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Buoyant Effects on the Flammability of Silicone Samples Planned for the Spacecraft Fire Experiment (Saffire)

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Flammability experiments on silicone samples were conducted in anticipation of the Spacecraft Fire Experiment (Saffire). The sample geometry was chosen to match the NASA 6001 Test 1 specification, namely 5 cm wide by 30 cm tall. Four thicknesses of silicone (0.25, 0.36, 0.61 and 1.00 mm) were examined. Tests included traditional upward buoyant flame spread using Test 1 procedures, downward opposed-flow flame spread, horizontal and angled flame spread, and forced-flow upward and downward flame spread. In addition to these configurations, upward and downward tests were conducted in a chamber with varying oxygen concentrations. In the upward buoyant flame spread tests, the flame generally did not burn the entire sample. As thickness was increased, the flame spread distance decreased before flame extinguishment. For the thickest sample, ignition could not be achieved. In the downward tests, the two thinnest samples permitted the flame to burn the entire sample, but the spread rate was lower compared to the corresponding upward values. The other two thicknesses could not be ignited in the downward configuration. The increased flammability for downward spreading flames relative to upward ones is uncommon. The two thinnest samples also burned completely in the horizontal configuration, as well as at angles up to 75 degrees from the horizontal. Upward tests in air with an added forced flow were more flammable. The upward and downward flammability behavior was compared in atmospheres of varying oxygen concentration to determine a maximum oxygen concentration for each configuration. Complementary analyses using EDS, TGA, and SEM techniques suggest the importance of the silica layer deposited downstream onto the unburned sample surface.

Nomenclature

$C_{p,s}$	=	Specific heat of silicone, J/kg-K
$C_{p,SiO2}$	=	Specific heat of silicon dioxide, J/kg-K
EDS	=	Energy dispersive X-ray spectroscopy
MOC	=	Maximum Oxygen Concentration
PMMA	=	Polymethyl methacrylate
ρ_s	=	Density of silicone, kg/m^3
ρ_{SiO2}	=	Density of silicon dioxide, kg/m^3
$\dot{q}''$	=	Critical heat flux needed to ignite sample, W/m^2
Saffire	=	Spacecraft Fire Experiment
SIBAL	=	Custom fuel fabric made of cotton-fiberglass blend
τ	=	Burn time, s
T_{ign}	=	Ignition temperature, K
T_∞	=	Ambient temperature, K
δ_s	=	Thickness of silicone
δ_{SiO2}	=	Thickness of silicon dioxide
TGA	=	Thermogravimetric Analysis
SEM	=	Scanning Electron Microscopy
ULOI	=	Upward Limiting Oxygen Index

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I. Introduction

THE Spacecraft Fire Experiment (Saffire) will be used to study microgravity flame spread with larger fuel samples than have been burned to date.[1,2,3] Saffire is funded by the Advanced Exploration Systems Program, and was initiated to develop spacecraft fire safety technology. The experimental data will also be used to verify complex numerical models of microgravity combustion events.

The Saffire experiments will be performed on three sequential flights of Orbital Science's Cygnus resupply vehicle after it deberths from the ISS. All three Saffire flight units have a sample card installed in the middle of a large flow duct. Saffire I and III will have a 40-cm-wide by 94-cm-long sample of SIBAL fuel (75% cotton and 25% fiberglass blend) burned at two different flow speeds, and Saffire II will have nine samples that are 5-cm wide by 30-cm long. Figure 1 shows a schematic of the flight payload for Saffire II and Figure 2 shows details of the samples.

The Saffire-II samples were chosen to match the size specified in the NASA 6001 Test 1 flammability test standard.[4] This is a "worst case" upward flammability test, and the material is said to fail if more than 15 cm is consumed. One main objective of the Saffire-II experiment is to ascertain if the flammability limits determined in 1-g using NASA-STD-6001 Test 1 are the same as those in low-gravity.

Four of the samples on Saffire II will be silicone. Silicone was chosen because its flammability limit is close to the expected test atmosphere (air; 21% O_2, 1 atm), and different thicknesses were available to enable producing a variety of burn lengths in upward 1-g testing. Downward flame spread tests in 1-g were conducted to determine if upward flame spread of silicone represents the worst case flammability scenario. The objective of this paper is to describe the results of the upward and downward flame spread tests in 1-g. The results

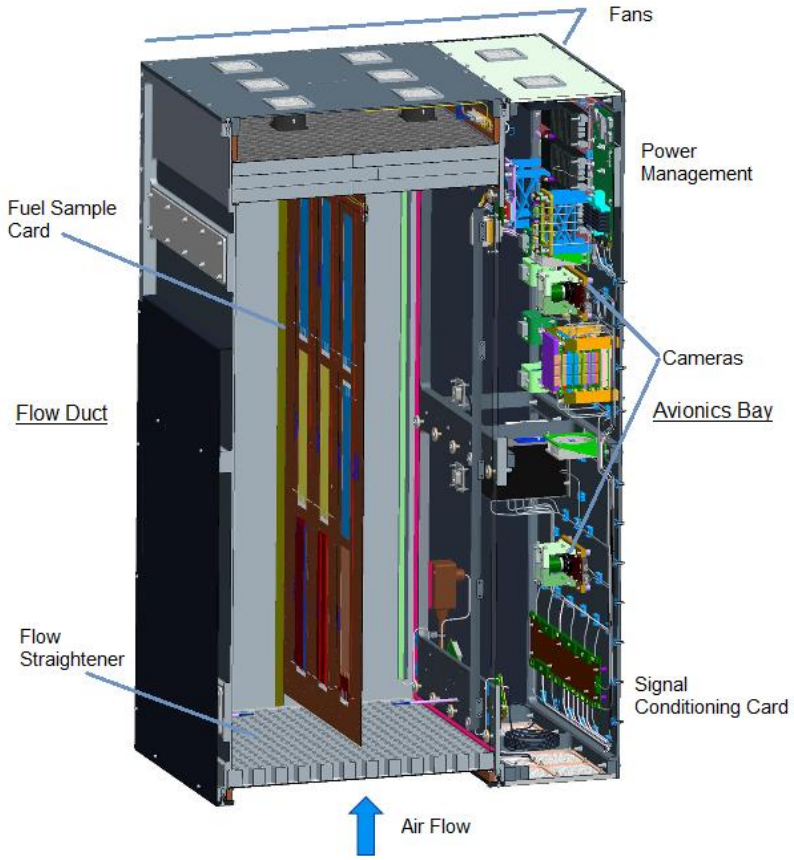

Figure 1. Saffire-II flight unit. *Shows schematically the direction of flow from bottom to top, sample card, flow duct, and avionics bay.*

