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

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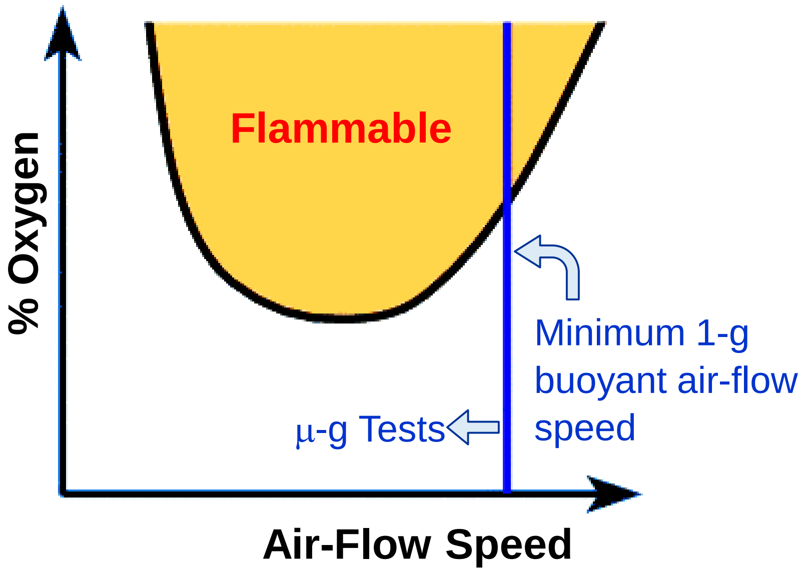
45th International Conference on Environmental Systems
July 14th 2015

Outline

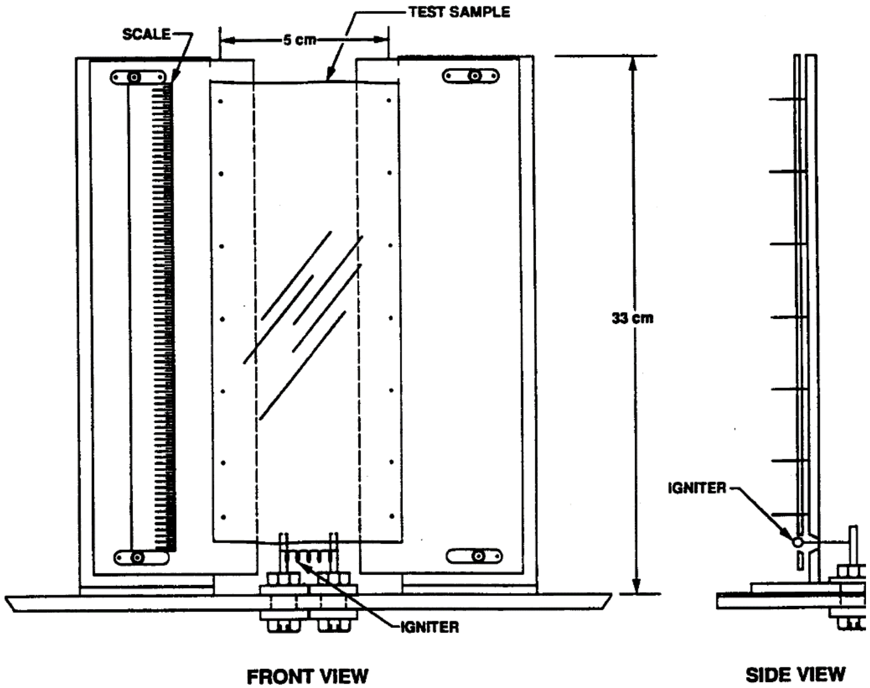
- Motivation
- Saffire Project
- Silicone Samples
- Facilities
- Results
- Residue Analysis
- Discussion and Model
- Summary and Conclusions

