

# Fire Safety Implications of Preliminary Results from Saffire IV and V Experiments on Large Scale Spacecraft Fires

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**The spread and growth of flames over large solid fuel samples and their effect on the pressurized spacecraft were studied inside the Cygnus spacecraft while in orbit after departing the International Space Station. These experiments were developed by NASA's Advanced Exploration Systems Division in the Human Exploration and Operations Mission Directorate. The ignited materials consisted of poly-methyl methacrylate (PMMA), cotton fabric and a cotton/fiberglass fabric blend. The samples were all 40 cm wide and with various lengths ranging from 18 cm for the PMMA samples to 50 cm for the fabrics. The overall results**

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from these tests and their impact on the spacecraft are presented with emphasis on the fire safety implications of the results. The experiments included, a post-fire cleanup system, vehicle internal volume measurements, and transport of acid gases (HCl and HF). Measurements included video images, flame spread rate, flame temperatures and radiant heat output; energy release through oxygen calorimetry; distributed measurements of CO<sub>2</sub> concentration and temperature at six locations in the spacecraft; CO<sub>2</sub>, CO, O<sub>2</sub>, HF and HCl concentrations; vehicle pressurized volume; and aerosol concentrations. Details of the flame growth and spread are discussed in other papers as are details of the post-fire cleanup system performance. The fire events had a measurable impact on the vehicle pressure, temperature, and carbon dioxide concentration. However, despite having heat release rates up to 10 kW, the average vehicle conditions did not rise to unacceptable levels. The combined results of the experiments provide significant new understanding of the impact of sample and flow duct height on flame spread and growth in addition to an improved perspective of the impact of a fire event on a spacecraft.

## Nomenclature

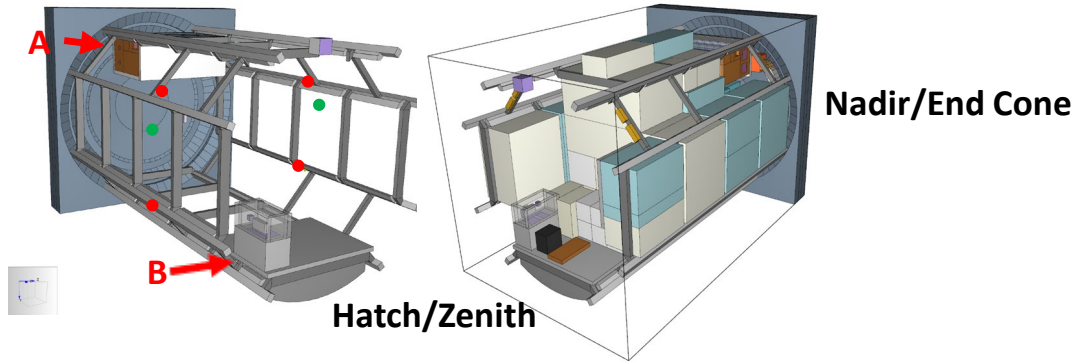
FFD	=	Far Field Diagnostics
NG	=	Northrup Grumman
MMA	=	methyl methacrylate
PMMA	=	polymethyl methacrylate
SFU	=	Saffire Flow Unit
SIBAL	=	Solid Inflammation Boundary at Low Speed

## I. Introduction

Assessing the risk due to spacecraft fires and developing measures to prevent and respond to fire events requires a thorough understanding of the rate of growth of potential fires and their impact on the spacecraft environment. The current level of understanding is insufficient to reliably predict the growth and ultimate size of spacecraft fires and to predict the impact of the fires on the spacecraft. Addressing these issues has been the purpose of a series of five spacecraft experiments referred to as Saffire I – V. The objectives of these flights were to: (1) observe the growth and spread of realistic fires in low gravity over thin and thick solid fuel samples at a range of atmospheric conditions including the current and anticipated environments for exploration missions; (2) to assess the impact of the fire on spacecraft and the transport of the heat and smoke; and (3) to provide a technology demonstration test of combustion product measurement and post-fire cleanup systems. The first three flights have been discussed previously.<sup>1,2</sup> the most recent experiments were conducted in May of 2020 and January of 2021 on the NG-13 and NG-14 flights of the Northrup Grumman Cygnus vehicle. As described in Refs. 1,2 the prior flights had a significant impact on our understanding of flame spread and growth in long duration and large-scale experiments. These tests demonstrated that spacecraft fires could grow to significant size and persist long enough to be of concern to the crew and the spacecraft. To examine the impact of the fires on the spacecraft and to further expand the size of the fires being studied, the Saffire concept was expanded to enable release of more of the heat from the fire into the spacecraft and to include remote diagnostics and fire response hardware elsewhere in the spacecraft. These tests were to be conducted over three flights as Saffire IV-VI. The first two flights (IV and V) are discussed in this paper with emphasis on the fire safety implications of the fire growth and spread results. Further analysis of the burning of the structured PMMA sample on Saffire V are presented in Ref. 3, and details of the smoke and product transport are presented in Ref 4.