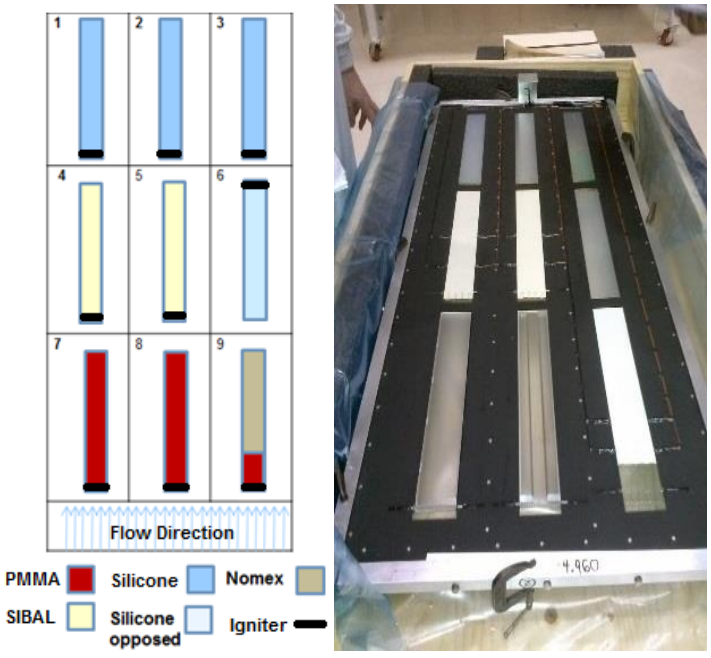

Figure 2. Schematic of the Saffire-II flight sample card. *Nine 5–cm-wide x 30-cm-long samples (left). Picture of sample card (right).*

obtained from several other burning configurations are also presented to help interpret the results of the upward and downward burning tests.

Previous research has shown that burning samples at various angles of inclination ranging from 0 degrees (horizontal) to 90 degrees (vertical) impacts the flame spread and can help understand differences between upward and downward flammability. Kashiwagi and Newman burned thin cellulose at various angles and concluded that the flame spread rate of the bottom flame had little dependence on the angle of inclination.[5] Huang and Gollner showed how burning PMMA at various angles affected turbulent transition.[6] When the bottom flame became unstable, the flame spread rate increased significantly. Quintiere reported findings on angled burns over thin fuels.[7] He concluded that upward (90 degrees) is the fastest spreading configuration and that for angled configurations, upward spread on the bottom is generally faster than upward spread on the top. Gollner found faster spread rates at angles slightly less than vertical for thick fuels.[8]

Thickness	MOC	ULOI
1.00 mm	22	23.4
0.61 mm	20	22.8
0.36 mm	19	21
0.25 mm	18	19.7
0.10 mm	17	17.5

Table I. *The minimum oxygen concentration and upward limiting oxygen index in percent mole (balanced with nitrogen) for five thicknesses of silicone fuel, as studied by Hirsch et al.*[11] *The chemical igniter provides approximately 3000 J for a duration of 25 ± 5 s.*

A forced convective flow also impacts material flammability and was studied in this work. Loh conducted experiments on thin-fuel samples with concurrent flow up to 4 m/s.[9] He determined that at low flow speeds (< 1 m/s), the flame spread rate increased with flow speed, and that the flame length decreased. At higher flow speeds, the flame spread rate was independent of flow speed. Chao performed flame spread studies over thick PMMA samples in concurrent flow up to 2 m/s.[10] It was determined that the flame spread rate increased with flow speed and oxygen concentration.

One of the measures of flammability used by NASA is the Maximum Oxygen Concentration (MOC). The MOC is the maximum percent oxygen by mole for which all of the six samples self-extinguish before spreading 15 cm, i.e., pass Test 1. The ULOI is the Upward Limiting Oxygen Index for which 50% of the repeat samples pass and 50% fail Test 1. Hirsch et al. determined the MOC for silicone samples as shown in Table I using the standard Test 1 chemical igniter.[11] Furthermore, they demonstrated that using a particular hot-wire igniter instead of the chemical igniter did not result in a significant difference in oxygen concentration flammability thresholds. Therefore we chose to use a hot-wire igniter, matching the power and duration reported by Hirsch et al.

II. Test Facilities

Normal-gravity upward (concurrent flow), downward (opposed flow), angled, and horizontal flame spread tests were performed. For some tests, upward forced air flow was added.

Most of the samples were burned in the material flammability test chamber at NASA Glenn Research Center as shown schematically in Figure 3. The chamber contained an unsealed enclosure approximately one cubic meter in volume. The top of the chamber was connected to