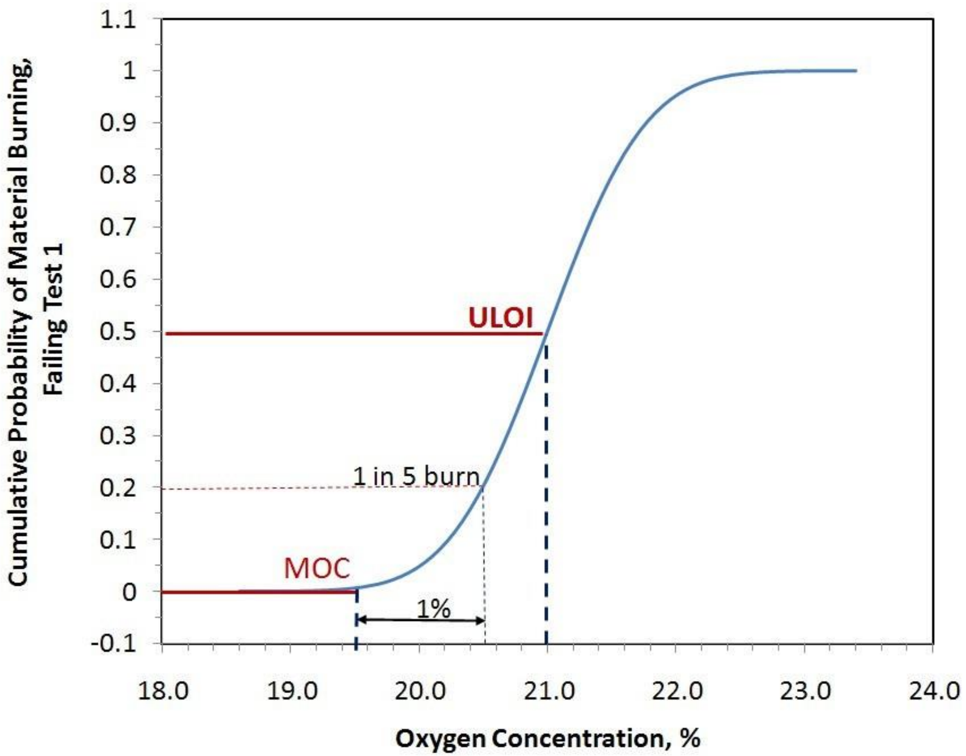
Research Motivation

- Fire can be a catastrophic hazard for the manned space flight program
  - ISS and S&MA community recently counted **516 discrete** flammable items
  - Increase of 40% over 3 years
  - Bungees, plastic Ziplocs, paper, and packaging
- For NASA material testing, the assumption has been that materials will burn more readily in 1-g compared to microgravity
- However, flame spread behavior in low-gravity is substantially different than in 1-g
- Low-speed air flow has a major influence on material flammability



