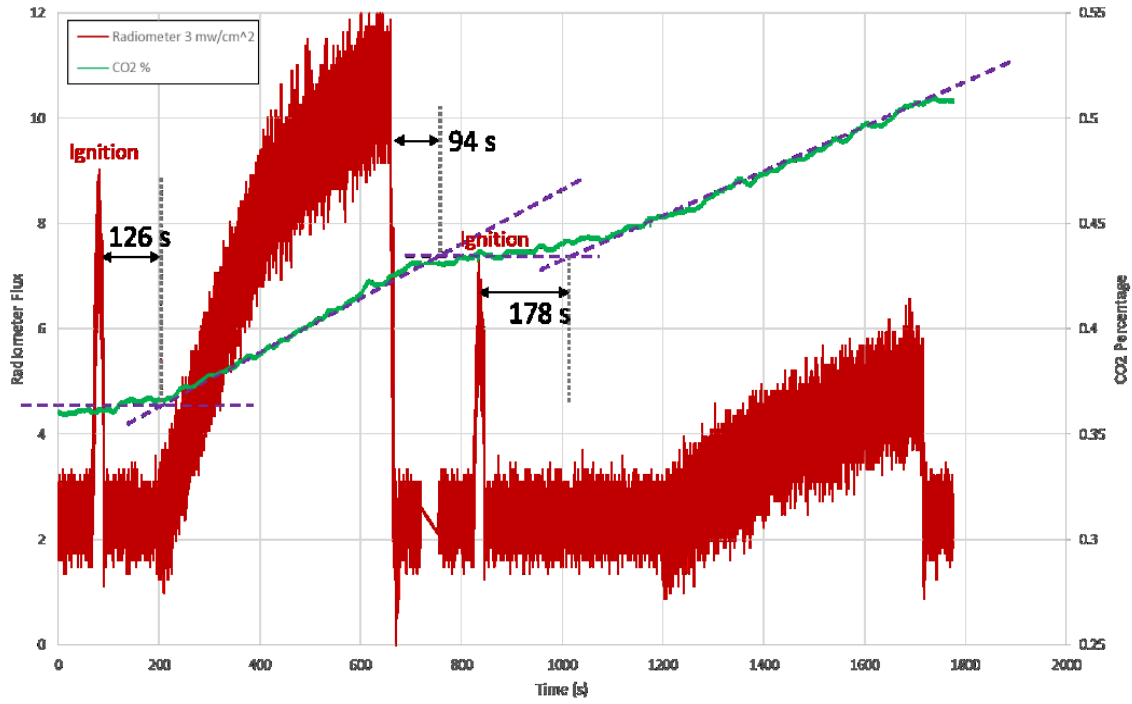


Saffire-1 Sample 1

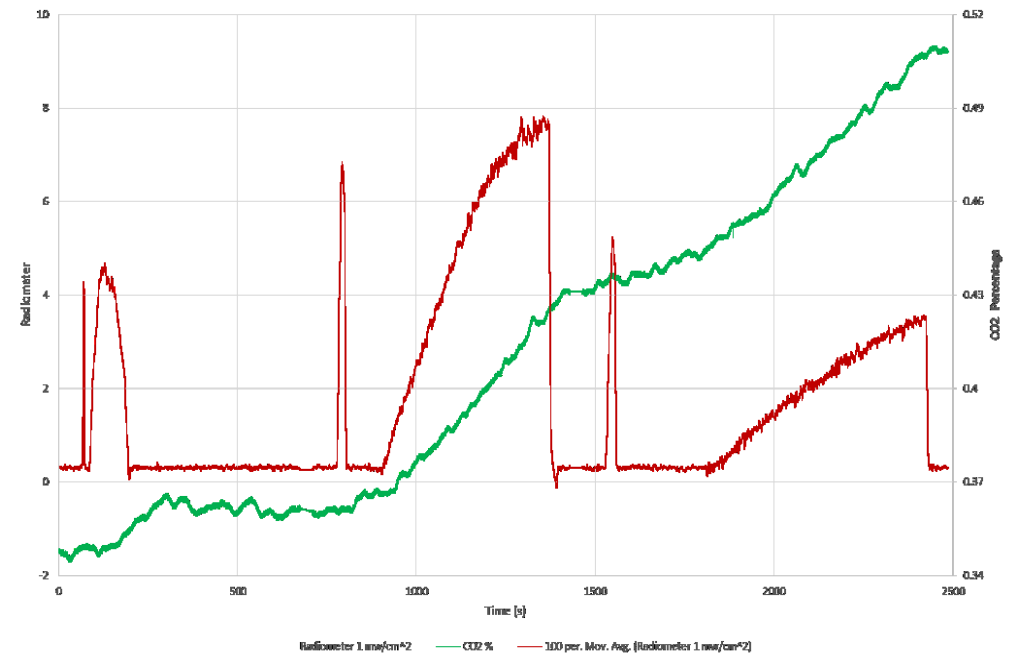


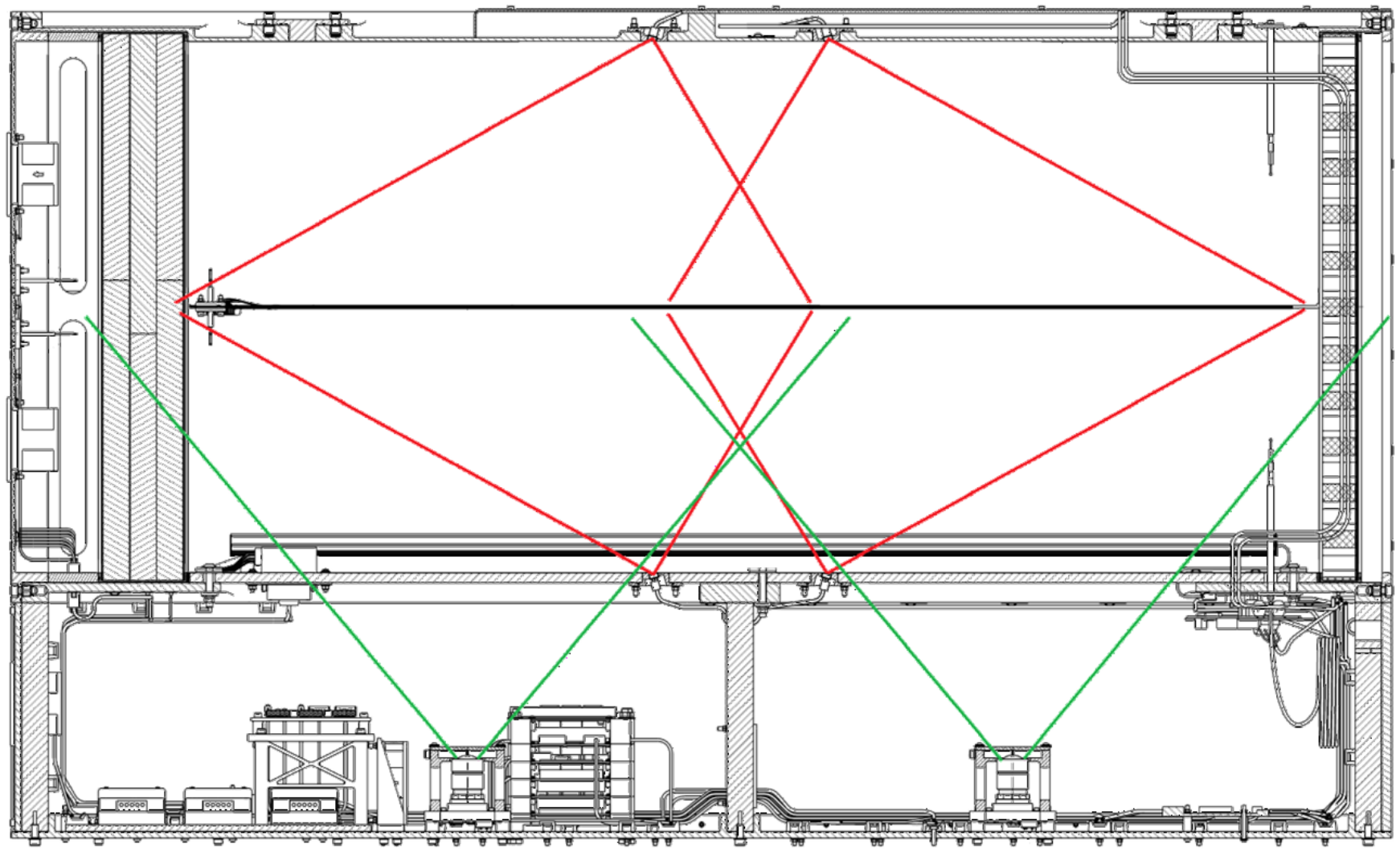


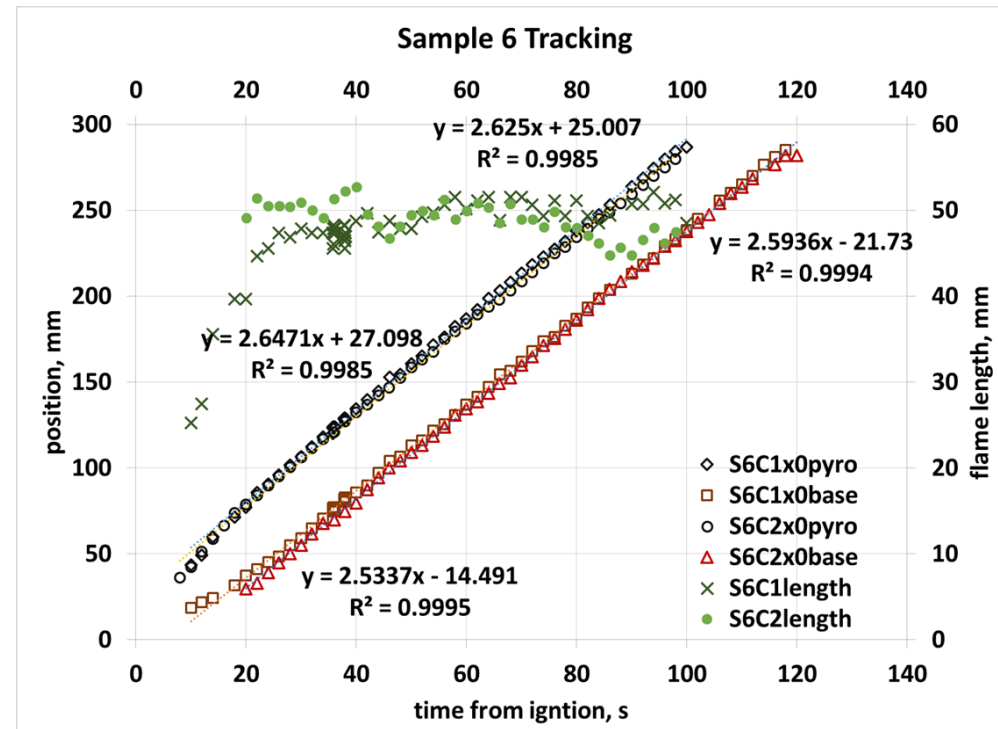
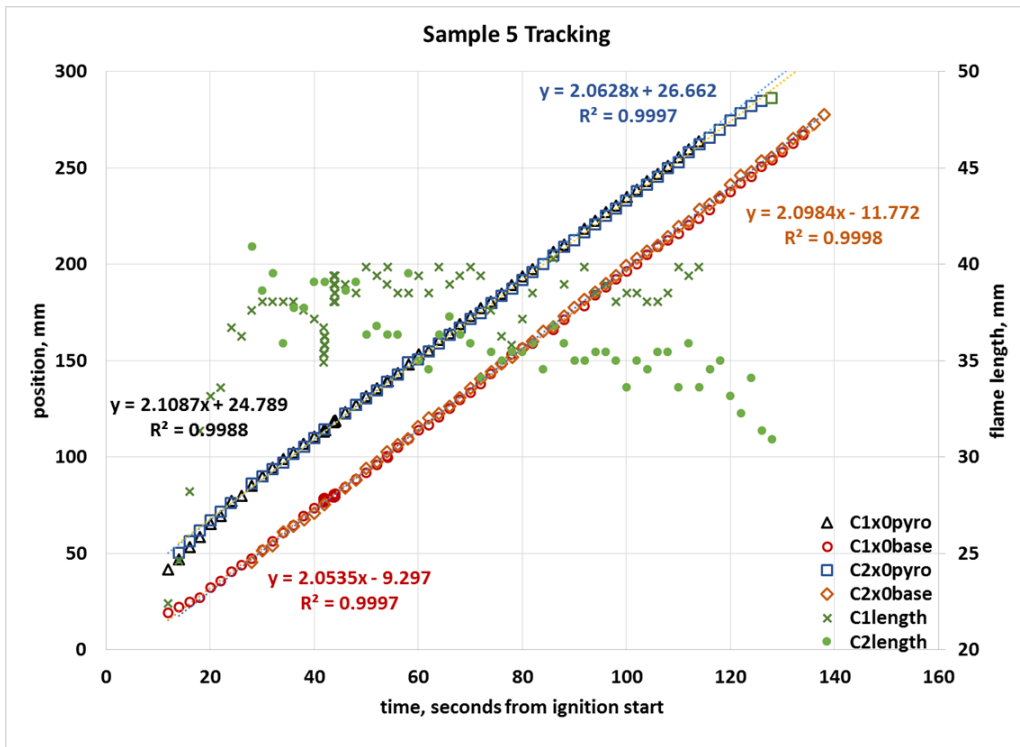
Saffire-2 Samples 8 and 9



Saffire-2 Samples 7, 8, and 9







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) 1,800 kg (4,000 lb) (Enh)
Payload capacity	2,000 kg (4,400 lb) (Std) 3,200 kg (7,100 lb) (Enh on Antares 230) ^{[2][3]} 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) 6.3 m × 3.07 m (20.7 ft × 10.1 ft) (Enh) ^{[5][6]}
Volume	18.9 m ³ (670 cu ft) (Std) 27.0 m ³ (950 cu ft) (Enh) ^[3]
Power	3.5 kW