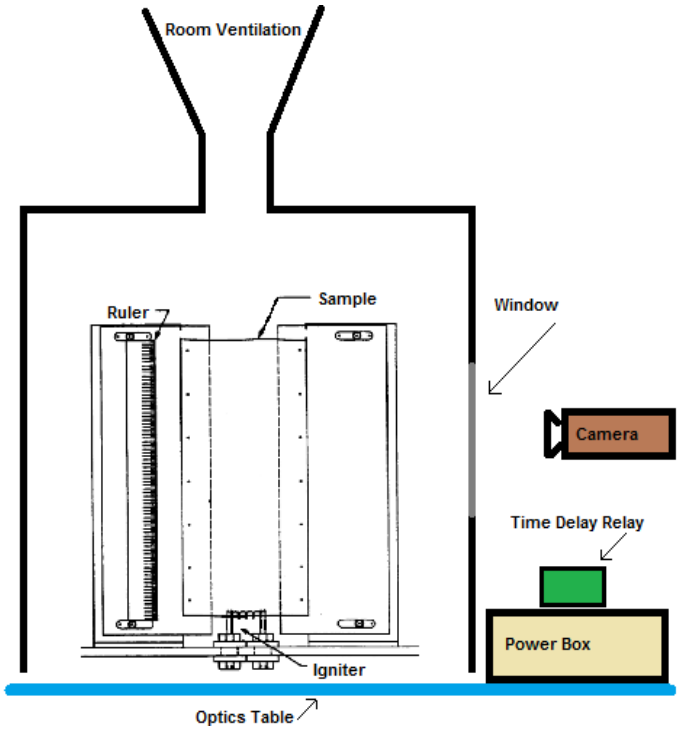

Figure 3. Material flammability test chamber. *Shows camera pointed at window, power box with time delay relay, sample card and aluminum frame through view of the door, and connected to room ventilation.*

an exhaust hood to dispose of any products of combustion. The images were recorded using a Panasonic™ Super Dynamic II video camera.*

A hot-wire igniter (29 AWG Kanthal™) was used for all tests, and a power source with a time delay relay set the igniter duration and current. The igniter had a cold resistance of 0.2215 ohm/cm, and the current for ignition was 3.8 amps. The igniter was powered for 8 s and the total energy release was 740 J. For comparison, the heat of combustion of the 0.36-mm-thick silicone sample in the vicinity of the igniter was approximately 3 kJ. The igniter wire was 26 cm long and it was interweaved around the edge of the sample using a sinusoidal pattern as shown in Figure 4.

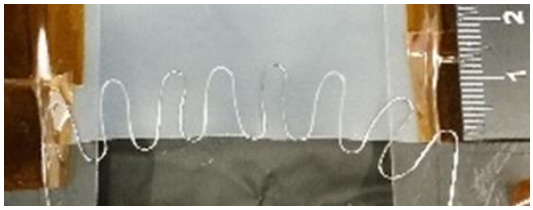

Figure 4. (a) Kanthal igniter. *0.2215 ohm/cm cold resistance, 3.8 amps Kanthal igniter in position to burn 0.61-mm-thick silicone sample.*

Forced air flow (if desired) was provided by five 7.5-cm-diameter fans placed beneath the sample as demonstrated in Figure 5. The flow was straightened by a 1.5-cm-thick honeycomb mesh. The fans provided up to 2 m/s forced flow.

For tests requiring other than room air conditions, a combustion chamber was used.[12] Within this 20-cm-diameter chamber, an upward "trickle" flow of gas at 2 cm/s was established. This slow flow was intended to provide oxygen replenishment while being well below the buoyant flow speed generated by the flame. The gas for the chamber and trickle flow was provided by pressurized precision-mixture bottles. All tests were at atmospheric pressure. The test chamber had two windows enabling a side and front view. The samples were 5 cm wide but could only be up to 10 cm in length. While this was shorter than the 30-cm length specified by NASA 6001 Test 1, the 10-cm samples were adequate for the purposes of this work.

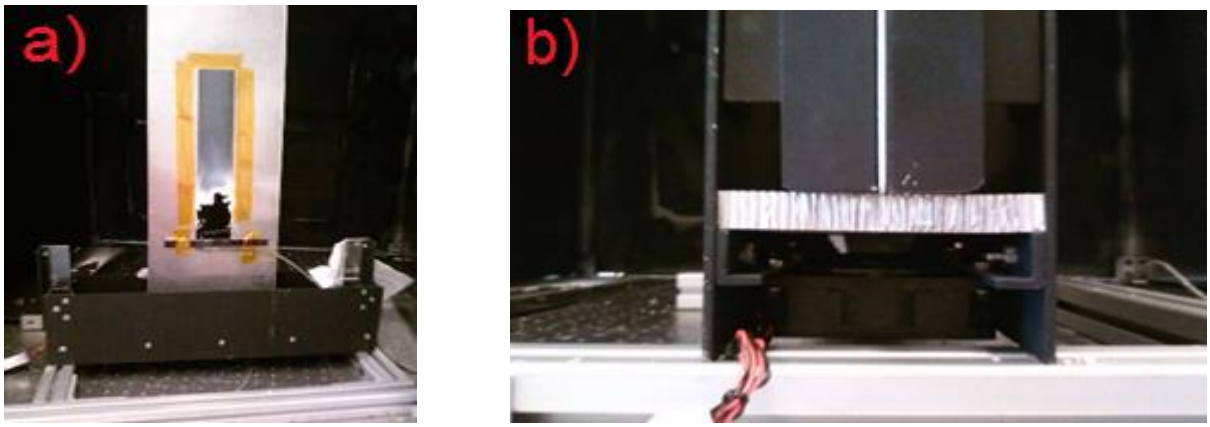

Figure 5. Forced-flow configuration. *a) Front view of sample card placed on top of fans. b) Side view showing the fan bank at the bottom, the 1.5-cm-thick honeycomb flow straightener, and the sample card above.*

In addition to flammability tests, Energy Dispersive X-ray Spectroscopy (EDS), Thermogravimetric Analysis (TGA), and Scanning Electron Microscopy (SEM) were performed on selected samples after they were burned. When burning the silicone, a solid particulate was formed that often deposited downstream onto the unburned sample. EDS was used to determine the composition of the deposit, TGA provided estimates of the pyrolysis temperature of the fuel, and SEM measured the thickness and structure of the deposit.

III. Results

Five different sets of flammability tests in room air were performed on silicone of different thicknesses: upward, downward, angled, upward with forced flow, and downward with forced flow. In addition, a limited series of upward

* Mention of trade names or commercial products is for descriptive purposes only and does not constitute endorsement or recommendation for use by the U.S. Government.

and downward tests were performed at different oxygen concentrations. An attempt was made to ignite each sample with the hot wire, and the burn length was measured. The burn length was defined as the linear distance from the base of the sample where the igniter was positioned to the farthest point of sample consumption. For some cases, the average spread rate, defined as the burn length divided by the burn time, is reported. The burn time is defined as the time from ignition to when the flame has stopped spreading. In some instances, flamelets can still be visible near the base of the sample, but are not consuming new material downstream. The burn time does not include this interval.