## II. Experiment Description

The Saffire Flow Unit (SFU) for flights IV and V was very similar to that used for Saffire I-III<sup>1,2</sup> with the addition of side view cameras, and gas sensors in the inlet and outlet to measure the oxygen consumption and production of carbon oxides. To accommodate the second set of cameras, the duct height was reduced from 25 cm to 15 cm (perpendicular to the sample surface) preserving the 45 cm width. The relative location of the Saffire units are shown in Figure 1 with the Saffire Flow Unit near the end cone of the Cygnus vehicle and the Far Field Diagnostics (FFD) containing the smoke cleanup system and smoke sensors was installed in a mid-deck locker accommodation location adjacent to the



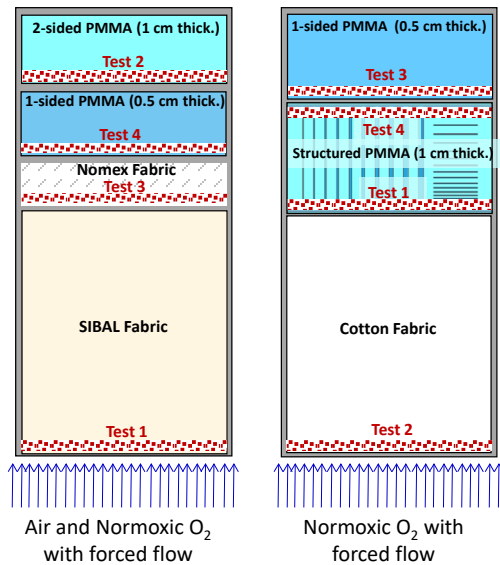
**Figure 1. Rendering of the position of the Saffire Flow Unit (A) and the Far Field Diagnostics (B) in the empty Cygnus module(left) and as fully packed for Saffire IV (right).** *The remote sensors in the standoffs are indicated with red dots and the ones in the end cone and hatch area with green dots. The four open wedge-shaped areas in the right image are referred to as the standoffs in the Cygnus vehicle. The top surface of both images is the port side of the vehicle with the bottom side being the starboard. The right-hand side of the cylinder is the forward side and the left is the aft. The SFU intake is in the aft-port standoff and the outlet is in the forward-port standoff. The standoffs provided a communication path for the air from the hatch area (zenith) (front surface in the images) to the end cone (nadir).*

hatch. Six remote sensors containing a thermocouple and a carbon dioxide sensor were located in each of the four standoffs at the mid plane of the vehicle, in the end cone and in the hatch area. After the spacecraft left the space station and arrived at the planned orbit for the testing, the system was powered up and stepped through the test sequence. Each test was separately triggered by ground command, but the detailed steps for the tests were predetermined by a command file.

The sample cards contained three or four samples and were configured for four ignitions. As will be discussed below, two samples on Saffire IV and one sample on Saffire V were not ignited. The conditions for the five successful tests are presented in Table 1 and the sample card layout is shown in Figure 2. The tests were conducted in a rectangular flow tunnel that was 30 cm high by 45 cm wide by 109 cm long. The ends of the ducts were equipped with flow straighteners that connected to plenums. The inlet and outlet ducts connected to these plenums and were parallel to the flow duct producing a folded geometry. These ducts enabled flow mixing and temperature and measurement of the concentrations of oxygen, carbon dioxide and carbon monoxide on the inlet and outlet. The flow was induced by a fan in the inlet duct and measured by a vane anemometer at the entrance of the inlet duct. The samples were affixed to a metal frame in the middle of the duct as depicted in figure 2. The sample materials were: “SIBAL” fabric (75%

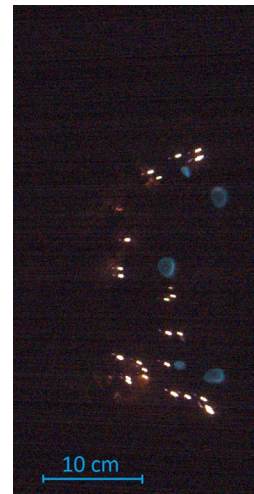
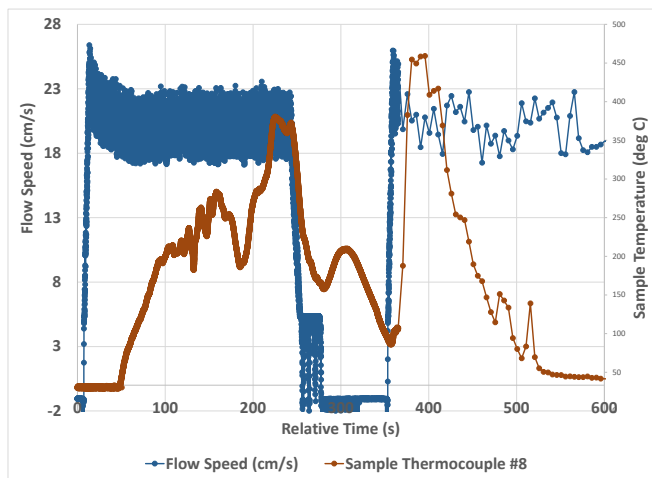
Table 1: Saffire IV-V Sample Test Conditions

Flight/Sample	IV-1	IV-2	V-2	V-3	V-4
Material/configuration	SIBAL Cloth	2-sided PMMA	Cotton Jersey	1 sided PMMA	Structured PMMA
Length (cm)	50	18	50	18	20
Air Flow Rate (cm/s)	20	20	20	20	20
Flow Direction	Concurrent	Concurrent	Concurrent	Concurrent	Opposed
Ambient Pressure (kPa)	100.0	100.0	70.7	71.3	72.6
Oxygen Concentration (mol %)	22.0	22.0	26.2	25.4	25.7
Pressurized Volume (m <sup>3</sup> )	18.7		19.2		
Free volume (m <sup>3</sup> )	17.9		19.0		



**Figure 2** Sample card layouts for Saffire IV (left) and Saffire V (right) Red dots indicate the location of the igniter wires.