NASA Standard 6001 Test 1

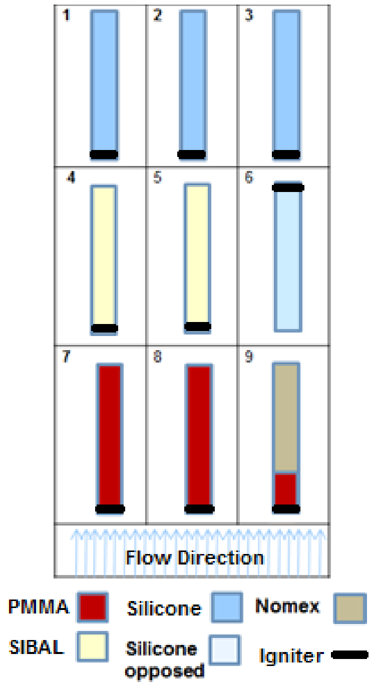


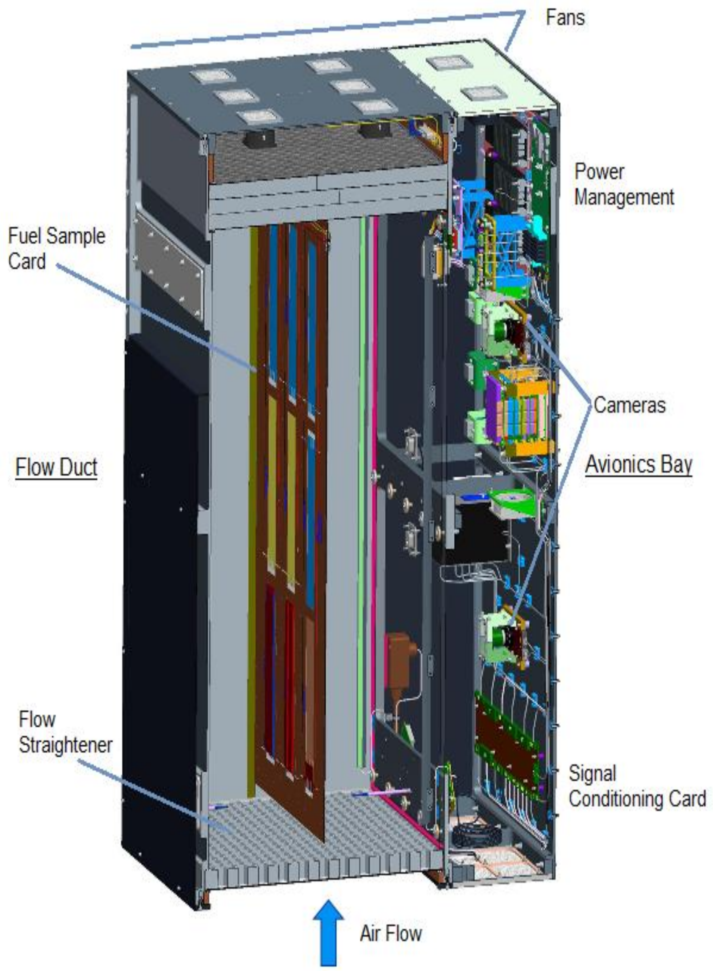


- Upward flame spread test
- Failed test if sample material is consumed past 15 cm
- 1-g upward flame spread is assumed to be worst case for flammability
- Some materials have shown downward flame spread to be worse
- Other figures of merit: MOC; ULOI

Saffire Project

- Spacecraft Fire Experiment
- Study microgravity flame spread
- Saffire I and III will study large sample
- Saffire II will study 9 small samples





Saffire Operations Concept

Antares Launch

Saffire Unpowered

Cygnus Destructively Re-enters Atmosphere With *Saffire*

Silicone Samples

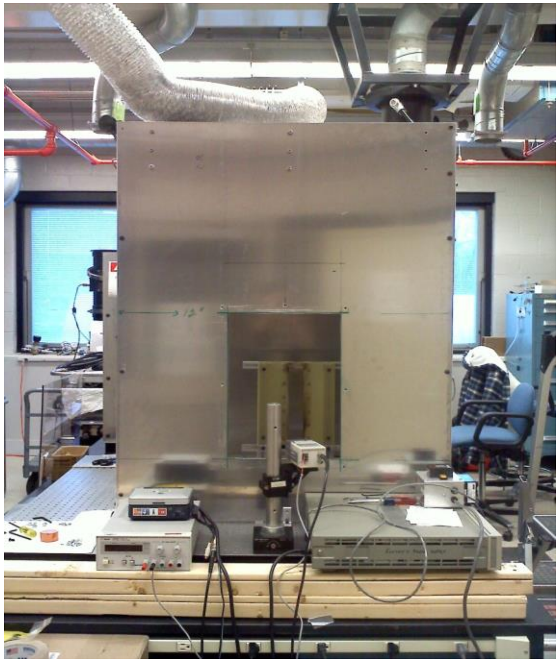
- 4 of 9 small samples on Saffire II will be Silicone
  - Polydimethylsiloxane (PDMS)
  - C_2H_6OSi
- Practical applications on ISS
  - Grips for spacesuit gloves
  - Microprocessor covers
- Flammability limits near expected test atmosphere
- Obtained different burn lengths for different thicknesses