Figure 6 shows sample flames for different spread configurations. The top left image shows upward spread, top right shows downward, bottom left shows the angled upward configuration, and bottom right shows upward with forced flow. Note that the flame for the upward buoyant-flow case (a) is longer compared to the forced-flow upward case (d), but the forced-flow upward flame is brighter and wider.

For the upward tests, the six 0.25-mm-thick samples burned an average of 27.5 cm. Half of the samples burned the entire 30 cm and half self-extinguished. When self-extinguishment occurred, the flame tip began to shrink and the flame spread slowed until the flame disappeared. All six samples burned more than 15 cm. The next thicker sample, 0.36 mm, burned an average of 14.8 cm, but one of the six samples did burn longer than 15 cm. For this reason, these results would have failed Test 1. The 0.61-mm-thick sample burned an average of 7.6 cm, with all six samples burning less than 15 cm. None of the 1.00-mm-thick samples ignited in ambient air. Figure 7 shows the differences in burn structure and particulate deposition for three thicknesses of silicone that were burned upward.

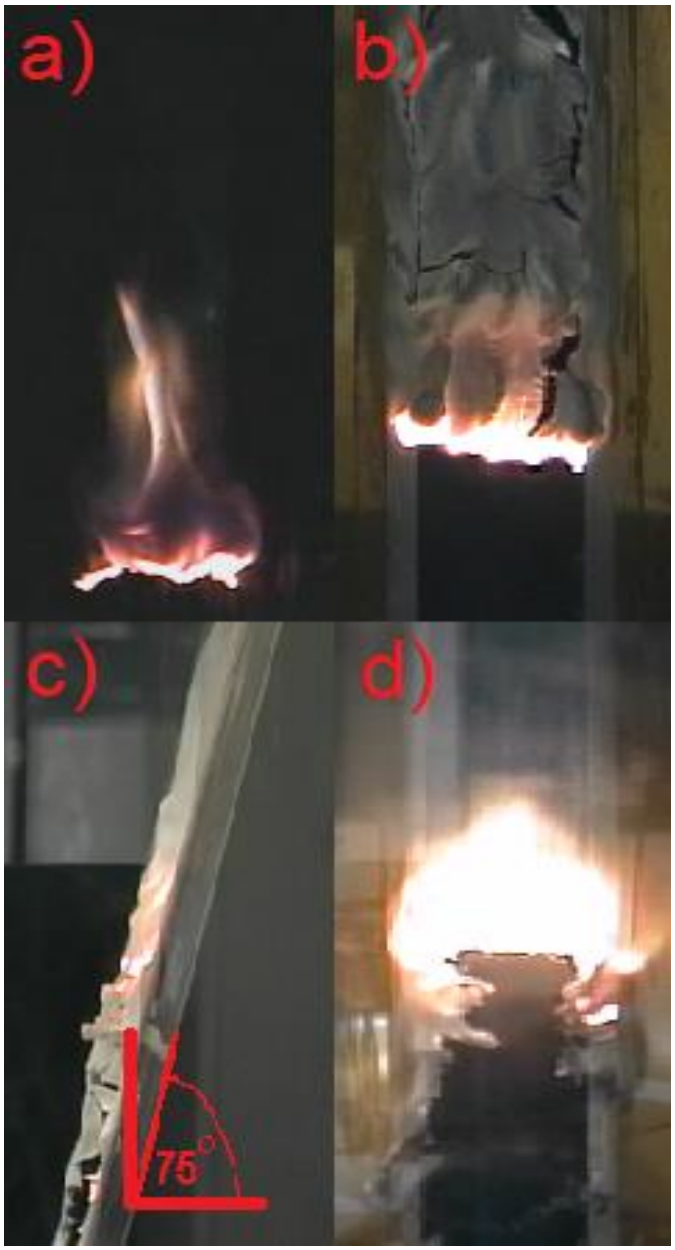

Figure 6. Flame spread images. *a) Buoyant-flow upward flame spread. b) Buoyant-flow downward flame spread. c) 75-degree angle buoyant-flow upward flame spread. d) Concurrent 2 m/s forced-flow upward flame spread.*

The downward tests produced slower average flame spread rates compared to the upward tests. The average spread rate was 2.90 mm/s upward vs. 0.56 mm/s downward for the 0.36-mm thickness and 5.22 mm/s upward vs. 1.01 mm/s downward for the 0.25-mm thickness. All the downward tests that ignited burned the full 30 cm. The 0.61-mm- and 1.00-mm-thick silicone samples did not ignite in the downward configuration.

Burn tests with sample inclinations of 60, 75 and 80 degrees were investigated. At 60 and 75 degrees, the 0.36-mm-thick sample did not self-extinguish, but at 80 degrees it did. The 0.61-mm-thick sample self-extinguished for all three angles.

Tests with upward forced flow were also conducted for upward and downward flame spread. Each thickness was tested at the maximum flow of 2 m/s. For the 0.25-, 0.36-, and 0.61-mm thicknesses, the entire sample burned upward for all three trials. The 1.00-mm-thick sample still would not ignite. A test was conducted in the upward configuration with the 0.36-mm thickness where the test was started with flow, and once the sample burned a length of 10 cm, the

flow was shut off. The sample burned another 7.5 cm before self-extinguishing. For the downward spreading of 0.25- and 0.36-mm thicknesses, the samples would not ignite with the flow on. When ignited with the flow off, the samples were blown out almost immediately when the flow was turned on. Test results for all tests conducted in room air are summarized in Table II.