One of the salient concerns in any fire response strategy is assuring fire extinguishment. Many thicker materials will self extinguish in quiescent conditions, but under some circumstances, thin materials and bubbling materials will continue to burn. This delayed extinguishment was seen for a thin material in Saffire V sample 2 (cotton fabric). Figure 3 presents the surface temperature of the sample and the fan speed. The sample burned steadily for the initial 300 seconds while the fan was on. At approximately 280 seconds, the fan was turned off and remained off for 70 seconds. Despite this long interval, the flame grew back when the flow was turned on again and continued to burn for another 150 seconds until the material was consumed. This result demonstrates that, for thinner materials, it is possible for flames to persist for an extended period without forced air



**Figure 3** Surface temperature and flow speed for Saffire V-2 (cotton jersey; left) and last recorded top-view image of the flame taken 10 seconds after the fan was turned off (right). The image covers the last 20 cm of the sample after the flow is turned off. Visible in the image are both glowing char embers and small blue flamelets.

flow. As seen in the image in Figure 3, there were both surviving flamelets and glowing char embers at the moment imaging stopped (~ 10 s after the flow was turned off). Since both flamelets and embers were present when the imaging stopped, it is not possible to determine if the flame survived the next 60 seconds due to the small flamelets, the char

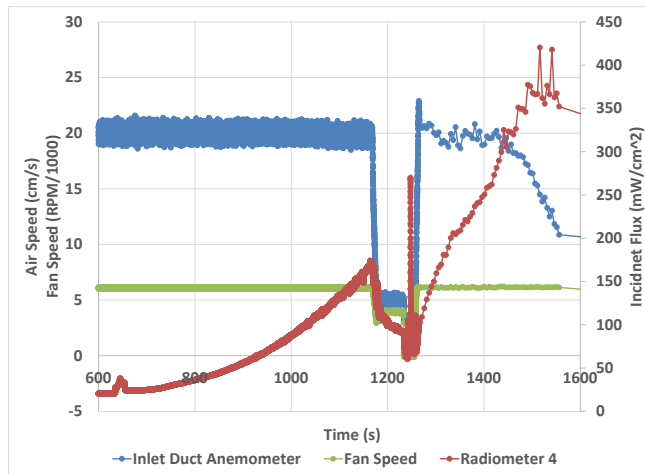
cotton and 25% fiberglass)<sup>1</sup> with a total area density of 18.05 mg/cm<sup>2</sup>; cotton jersey material with an area density of 18.1 mg/cm<sup>2</sup>; or cast polymethyl methacrylate (PMMA) (either one-sided 5 mm thick or two-sided (10 mm thick)). Two of the PMMA samples had flat surfaces and one was a “structured” sample that had a series of grooves and ridges of increasing dimension or separation. More details of the PMMA tests are in Refs 2 and 3. The exhaust gases exited the SFU and entered the forward port standoff of the spacecraft. The overall flow in the spacecraft carried the gases to the FFD in the hatch area. The FFD contained aerosol and species diagnostics and a smoke cleanup system. More details of the smoke transport and preliminary FFD results are in Ref. 4.

### III Results and Their Fire Safety Implications

#### A. Flame Extinguishment

One of the salient concerns in any fire response strategy is assuring fire extinguishment. Many thicker materials will self extinguish in quiescent conditions, but under some circumstances, thin materials and bubbling materials will continue to burn. This delayed extinguishment was seen for a thin material in Saffire V sample 2 (cotton fabric). Figure 3 presents the surface temperature of the sample and the fan

embers, or both. However, since the embers are typically isolated in a larger area of charred material and the flamelets are typically at the edge of unburned fuel, it is likely that survival of a flamelet led to the reignition. Delayed extinguishment was also seen on Saffire IV, sample 2 (Figure 4). In this case the sample was a non-charring thick material (PMMA) burning on both sides. While the flow was on, the flame grew and was marked by continuous small disturbances (3-5 mm in diameter) in the flame due to fuel vapor bursting out of the melted polymer. The long burning interval allowed the sample to accumulate heat such that when the flow was turned off, the sample continued to bubble actively. These jets of fuel emerging from the surface provided sufficient mixing to keep the flame alive over the 15 second interval of no flow. The flame continued to grow extensively until it produced enough soot that it damaged the outlet screens and reduced the air flow. Similar behavior with bubbling jets of fuel vapor was seen by Kimzey in a flammability test with nylon on Skylab.<sup>5</sup> On Saffire V, an approach was tested to promote more rapid extinguishment. Instead of abruptly turning off the flow after a 65 s interval of reduced air flow as in Saffire IV-2, the air flow for Saffire V samples 3 and 4 was reduced from the starting condition of 20 cm/s to 5 cm/s and held at 5 cm/s for 300 seconds. This extended time at reduced flow allowed the sample to cool more effectively than in the

