53rd International Conference on Environmental Systems
21-25 July 2024, Louisville, Kentucky

ICES-2024-365

Preliminary Results from the Saffire VI Experiment

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Preliminary results are presented for one test of the last flight of the Spacecraft Fire Experiment (Saffire VI) which was conducted on an orbiting Cygnus spacecraft. These experiments directly address the risks associated with our understanding of spacecraft fire behavior at practical length scales and geometries. The lack of this experimental data has forced spacecraft designers to base their designs and safety precautions on 1-g understanding of flame spread, flame self-extinguishment, fire detection, and suppression. The Saffire experiment was developed by an international team of investigators with the goal of addressing open issues in spacecraft fire safety. NASA's Spacecraft Fire Safety Demonstration Project was formulated with the goal of conducting a series of large-scale experiments in

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spacecraft environments that represent practical spacecraft fires. These tests spanned 1.5 to 3.2 kW with free air volumes of 17 to 19 cubic meters. The final flight in the series of six experiments examined concurrent spread over large samples (all 41 cm wide) including a thin sheet of flammable fuel (cotton/fiberglass 50 cm long); 2-sided spread over 1 cm thick polymethyl methacrylate (PMMA) (18 cm long); 1-sided spread over 0.5 cm thick (18 cm long); and Nomex fabric (7 cm long). Results are presented for the PMMA samples, the SIBAL sample, and the thin cotton samples from Saffire IV and V. The flame heat release is determined and compared to the overall temperature rise in the spacecraft and the change in the concentration of carbon dioxide and carbon monoxide in the spacecraft. Overall, the temperature and pressure rise in the spacecraft were found to be less significant than the increase in carbon dioxide and carbon monoxide.

Nomenclature

FFD	=	Far Field Diagnostics
PMMA	=	polymethyl methacrylate
Saffire	=	Spacecraft Fire Safety Demonstration Project
SFU	=	Saffire Flow Unit
SIBAL	=	Solid Inflammation Boundary at Low Speed
SMAC	=	Spacecraft Maximum Allowed Concentration

I. Introduction

Although spacecraft fires have long been recognized as a potentially catastrophic hazard, the impact of a spacecraft fire on the vehicle habitability was not examined experimentally before the initiation of the Saffire experiment series. In terrestrial fires, the smoke and its constituents are generally a greater hazard than the heat from the fires. In the confined space of an orbiting spacecraft, any of these hazards can become a critical hazard for the mission and the crew. Specifically, excessive temperature rise will potentially cause thermal injury, while increase in the levels of carbon dioxide and carbon monoxide may pose a more significant and acute hazard to the crew. Given the difficulty in predicting the impact of the heat and pressure rise from a spacecraft fire compared to the hazardous products, one of the major goals of the Saffire VI flight was to provide such a comparison. This increased understanding of the relative impact of various fire impacts can be used to guide spacecraft designs. Other than the thin cellulose samples on prior flights, the heat release on Saffire IV and V for the thick PMMA samples was not determined. The first three flights have been discussed previously.[1,2] and flights IV and V were presented in Urban et al. 2021[3]. As described in Refs. 1,2, and 3 the prior flights had a significant impact on our understanding of flame spread and growth in long duration and large-scale experiments. The prior flights revealed that, under typical spacecraft conditions, fires can develop to significant size. Overall, the average temperature and pressure rise were not particularly of concern however the increase in hazardous products (carbon monoxide and carbon dioxide) were enough to be of health concern. However, the utility of these results as reference data sets for model validation was limited owing to the absence of heat release data for the PMMA (high heat release) cases. Improvements were made for the final Saffire VI flight to ensure accurate heat release measurements. Further analysis of the burning of the structured PMMA sample on Saffire V are presented in Ref. 4, and details of the smoke and product transport are presented in Ref. 5.