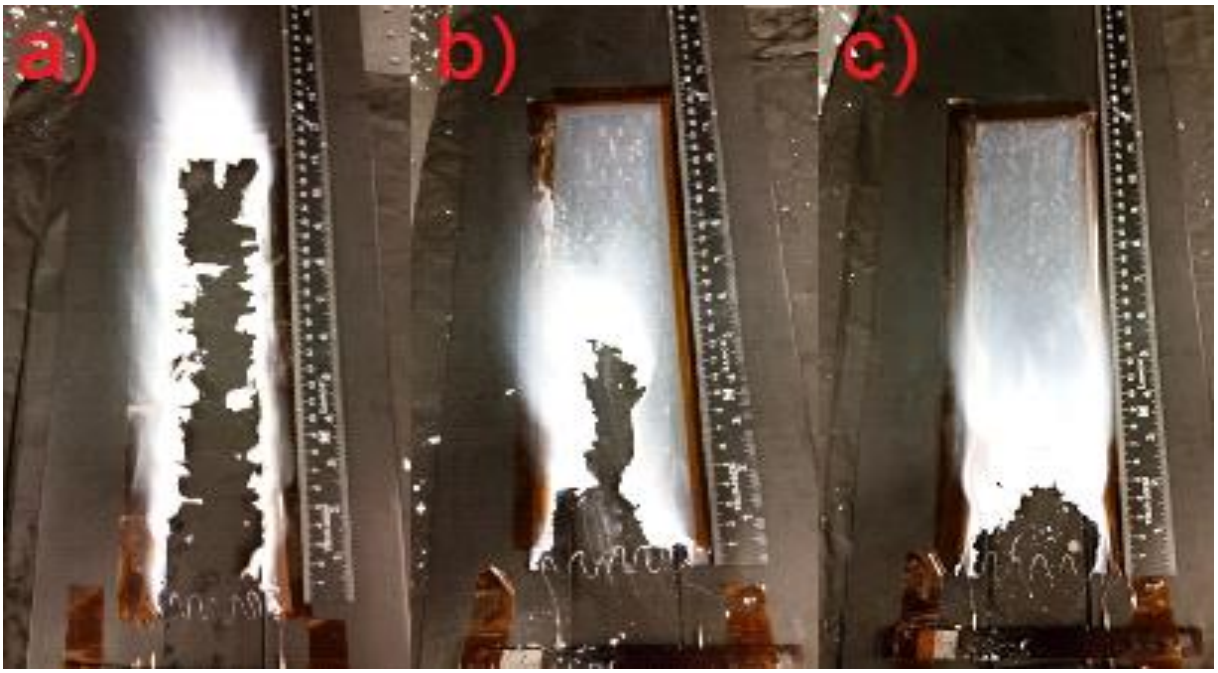

Figure 7. *Post-burn images of silicone samples of various thicknesses showing burn-out pattern and particulate deposition: a) 0.25 mm, b) 0.36 mm, and c) 0.61 mm.*

Test Name	Sample thickness (mm)	Burn Length (cm)	Burn Time (s)	Burn Velocity (mm/s)
Upward	0.25	27.51	52.67	5.22
Upward	0.36	14.81	51.05	2.90
Upward	0.61	7.62	60.83	1.25
Upward	1.00	0.00	0.00	0.00
Downward	0.25	30.00	295.68	1.01
Downward	0.36	30.00	539.45	0.56
Downward	0.61	0.00	0.00	0.00
Downward	1.00	0.00	0.00	0.00
Horizontal	0.25	30.00	287.34	1.04
Horizontal	0.36	30.00	530.87	0.57
Horizontal	0.63	0.00	0.00	0.00
60 degree upward	0.36	30.00	141.89	2.11
60 degree upward	0.61	9.53	93.23	1.02
75 degree upward	0.36	30.00	103.67	2.89
75 degree upward	0.61	9.86	83.10	1.19
80 degree upward	0.36	15.80	54.29	2.91
80 degree upward	0.61	9.43	72.94	1.29
Upward forced flow	0.36	30.00	88.55	3.39
Upward forced flow	0.61	30.00	198.93	1.51

Table II. *Flammability results for 1-g tests in air. Results are an average of 6 tests per case.*

Figure 8 shows the average burn length of six tests for each thickness for the upward, downward, and upward forced-flow cases. In the downward configuration and upward with forced flow cases, if the sample could be ignited then it burned the entire length. The 0.61-mm-thick sample failed to ignite downward, and the 1-mm-thick sample failed to ignite both upward and downward. The average upward burn lengths for the 0.25-mm, 0.36-mm, and 0.61-mm samples are plotted. The uncertainty bars on the burn length represent the standard deviation of the six tests.

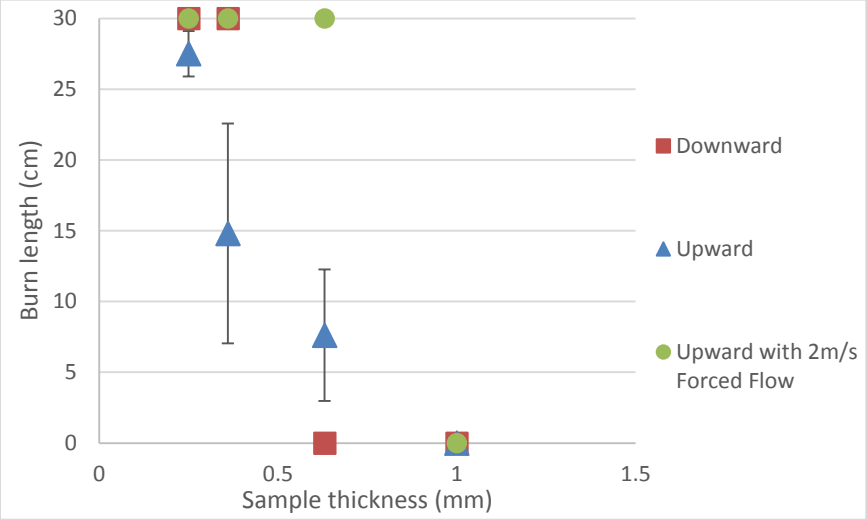

Figure 8. Burn length of downward, upward, and upward forced-flow tests. *Each sample was 30 cm in height. The 1.00-mm-thick sample failed to ignite in the upward and downward configuration. The downward and forced-flow cases, if ignited, burned the entire sample.*

Testing with various oxygen concentrations with nitrogen balance was performed in a sealed combustion chamber and the results are shown in Figure 9. The test chamber can only hold a 5-by 10-cm sample. This was suitable for determining the limiting oxygen index for downward burns. Upward tests were conducted as well, and self-extinguishment was observed; however, a longer sample is needed for complete comparison with the previous testing done in room air.