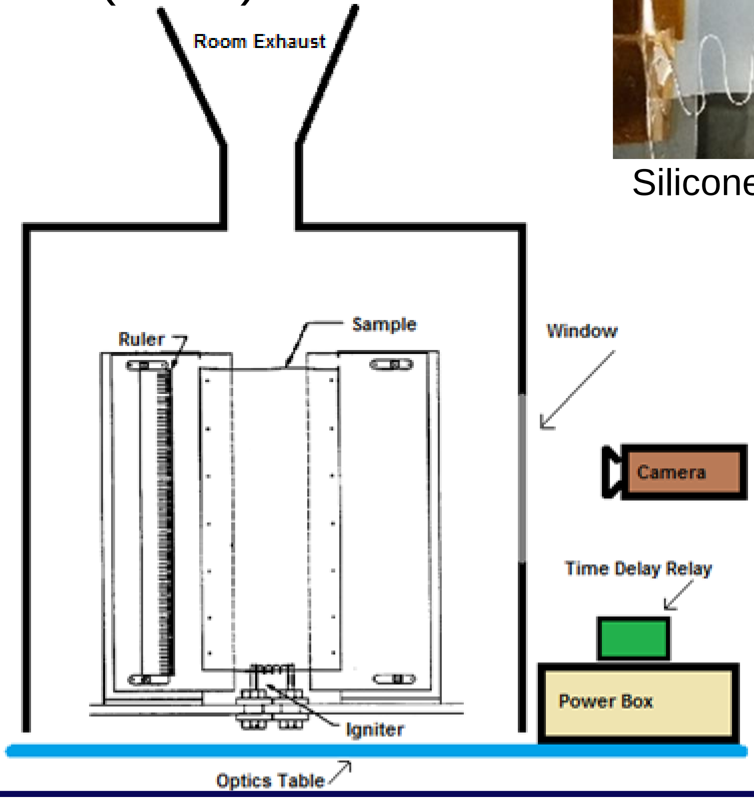
Thickness (mm)	MOC	ULOI
1.0	22	23.4
0.61	20	22.8
0.36	19	21
0.25	18	19.7
0.10	17	17.5

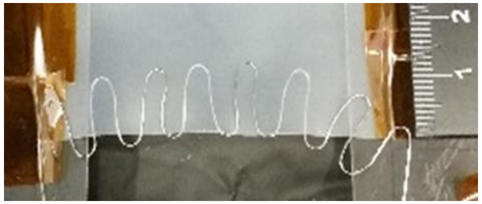
The maximum oxygen concentration and upward limiting oxygen index (in percent O_2) for five thicknesses of silicone fuel [from Hirsch et al.] The chemical igniter provided 3000 J in 25 $\pm$ 5 s.

Test Facilities: Large Enclosure

- Most tests conducted in material flammability test chamber
- Unsealed enclosure ~ 1 m^3 in size attached to room exhaust
- Hot wire igniter
    - 29 AWG Kanthal™
    - 3.8 amps for 8 seconds (92 W)