II. Experimental Hardware

The Saffire Flow Unit (SFU) for flights IV - VI was very similar to that used for Saffire I-III[1,2] 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. On Saffire IV and V, the outlet gas sensor location was found to have been moved from the location where mixing had been verified and therefore not see a fully mixed outlet flow, so the gas measurements were not useful. For Saffire VI it was moved to the verified location at the end of the duct to provide oxygen consumption calorimetry needed to enable measurement of the heat release from the flame. To accommodate the second set of cameras, the duct half-height was reduced from 25 cm (for Saffire I-III) to 15 cm for Saffire IV-VI (perpendicular to the sample surface) preserving the 45 cm width. The locations 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 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 cargo was unloaded, the vehicle was repacked with trash which was an essential task for the mission but also was essential to the Saffire experiment as it filled extra volume enabling the experiment to adjust the oxygen concentration in the spacecraft. 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

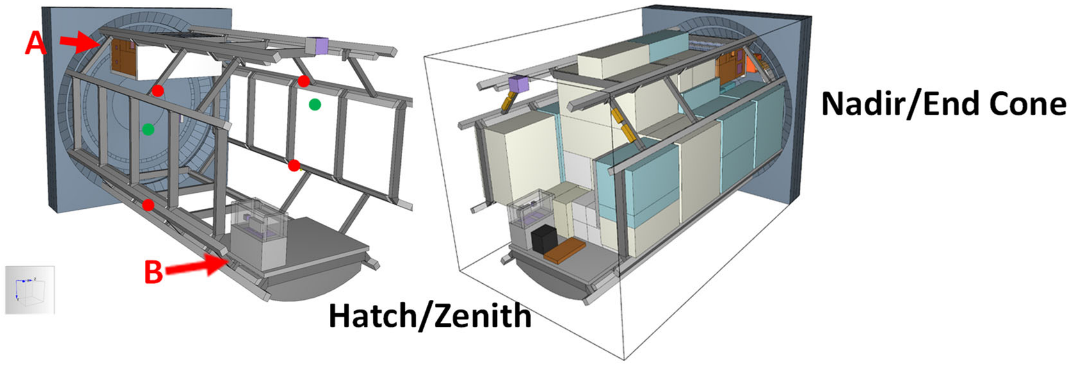

Figure 1. Rendering of the position of the Saffire Flow Unit (A) and the Far Field Diagnostics (B) in the empty Cygnus module(left) and as fully packed for Saffire IV (right). The remote sensors in the standoffs are indicated with red dots and the ones in the end cone and hatch area with green dots. 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 forward, and the left side is the aft. The SFU is at the nadir end of the vehicle with the SFU intake in the aft-port standoff and the outlet 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).

predetermined by a command file. Before the tests were initiated, the free volume in the spacecraft was measured by releasing a known volume of carbon dioxide and observing the change in concentration over time. This volume was then used to select a targeted pressure reduction and oxygen backfill. The Northrup Grumman operators vented the spacecraft to the requested pressure and the Saffire experiment then released oxygen to bring the spacecraft to the desired condition (Table 1).

The Saffire IV and V tests were discussed in detail in Urban et al.[3] For this paper, the thin cotton samples from each flight will be included in this analysis because the heat relase rate can be estimated from the spread rate for thin fuels. The Saffire VI sample card contained four samples and was configured for four ignitions. As with Saffire IV

Table 1. Saffire IV-VI Sample Test Conditions considered in this paper.

Flight/Sample	IV-1	V-2	VI-2	VI-3	VI-4
Material	SIBAL Cloth	Cotton Jersey	SIBAL Cloth	Two-Sided PMMA	One-Sided PMMA
Length (cm)	50	50	50	18	18
Air Flow Rate (cm/s)	20	20	20	20	20
Flow Direction	Concurrent	Concurrent	Concurrent	Concurrent	Concurrent
Ambient Pressure (kPa)	100.0	70.7	54.1	54.6	55.2
Oxygen Concentration (mol %)	22.0	26.2	31.0	30.3	28.8
Free volume (m^3)	17.9	19.0	16.7	16.7	16.7

and V, 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 measurement of the temperature and 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 (Figure 2) in the middle of the duct. Similar to Saffire IV & V, the sample materials were: "SIBAL" fabric (75% cotton and 25% fiberglass)[1] with a total area density of 18.05 mg/cm^2; or flat, cast, polymethyl methacrylate (PMMA) (either one-sided 5 mm thick or two-sided (10 mm thick).