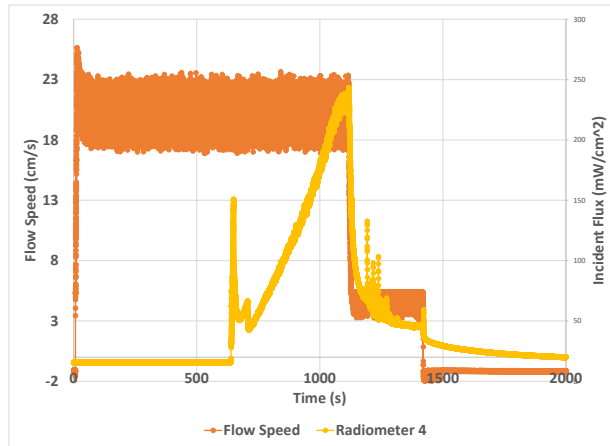


**Figure 4: Air flow speed, fan speed, and radiant flux for Saffire IV-2 (2 sided PMMA in air).** *Although the flame shrank during the reduced flow starting at 1150 seconds, the flame recovered and grew substantially when the air flow was restarted at about 1300 seconds. After 1400 seconds the air flow reduced due to apparent blockage of the outlet screen.*

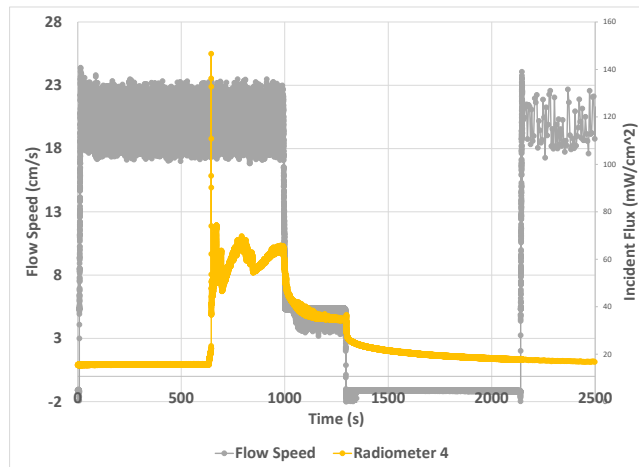
quiescent conditions seen in Saffire IV while preventing the accumulation of fuel vapor near the sample surface. Consequently, when the fan was turned off in Saffire V-3 and V-4, the sample extinguished immediately (Figures 5 and 6). These results indicate that extinction of the fire cannot be assumed to occur quickly under quiescent conditions. Thin materials, higher oxygen concentrations and heating of the solid fuel can all support extended burning. Furthermore, using reduced air flow rather than going to zero air flow can lead to more rapid extinction due to the convective cooling. However, as an extinguishment strategy, this would carry other risks given the uncertainty of configurations and flow rates in a spacecraft.

## B. Ignition

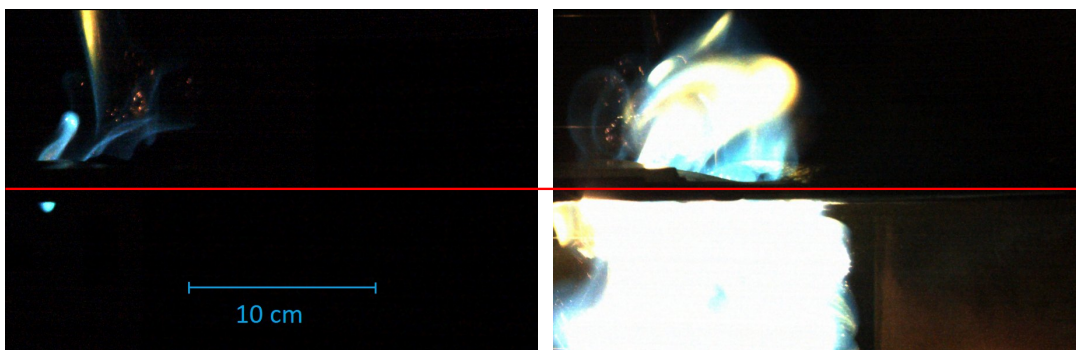
Two Saffire samples (IV-2 and V-4) exhibited intense ignition processes of deflagration because of a stratified mixture as recorded in both the video and the radiometer data. Unlike in normal gravity where buoyancy tends to move hot vapors away from the source, in low gravity hot fuel vapors can more easily accumulate. Figure 7 shows the edge view of Saffire IV-2 after the flow was reduced to 5 cm/s. The flame persisted on the upper surface with a series of pulsations induced by bursting bubbles of molten PMMA, which ejected MMA vapor from the sample surface. On the lower surface, the flame has extinguished but continued emitting vapor. In the image the flame has penetrated through a gap at the leading edge of the sample to the lower area. Immediately afterwards, a strong deflagration spread below the sample and the induced flow generated a strong flame above the sample as well.