For upward spread, ignition was first observed at 18% O_2 for the 0.25-mm thickness. At 19% O_2, the 0.25-mm thickness consistently burned the entire 10 cm, a full one percent below the oxygen required to even ignite this thickness in the downward configuration. For the 0.36-mm thickness, both upward and downward ignition is achieved at 20% O_2, but self-extinguishment is observed in the upward configuration. For samples of 0.36 mm and thicker and at a given O_2 level, self-extinguishment is observed in the upward configuration while the downward burns the fuel completely. Based on the tests in ambient air (~21% O_2), it is expected that self-extinguishment of the 0.25-mm-thick samples would have occurred at 20% O_2 for the

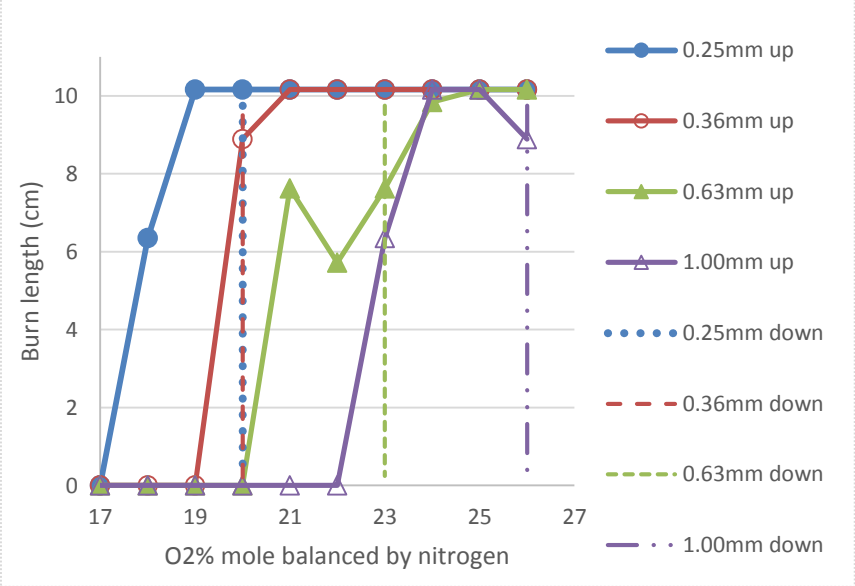

Figure 9. Burn length for upward and downward flame spread in atmospheres of varied oxygen concentration. *Vertical dashed lines represent the minimum O_2 level a thickness needs to ignite in the downward configuration. For all downward samples, once ignited, the sample burned all 10 cm. Markers represent the average of three tests. Solid lines are drawn for clarity.*

Chamber % O_2	Upward Burn Length (cm)			
	0.25 mm	**0.36 mm**	**0.61 mm**	**1.00 mm**
17	0	0	0	0
18	6.35	0	0	0
19	10.16	0	0	0
20	10.16	8.89	0	0
21	10.16	10.16	7.62	0
22	10.16	10.16	5.72	0
23	10.16	10.16	7.62	6.35
24	10.16	10.16	9.84	10.16
25	10.16	10.16	10.16	10.16
26	10.16	10.16	10.16	8.89

Table III. *Upward burn lengths for four fuel thicknesses. Each entry is an average of 3 tests.*

Chamber % O_2	Downward Burn Length (cm)			
	0.25 mm	**0.36 mm**	**0.61 mm**	**1.00 mm**
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	10.16	10.16	0	0
21	10.16	10.16	0	0
22	10.16	10.16	0	0
23	10.16	10.16	10.16	0
24	10.16	10.16	10.16	0
25	10.16	10.16	10.16	0
26	10.16	10.16	10.16	10.16

Table IV. *Downward burn lengths for four fuel thicknesses. Each entry is an average of 3 tests.*

upward burns if the sample were longer. Plans to extend the chamber to enable burning full 30-cm-long samples are underway. Tables III and IV summarize the upward and downward tests respectively in the sealed chamber.

EDS was performed on the solid particulate deposited onto a 0.36-mm sample. Only two elements, silicone and oxygen were detected. Using stoichiometery, it was inferred that the solid deposit is silica (SiO_2). TGA was performed on one of the 0.61-mm-thick samples after it was burned. Figure 10 shows the different areas that were tested including two areas damaged by the flame (2.5 cm and 7.5 cm from the leading edge of the sample) which had a silica layer formed on the surface, an undamaged area (13 cm from the leading edge) that had a deposited silica layer, and a remote area (30 cm from the leading edge) that essentially consisted of the original silicone with no silica deposition.

Figure 11 shows the results from the four areas. Noticeable mass loss for all four samples started at around 400°C. Different levels of mass loss are shown, reflecting the different levels of damage from the flame. The original fuel and undamaged silica covered samples have identical traces, likely because the silicone was undamaged in both cases. The

Figure 10. Sample of burned, originally 0.61-mm-thick silicone. *Pieces at given distances away from the leading edge circled in red were cut out and analyzed using TGA.*