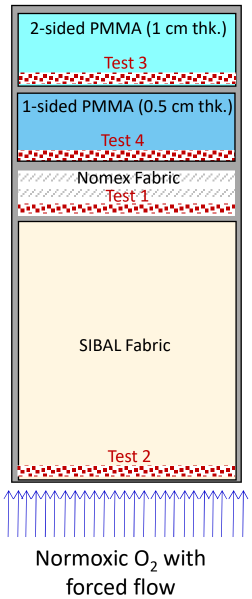

Figure 2. Sample card layout for Saffire VI Red dots indicate the location of the igniter wires. The Nomex sample did not ignite.

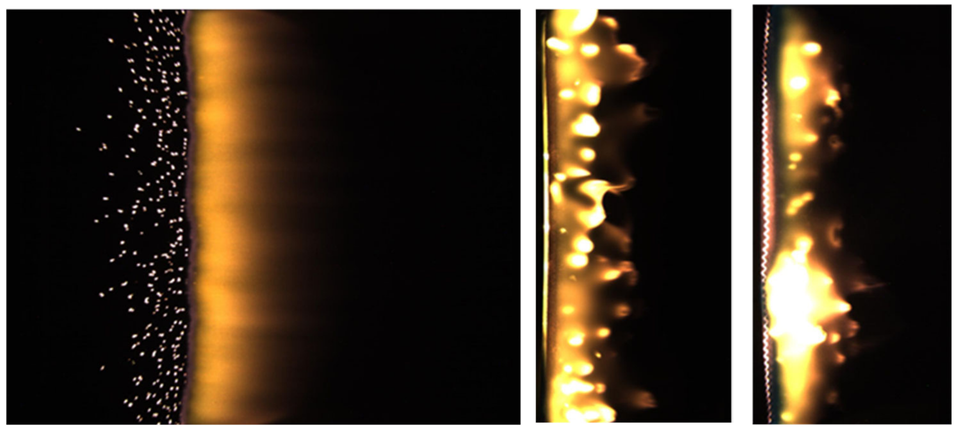

Figure 3. Representative front-view (sample surface) images for each Saffire VI test after the flame is well established. From left: SIBAL fabric (test 2), 2-sided PMMA (test 3), and 1-sided PMMA (test 4). Oxidizer flow is from the left at 20 cm/s in all cases.

The Nomex sample did not ignite and so it will not be included in this paper. 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 Fortenberry et al.[5].

III. Results and Their Fire Safety Implications

Representative front-view images of the flames are shown in Figure 3. Overall, the flame growth and spread were consistent with prior Saffire flights discussed previously[3]. The SIBAL sample (left image) achieved a steady size and spread rate quite rapidly where the two PMMA samples grew continuously until the flow speed was reduced. This continued growth is evident in Figure 4 where the outlet duct temperature rises continuously. Likewise, the oxygen consumption (Fig. 5) and the CO and CO_2 (Fig. 6) concentrations at the SFU outlet increase continuously until the flow is reduced at 1120 seconds. At the same time the temperatures and gas temperature at the outlet of the SFU outlet is significant (70 °C) the temperature near the FFD (zenith) only changes slightly from the prior baseline. The CO and CO_2 levels are also very high exiting the SFU, but they are also attenuated at the location of the FFD (Fig. 6). The increase at the FFD is reported in Table 2. Since carbon dioxide scrubbing only occurred twice on the Saffire flights and there was limited carbon monoxide removal, the values reported here are the increases in the average concentration in the space craft due to each test.

Figure 5 presents the heat release calculated from the oxygen consumption using the method of Huggett[6] where the heat release is estimated for a wide range of combustibles to be 13.1 kJ per gram of oxygen consumed. The heat release can be seen to be consistent with the radiometer. These results are tabulated in Table 2 with the thin fuel results from Saffire IV and V and all the successful ignitions from Saffire VI. The fires were generally of 1.5 to 3 kW in intensity which is a small fire by terrestrial standards. The table also includes the heat release calculated using the fuel consumption rate for the thin materials. For the thick materials, much of the material burning is from the surface which cannot be detected by the cameras, so it is not possible to estimate the heat release from the flame imaging. For the VI-2 sample (SIBAL) both methods were used and agree within 15% which is reasonable for this type of analysis.