**Figure 5: Flow speed and radiant flux for Saffire V-3.** After an extended (300 second) interval at reduced air flow (5 cm/s), the flame extinguished quickly when the flow was turned off.

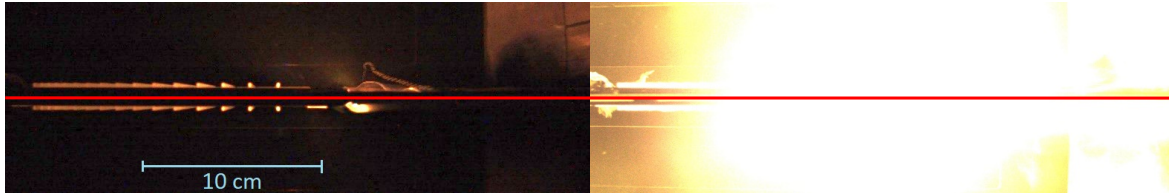


**Figure 6: Radiant flux and flow speed for Saffire V-4** Evident is the rapid extinction after 300 seconds of cooling at low air flow (5 cm/s) before the flow was stopped completely.



**Figure 7 Deflagration during Saffire IV-2,** Images are edge view, the red line denotes the approximate middle of the sample edge. Air flow is from left to right at 5 cm/s. In the left image a weak flame on the upper surface of sample is just beginning to propagate to the lower side where the flame has been extinguished for 6.4 seconds. The right image is 267 ms later and the flame has filled the entire region below the sample and has induced a stronger flame above the sample.

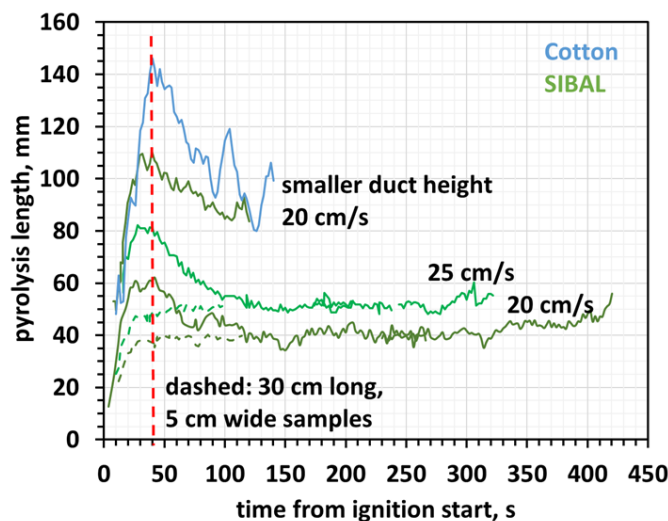
Saffire V sample 4 also exhibited a deflagration when it was first igniting (Figure 8). In this case, the ambient gas flow was 20 cm/s and ignition first occurred on the underside of the sample. Within 100 ms, the flame had expanded to fill the field of view. Development of the stratified mixture in this case was not expected given the gas velocity however the curled ash from sample 2 may have provided enough recirculation to enable the stratification. The relative ease by which these stratified mixtures could develop poses risk for fire response strategies and suggests that reduced air flow and complex flow obstructions can allow the accumulation of fuel vapor, thereby creating a readily-ignited mixture that can produce a strong deflagration.



**Figure 8: Saffire V-4 deflagration during initial ignition of sample** Images are edge view, the red lines denote the approximate middle of the sample edge. Air flow is from left to right at 20 cm/s. Ignition occurred after a planned 10 minutes of preheating (top image) within 100 ms (bottom image) the flame has bloomed to fill the field of view. Images correspond to the sharp peak at 645 s in figure 6.

### C. Flow / Configuration Effects on Thin Fuel Flame Spread

In the first Saffire flights (I-III), the duct size and boundary layer development were shown to affect the flame spread and flame size.<sup>1,6</sup> As described in detail in a prior paper,<sup>1</sup> one of the objectives of the Saffire experiments was to determine if steady concurrent flame spread would be observed for thin fuels. In all of these tests on Saffire I-V, the Cotton and SIBAL fuel samples established a steady opposed spread rate and flame size as identified in Figure 9 and Table 2. Although upward flame spread is usually acceleratory in 1-g, as discussed in Ref. 1, steady spread was seen in ground tests with SIBAL cloth if the flame size was constrained by heat loss or lower pressure. As expected, this spread rate was affected by oxygen concentration and flow rate, but it was also shown to be affected by duct height which was discussed in detail by Li et al.<sup>7,8</sup> Using a numerical model, these studies showed that, for concurrent flame spread and beyond a critical separation distance, increasing the duct height reduced the air velocity above the flame owing to the reduced impact of the flow restriction caused by the flame. Since the concurrent flame spread rate increases with air velocity, increasing the duct height slowed the flame spread. Saffire IV continued this investigation by including another SIBAL sample and using the reduced duct height in Saffire IV-V. The additional data point is



**Figure 9: Pyrolysis lengths and positions of the flame bases and tips for Saffire I-V.** Sample dimensions and conditions are in Table 2.