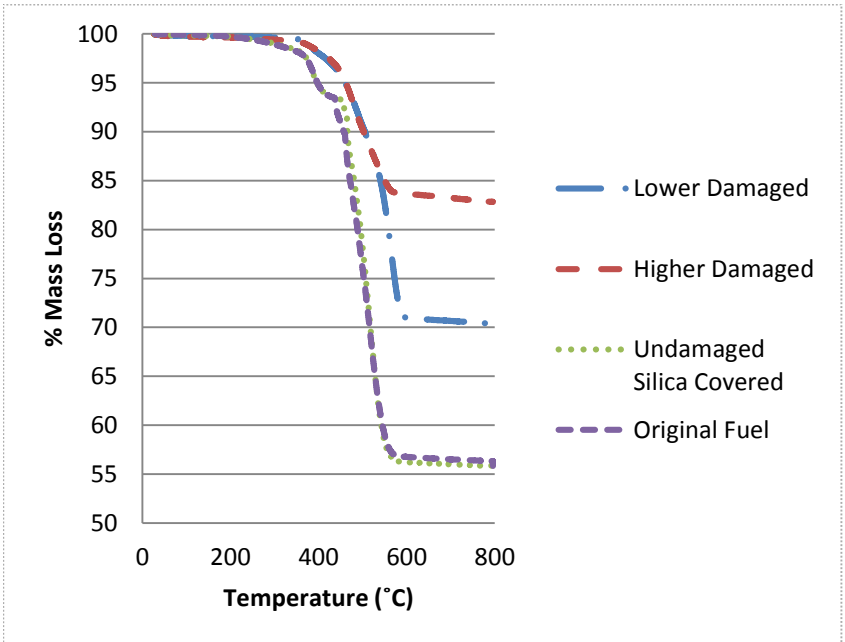

Figure 11. A small sample of originally 0.61-mm-thick silicone was submitted for TGA, per Figure 10. *The sample at 13 cm away from the leading edge which is unburnt but covered with silica has the same profile as the fresh silicone sample at 30 cm away.*

more the sample was pyrolyzed by the flame, the less percent mass loss resulted in the TGA because there was less fuel for the TGA to vaporize.

An area of the originally 0.36-mm-thick silicone was analyzed after an upward burn using SEM. Figure 12 shows

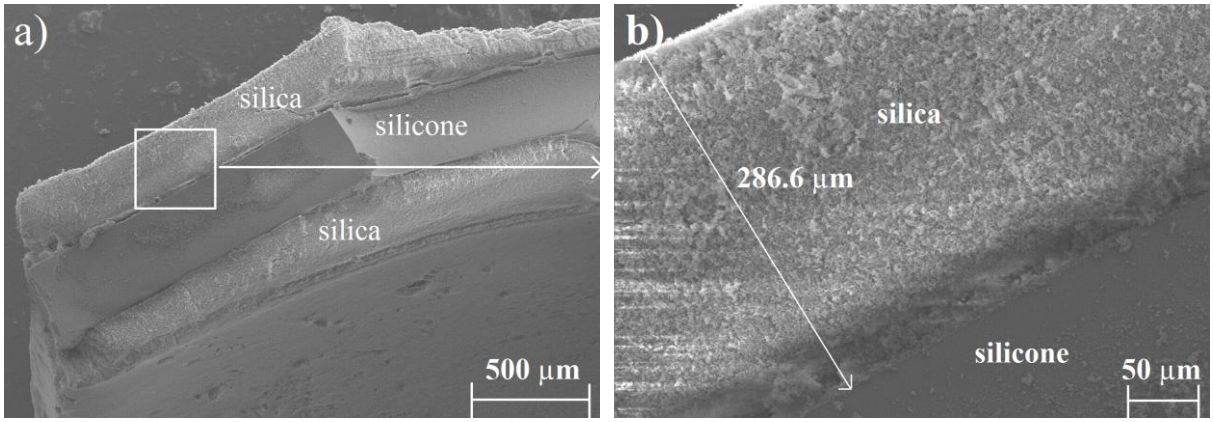

Figure 12. *SEM images.* *(a) SiO_2 layers formed on both sides of the originally 0.36-mm-thick silicone sample after an upward burn, 50 times magnification. (b) SiO_2 layer 286 μm thick was formed over the silicone sample, 300 times magnification.*

50x and 300x magnifications. At the point where self-extinguishment occurred, the deposited layer of silica measured to be 286 μm thick on the top half of the sample. The unburned fuel measuring 0.36 mm thick is visible in the middle of Figure 12a showing that the original silicone buried and sandwiched between the silica layers on both sides is undamaged.

IV. Discussion

Most of the results from the ground-based flammability testing of silicone were as expected. The one phenomenon that was unexpected was the self-extinguishment of the silicone in the upward configuration for the thinnest two samples while the corresponding cases in the downward configuration burned the entire sample. When burning in the upward configuration, silica formed in the gas phase deposits onto the unburnt downstream silicone sample, providing an insulating thermal barrier and inhibiting the silicone from pyrolyzing. The silica deposit layer may also be providing a diffusional barrier for the fuel vapors to reach the surface by creating a tortuous path through the deposit thickness. The deposit layer may be formed by a combination of vapor and particulate silica arriving on the silicone sample surface. In the downward configuration, the silica is carried up by buoyancy, and does not deposit on the unburnt silicone. Maradey et al. saw similar flammability results by burning polyurethane foam in the upward and downward configuration.[13] They hypothesized that the char from the foam caused self-extinguishment in the upward configuration. The results of the angled tests as well as the uward forced flow cases support this hypothesis. When at a 75-degree angle or lower, the silica is carried up with the buoyant flow, away from the unburnt silicone surface on one side of the sample. When buoyant flow is aided by forced flow, the higher air flow rate convects vapor-phase silica away and hence reduces the downstream deposition rate on the fresh silicone surface.

Work has been published that shows the effect of silica on flammability. Buch et al. have deposited uniform layers on silicone samples to show how the layers slow the pyrolysis rate.[14] Romenesko and Buch own a patent for using a siloxane polymer powder with silica filler to reduce the flammability of organic resins.[15] Solid coatings have been developed for the purpose of creating a protective residue upon burning. Kim and Davis developed a multi-walled carbon nanotube layer-by-layer coating that reduced heat release rate and burn time of polyurethane foam.[16]

Figure 12 shows a silica layer of 286 μm at the point of self-extinguishment on top of the originally 0.36-mm-thick silicone. This deposit layer is thicker than the half-thickness of the original silicone sample. While crystalline silica has a larger density than silicone (2600 kg/m^3 vs. 960 kg/m^3), the silica layer is not perfectly crystalline (as would be expected from the molecular vapor deposition of silica alone) but rather has a porous structure resulting from the co-deposition of both silica vapor and various sizes and shapes of the silica particles. The deposit layer has a lower density, and also a lower thermal conductivity than pure silica. Below, we show that the thermal effect alone (i.e., ignoring the mass transfer barrier effect) is sufficient to explain the observed self-extinguishment of upward tests. Equation 1, which is based on a well-established thin-fuel flame spread model[17], represents the critical heat flux needed

to raise the thermal inertia of the fuel and a deposit silica layer to the ignition temperature, which in this case is the pyrolysis temperature.