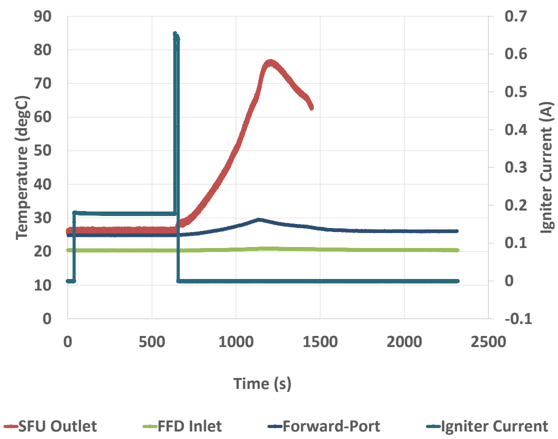

Figure 4. Temperature results for Saffire VI-3 (two-sided PMMA). The duct flow was reduced at 1120 s and terminated at 1420 s so the inlet and outlet traces end. The forward port sensor is the nearest to the Saffire flow duct outlet.

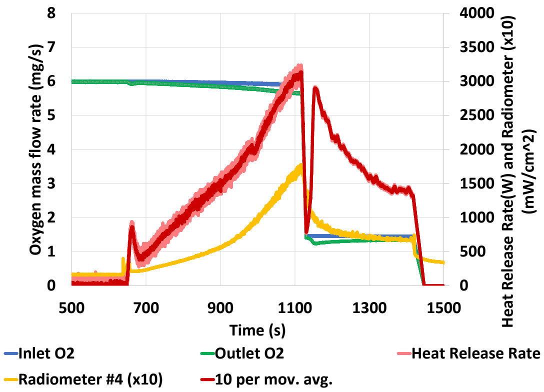

Figure 5. Inlet and outlet oxygen concentrations for Saffire VI-3 (two-sided PMMA) with the calculated heat release based on the oxygen consumption. The flow was changed from 20 cm/s to 5 cm/s at 1120 s and terminated at 1420 s. The dip at 1120 s is due to the impact of the transient flow change on the oxygen sampling.

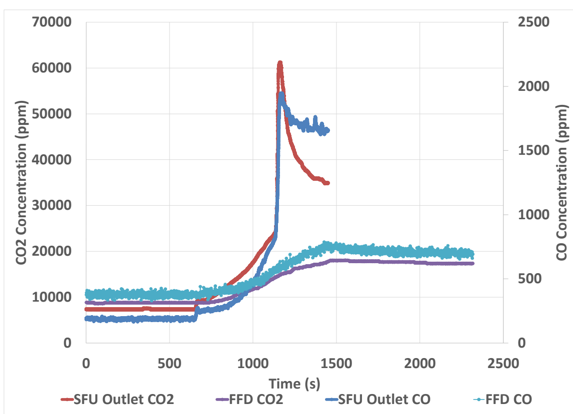

Figure 6. CO and CO_2 concentrations for Saffire VI-3 (two-sided PMMA) The duct flow terminated at 1420 s so the outlet traces end. The flow was changed from 20 cm/s to 5 cm/s at 1120 s. At this lower flow rate, the outlet CO_2 and CO levels increased due to the lower ambient flow. The forward port sensor is the nearest to the Saffire flow duct outlet and the zenith sensor is near the far field device.

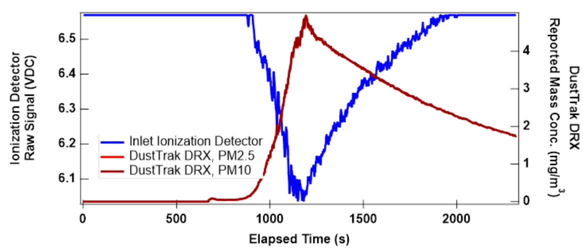

Figure 7. Far field ionization smoke detector and particulate matter measurements for Saffire VI-3 (two-sided PMMA).