Table 2 Test Conditions and flame size for thin samples

Flight-Sample	I-1	II-5	II-6	III-1	IV-1	V-2
Air flow (cm/s)	20	20	25	25	20	20
Oxygen concentration (%)	21	21	21	21	22	26.2
Pressure (kPa)	100	100	100	100	100	70.7
Material	SIBAL	SIBAL	SIBAL	SIBAL	SIBAL	Cotton jersey
Steady state size (cm)	4	4	5	5	8.5	10.0
Maximum size (cm)	6.2	4	5	8.2	11.0	14.0
Duct Height (cm)	46	46	46	46	30	30
Sample Width (cm)	41	5	5	41	41	41
Sample length (cm)	94	30	30	94	50	50

plotted with the results from Saffire I-III<sup>1</sup> in figure 10. As expected, the spread rate increased (about 100%) with the reduced height flow duct compared to Saffire I and III. Saffire I and III also produced the novel observation of a (~30%) flame size overshoot owing to the boundary layer development on the sample surface.<sup>1</sup> This overshoot was not seen for the SIBAL samples on Saffire II, which were positioned on the sample card such that there was a long

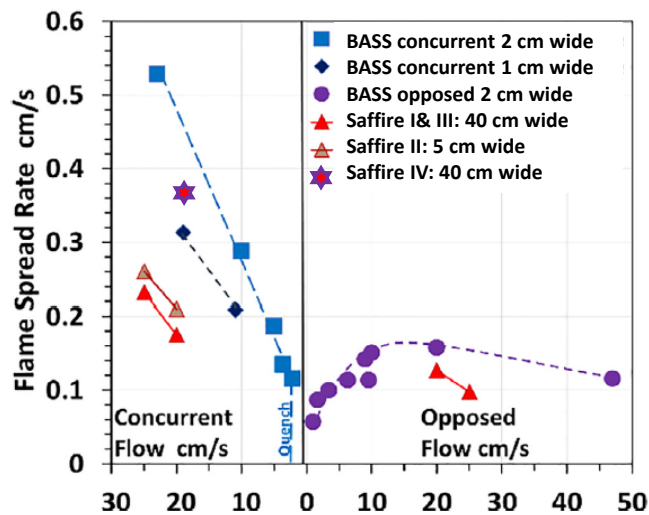


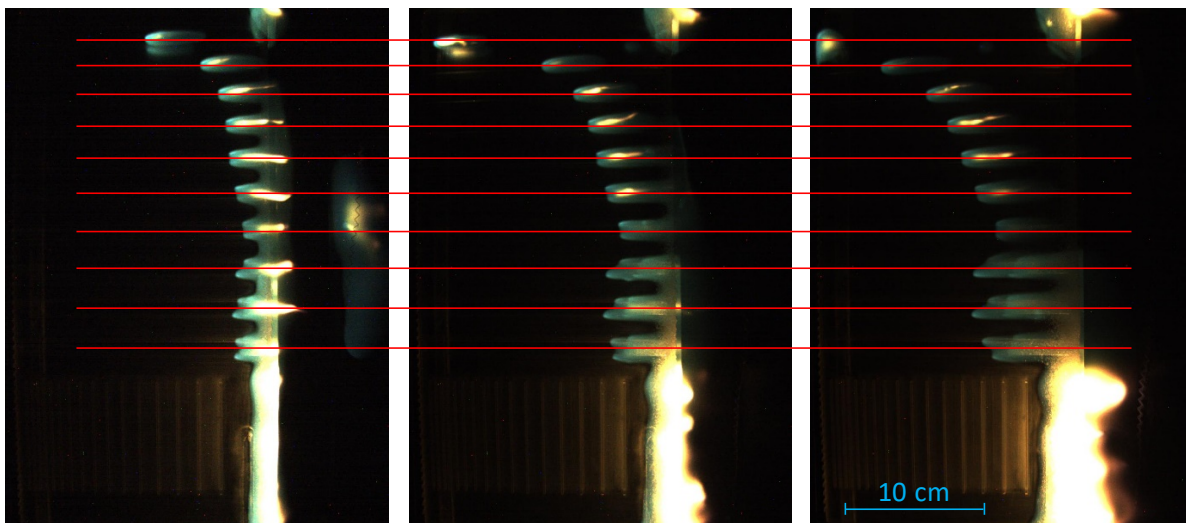
Figure 10: Steady spread rate summary for the cotton-fiberglass fabric burning in microgravity.<sup>1</sup> Concurrent flames are shown on the left of the origin and opposed to the right. Saffire I-III were in a 46 cm duct and Saffire IV was in a 30 cm duct.

entrance length. At the beginning of the duct, the undeveloped boundary layer is thinner with higher velocities near the sample surface. These higher velocities induce faster spread as expected. The steady state flame lengths are summarized in Table 2. Compared to Saffire I-III, thin-sample flame sizes increased owing to the reduced duct height on Saffire IV and with the Saffire V cotton sample, which was a thinner material and was in a higher ambient oxygen concentration. From a fire safety perspective, these results are significant because they demonstrate that under a variety of conditions, concurrent flames spreading over thin fuels will achieve a limiting size. This behavior contrasts with normal gravity upward spread where flames tend to grow continuously.