Figure 13 shows the critical heat flux calculated from Eq. (1) in order to continue the upward flame spread of a silicone sample with a particular thickness as a function of added silica layer thickness. Symmetry of the deposit silica is assumed by using the half thickness of silicone in the calculation. Table V lists the physical properties used in Eq.

$$\dot{q}'' = \frac{[(\rho_s c_{p,S} \frac{\delta_s}{2}) + (\rho_{SiO_2} c_{p,SiO_2} \delta_{SiO_2})](T_{ign} - T_\infty)}{\tau} \qquad (1)$$

(1). The burn time of 55 seconds is the average burn time of the 0.25-mm, 0.36-mm, and 0.61-mm upward samples. The ignition temperature of 673 K was determined from the approximate start of mass loss from the TGA results.

As expected, the more silica deposited, the more heat flux is needed for upward flame spread. The black line represents the calculated minimum heat flux for a 0.36-mm-thick silicone sample with a 286-µm-thick silica deposit, since this is the point where the flame is known to self-extinguish. This line is quite consistent with other known data points for the flame spread of fresh silicone samples with no silica deposit. For example, the 1-mm-thick silicone sample with no silica deposit falls above the line and is known to not ignite, while the other three thicknesses of silicone samples with zero silica deposit fall below the line and will sustain flame spread. It is seen that upward flame spread is not possible above a certain total thickness of silicone sample and overlaying silica deposit including cases with no silica deposit.

ρ_s (kg/m^3)	970
$C_{p,s}$ (J/kg-K)	1050
ρ_{siO2} (kg/m^3)	2600
$C_{p,siO2}$ (J/kg-K)	1591
T_{ign} (K)	673
T_{oo} (K)	293
τ (s)	55

Table V. *Model properties used in Eq. (1).*

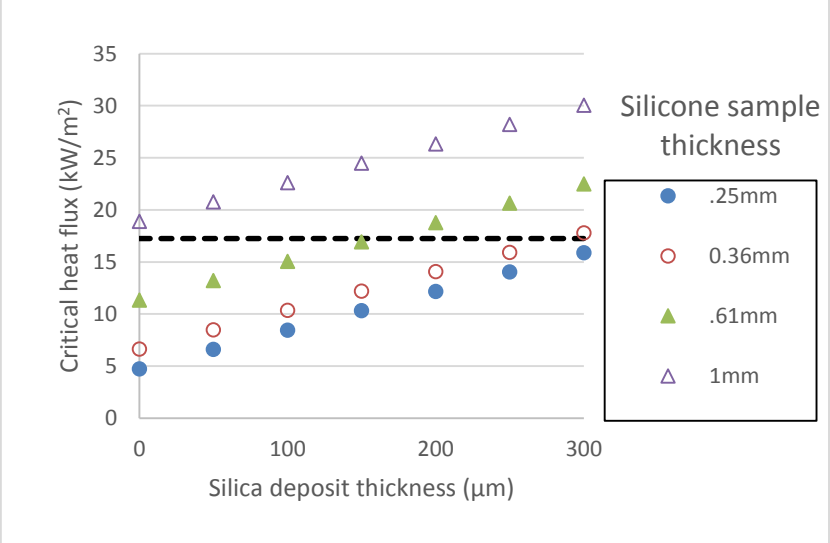

Figure 13. The critical heat flux needed to raise the thermal inertia of half the thickness of a particular silicone sample plus silica deposit vs. the overlaying silica deposit thickness.

Besides the thermal insulating effect, the deposit layer could be acting as an inhibiter by other mechanisms, as briefly mentioned above. For example, as a physical barrier to mass transfer, it may be hindering fuel vapors (formed after pyrolysis) from reaching the flame and thus facilitating extinguishment of the upward burn cases. The silica layer may also have an effect on the flame stabilization zone. T'ien et al. have tested upward and downward burning of polyurethane foam.[18] In their work, a region is identified where the upward MOC is higher than the downward MOC, and it is suggested that the char produced affects the flame stabilization zone.

V. Summary and Conclusions

Silicone samples were tested for 1-g flammability characteristics in preparation for Saffire flight II. Burning the samples of increasing thickness in an upward configuration yielded inversely proportional burn lengths, as expected. The 0.25-mm- and 0.36-mm-thick samples had a greater burn length in the downward configuration than their corresponding upward cases. The reason for the increased flammability in the downward direction compared to upward is attributed to the deposition of a silica layer onto the fresh fuel in the upward case. It has been shown that this layer acts as a thermal barrier, which prohibits the fuel from reaching the pyrolysis temperature fast enough to sustain flame spread. Burning the 0.36-mm-thick sample in the horizontal configuration, and at a 60-degree and 75-degree angle from the horizontal prevented the silicone from self-extinguishing, likely due to the silica generated by

the flame being entrained up and away from the fuel sample, preventing deposition. In all atmospheres tested, if the silicone could be ignited in the downward configuration then it would burn the entire length of the sample.

When a forced upward flow of air (2 m/s) was imposed, all thicknesses that were ignited burned to completion in the upward configuration but were extinguished in the downward configuration. Upward burning tests were done with fan flow at the start, and then the flow was shut off. The samples self-extinguished soon after. This is further evidence that the deposition of silica is inhibiting flame spread since the higher air flow rate convects vapor-phase silica away and hence reduces the deposition rate on downstream fresh silicone surface. The impact of the silica layer on the flame spread characteristics of silicone that is reported in this study will be critical in interpreting the data that will be obtained in the Saffire-II flight test.

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