Figure 7 presents the smoke concentrations at the FFD and the response of a terrestrial ionization detector. The smoke levels can be seen to rise rapidly and subsequently decrease, presumably due to particle loss from impaction on multiple surfaces. Selecting 1 mg/m^3 as a relatively tight alarm threshold, the FFD detector reached that threshold at 981 seconds. By this point, much of the hazardous gas release had occurred. This is comparable to predictions based on smoke versus hazardous product emission by overheated materials[9]. Although the CO and CO_2 diluted rapidly in these tests, the increases observed from these tests are quite significant from a toxicology standpoint. For carbon monoxide, NASA establishes a Spacecraft Maximum Allowed Concentration (SMAC) value based on the exposure duration. For carbon monoxide, the 1-hour SMAC is 425 ppm, and the 24-hour SMAC is 100 ppm[7]. For carbon dioxide, which is prevalent in manned spacecraft, the limits are established differently in NASA-STD-3001[8] which limits the 1-hour average CO_2 partial pressure to no more than 3 mm Hg. As can be seen in Table 2, the allowable CO_2 level was exceeded by both of the PMMA tests on Saffire VI. For carbon monoxide the levels were well above the 24-hour SMAC and quite close to the 1-hour level.

Table 2. Saffire IV-VI Heat release and increase of carbon oxides*.

			Oxygen Consumption Calorimetry		Fuel Consumption Calorimetry						
Saffire Flight/ Sample	Material	Burn duration (s)	Peak Heat Release (W)	Total Heat Release (kJ)	Average Heat Release (W)	Total Heat Release (kJ)	Max Temp at SFU outlet (°C)	Max Temp at FFD or nearest location (°C)	FFD inlet CO_2 increase (ppm)	CO_2 partial pressure increase (mmHg)	FFD inlet CO increase (ppm)
IV-1	SIBAL	130			3,150	409	45	25	1390	1.03	80
V-2	Cotton Jersey	200			2,800	560	46	23	2360	1.26	83
VI-2	SIBAL	112	3217	580	3,650	409	48	20	2800	1.15	120
VI-3	2-sided PMMA	780	3080	1280			77	21	8539	3.51	308
VI-4	1-sided PMMA	1200	1507	830			57	21	8117	3.37	320

*Empty fields were cases where the data were not available.

IV. Conclusion

Practical scale fires ranging from 1.5 to 3.2 kW were tested in unmanned spacecraft with free air volumes of 17 to 19 cubic meters. Despite these fires, the temperature only increased significantly very near to the fire itself. However, the ambient concentrations of carbon monoxide and carbon dioxide rose significantly with the PMMA tests exceeding the 1-hour carbon dioxide limit and the 24-hour carbon monoxide limit. The smoke from the fire event was readily detected by an ionization detector and a light scattering system but a typical alarm threshold was only achieved at 981 seconds. By this time most of the hazardous gas release had occurred. Collectively these results demonstrate that the human hazard from a fire in a spacecraft is very similar to terrestrial fires where the heat from the fire is not the principal hazard and rather the smoke and gaseous products are a much greater concern. These results are helpful for defining fire response approaches for spacecraft. Further work will be needed to extend these results to the partial gravity environment expected on future mission to the moon and Mars. Additional analysis and modeling of these fire scenarios will be the topic of future articles.

Acknowledgments

The authors acknowledge the support of the NASA Mars Campaign Office, for the sponsorship of the Spacecraft Fire Safety Demonstration Project and the Saffire experiments. In addition, the authors acknowledge the support of the various space and research agencies that have supported this work including but not limited to the Japan Aerospace Exploration Agency (JAXA), the European Space Agency, the Russian Space Agency, the National Centre for Space Studies (CNES), the German aerospace Center (DLR), the European Union, the Russian Academy of Sciences and NASA. The excellent support by the engineering team (NASA and Zin Technologies), Northrup Grumman and the on-orbit crew are gratefully acknowledged.

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