#### D. Flow / Configuration Effects on Thick Fuel Flame Spread and Growth

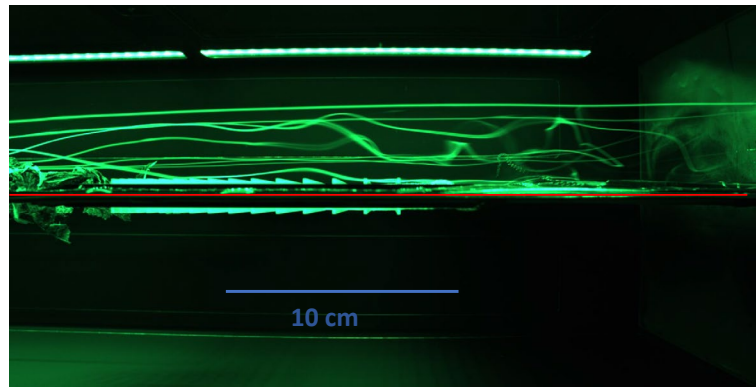
The Saffire IV and V flights included three successful tests burning PMMA slabs as described in Table 1 and in more detail in Refs. 2 and 3. These tests produced several results relevant to spacecraft fire safety. Both concurrent samples (IV-2 and V-3) did not spread appreciably and instead remained fixed at the leading edge of the sample, advancing through surface regression only. This phenomenon is typical for thick fuels in low gravity but is different from what is seen in normal gravity. These concurrent flames initially grew but then assumed a steady flame size for the remainder of the burn duration. For Saffire II, the two PMMA 5 cm wide, two-sided samples grew to flame lengths of 8.0 cm for the grooved sample and 9.5 for the flat sample.<sup>2</sup> For Saffire IV-2, the two-sided PMMA sample flame

burning in air grew to 9.5 cm after 400 seconds. In Saffire V-3, the one-sided PMMA sample flame (in 25.4% oxygen) grew to 11 cm after 450 seconds. This result is similar to the limiting flame size seen for the thin samples. In all these cases the flame length reached an upper limit contrary to similar 1-g tests that did not reach a steady length.<sup>9,10,11</sup> Reaching a limiting length, especially for a thick solid, may seem a surprise since for a sample of this size an upward flame will continue its growth in normal gravity. It has been suggested that the reason why the flame tip stops advancing has to do with the surface energy balance at the pyrolysis front (flame tip) region.<sup>12,13</sup> Assuming convection is the primary heat transfer mode, the magnitude of gas phase heat flux to the pyrolysis front decreases with downstream distance. When its magnitude becomes comparable to the surface radiative heat loss, the net heat feedback and hence the local solid burning rate become vanishing small, local flame tip quenching occurs and the flame become stationary for a thick solid. Increasing the ambient oxygen concentration can be expected to reduce the standoff distance. Consequently, the final length of the Saffire V-3 flame is greater than the other samples due to the enhanced oxygen concentration. This oxygen limitation was also seen in Saffire V-4 where the opposed flame spread was also affected by limited oxygen availability as seen in Figure 11. Visible in the left-hand image is a downstream flame that developed on the adjacent sample, V-3, which established quickly on the warm sample but then was extinguished when the upstream flames grew to sufficient size to consume the available oxygen. The downstream V-3 sample was 4.5 cm from the upstream sample and was ignited by the upstream flame that was driven to a larger size because the igniter was adding substantial heat to the system even after the flame was ignited. Unlike in normal gravity, the PMMA extinguishes behind the spreading flames potentially due to the oxygen shadow<sup>14</sup> combined with the surface energy balance issue described above<sup>12,13</sup> resulting in nearly constant sizes for the flames in Figure 11.



**Figure 11: Opposed flame spread on ribbed PMMA.** Images are top view. Flow is from left to right at 20 cm/s. Sample rib centerlines (red lines) are indicated. Ribs are 3 mm high with widths increasing from 1 mm to 10 mm by 1 mm increments from the top to the bottom red line. There is 2 cm between adjoining rib faces. Flow is from the left to the right. Images are 100 seconds apart. On the wider ribs, the flames at the corners spread ahead of the center. In the right-hand image, two flames are visible on some ribs (front and back sides of the sample). In the first image (left) a flame can be seen near the right side of the frame. This is a flame that developed on the adjacent downstream sample (V-3). This flame developed briefly at the start of the test and then extinguished, presumably due to oxygen deprivation.

Also evident in Figure 11 is the difference in spread rate as function of the rib width. The ribs of the structured PMMA were 3 mm high which was sufficient to support an individual flame at the top of the rib, making the effective sample size the rib width. The top rib is 1 mm wide, the second rib is 2 mm wide and so forth until the tenth rib which is 10 mm wide. The distance between adjoining rib faces is a constant 2 cm so that the flow in the “channel” between ribs is expected to be similar. The flame spread more rapidly on the thin ribs at the top of the image with decreasing spread rate as the ribs become wider. This change in spread rate is non-monotonic as seen with rib 7 lagging behind the thicker rib 8. This is attributed to a partial flow obstruction caused by the curled char and ash from cotton sample V-2. This curled char occurred late in the burn for sample V-2 and is clearly evident on the post-test images, (Figure 12). The curled char is most prominent in the middle of the sample, well aligned with the locations of the delayed flame spread on the middle ribs on sample V-4. The post-test flow visualization (smoke traces) validated the flow



**Figure 12: Edge view of the flow visualization after all tests are completed.** *Sample V-4 is in the middle of the image and V-3 is to the right. The crumpled char from sample V-2 is evident on the left as are the distorted smoke traces from heated rosin on a wire at the duct inlet. Air flow is from left to right at 20 cm/s the red line denotes the approximate middle of the sample edge.*

disturbance over the middle of the structured sample. The combined interpretation of these results demonstrates the strong influence of the flow characteristics on flame spread and growth in low gravity. Unlike in normal gravity where flames can induce substantial flow through buoyancy, in low gravity, the flame growth is controlled by the flow environment. This dependency on flow makes assessment of the fire growth or spread in low gravity more difficult, as one cannot assume simple growth predictions (e.g.  $t^2$ ) as is typically done for normal gravity fires.

Furthermore, the best fire prevention strategies may be different from the best extinguishment strategies. As seen above, quiescent conditions reduce the air flow, but bubbling fuels or charring materials may extinguish more rapidly if there is some convective cooling and mass transport. For ignition, however, quiescent conditions will likely make the sample less ignitable than with convection present. The most ignitable condition is likely to be at low flow rates since as the flow velocity increases, ignition becomes delayed or deterred due to heat losses from the surface of the fuel the adjacent flow.<sup>15</sup>

One of the more subtle observations from these tests is that the test configuration to assess the flammability of materials for use in spacecraft, NASA STD 6001 Test 1<sup>16</sup> does not correspond to overall fire behavior in low gravity. Various aspects of this test and how it relates to low-gravity conditions discrepancy have been discussed in the past, but the Saffire experiments have shown phenomena of relevance. NASA Test 1 is based on an upward flammability test where a 30 cm long material sample is ignited at the bottom and if the flame grows or spreads past 15 cm, the sample is deemed to fail the test at that condition. As discussed above, flames on thick fuels will not grow or spread concurrently in low gravity and instead depend on surface regression to move the flame forward; instead, spread is more likely to be seen in opposed (downward) spread. This result does not indicate that the normal gravity test is not useful. The test is quite successful at identifying highly flammable materials; however, the test cannot be assumed to indicate that a material will not burn under those conditions in low gravity. Another significant result was the demonstration of the importance of surface structure on the flammability. Although the Saffire V-4 sample was 10 mm thick, the relevant dimension for flame spread was the width of the ribs. NASA STD 6001 requires testing with the worst case (usually the thinnest) sample. These results indicate that relatively thin surface structures must be considered.

## IV Summary of Results

To date, the Saffire Experiments have produced a notable set of results that are relevant to spacecraft fire safety design and assessment. These results include:

### Extinguishment

- Extinguishment of thin charring fuels at increased oxygen cannot be assumed to occur rapidly in quiescent conditions.
- Extinguishment of bubbling polymers cannot be assumed to occur rapidly in quiescent conditions
- In some circumstances, reducing air flow to a small value rather than quiescent conditions may be useful to disperse fuel vapor and help cool the material to enable extinction

### Ignition

- Overheated materials in quiescent conditions or in low-flow zones in low gravity can produce stratified fuel mixtures that can result in dramatic deflagrations during ignition.

### Flow/configuration

- The dimensions of the flow environment relative to the size of the flame can have a significant effect on the spread rate over thin materials.
- Near the entrance of a flow environment, the undeveloped boundary layer can lead to flame sizes that are initially 30% larger than occur with developed flow until the flame spreads into a region with developed flow.
- In opposed spread over thick materials, the size of ridges or other surface shape structures can have a significant effect on flame spread.

### Spread and Growth

- Flames were seen to develop to nearly steady lengths in all configurations. This includes concurrent and opposed spread on thin fuels and on thick fuels. The steady state size was affected by the oxygen concentration and the flow velocity. This contrasts with upward spread in normal gravity which usually shows continued growth.
- Flames on thick fuels in concurrent flow did not spread and were instead pinned to the leading edge of the sample and propagated as the fuel was consumed. In opposed flow the flames spread toward the leading edge where they became pinned. As it spread, the flame did not grow, instead the downstream tail extinguished behind it as it spread.
- Once a flame achieved its limiting size, downstream flames were inhibited or extinguished by the oxygen “shadow” of the upstream flame.
- Thick fuel flame growth was found to be dissimilar from that seen in NASA STD 6001 Test 1. This does not invalidate the test but does affect the interpretation of the test results
- In one case, a flame was seen to jump a 4.5 cm gap to ignite a previously warmed PMMA surface.

Collectively, these results provide new understanding of the behavior of fires in low gravity in practical configurations. These observations and the accompanying analyses described in the references will be incorporated into spacecraft fire safety requirements and guidelines for exploration spacecraft and habitats. Saffire-VI is in storage and, when flown, will undoubtedly provide additional data and observations to strengthen or clarify the conclusions of this paper. The continued analysis of the data from Saffire-I-VI will extend the application of these results to quantify the impact of a fire to exploration spacecraft.

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