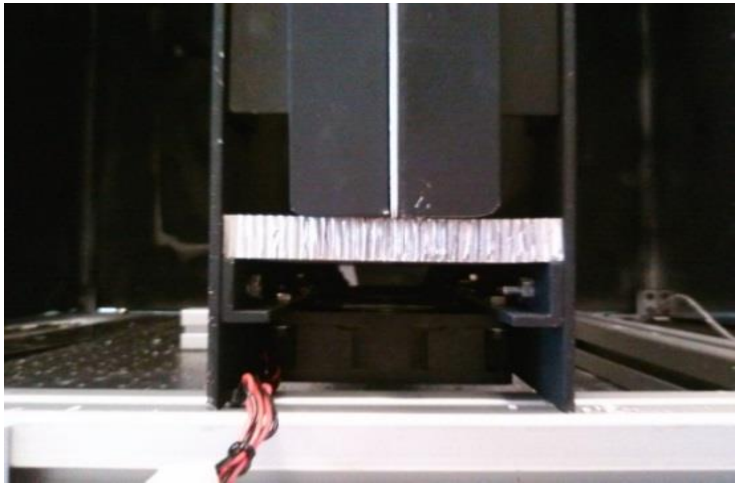


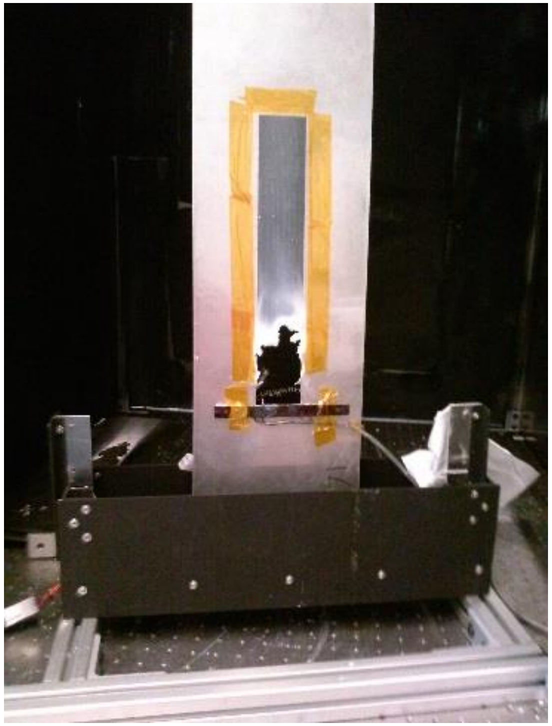


Silicone sample with igniter

Test Facilities: Forced Flow Addition

- 5 lateral 7.5-cm diameter muffin fans
- Flow straightened by 1.5-cm thick honeycomb mesh
- Up to 2 m/s flow



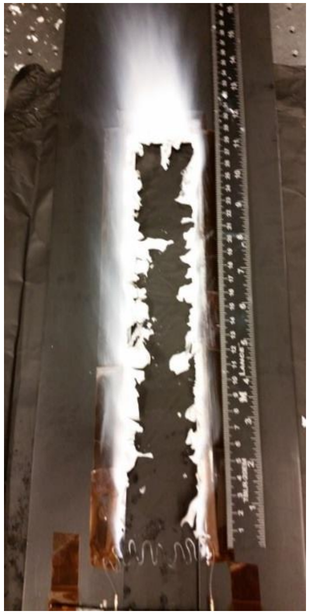


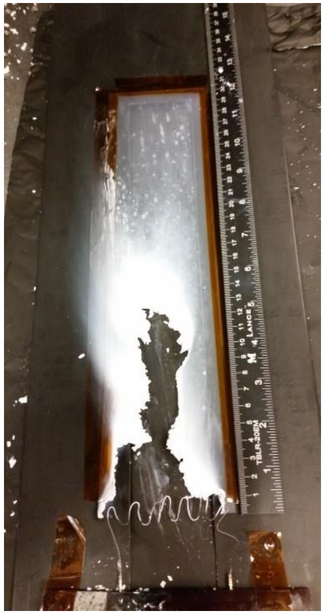
Test Facilities: Sealed Chamber

- Used to vary oxygen concentration
- Gas flow (from pressurized bottles) between 0 and 30 cm/s achievable
- Chamber: 20-cm inner diameter
- Samples were 10-cm tall by 5-cm wide

Results: Upward Spreading Buoyant Flow

- 3 of the 4 thicknesses ignited
- Every thickness that ignited has at least 1 sample that self-extinguished





Thickness (mm)	Burn Length* (cm)	Burn Time* (s)	Spread Rate* (mm/s)
0.25	27.5	52.7	5.2
0.36	14.8	51.0	2.9
0.61	7.6	60.8	1.2
1.00	0.0	0.0	0.0

* Values represent the average of 6 tests for each thickness

Results: Downward Spreading Buoyant Flow

- 2 of the 4 thicknesses tested ignited
- Every sample that was ignited burned the full length
- Significantly slower than upward flame spread

Thickness (mm)	Burn Length* (cm)	Burn Time* (s)	Spread Rate* (mm/s)
0.25	30.0	295.7	1.0
0.36	30.0	539.4	0.6
0.61	0.0	0.0	0.0
1.00	0.0	0.0	0.0

* Values represent the average of 6 tests for each thickness

Results: Angled Spreading Buoyant Flow

- Horizontal flame spread burned similar to downward flame spread
- Some angles for the 0.36-mm samples allowed complete burning

Angle (deg)	Burn Length (cm) (0.36-mm thick)	Burn Length (cm) (0.61-mm thick)
0	30.0	0.0
60	30.0	9.5
75	30.0	9.9
80	15.8	9.4
90	14.8	7.6

* Values represent the average of 6 tests for each thickness

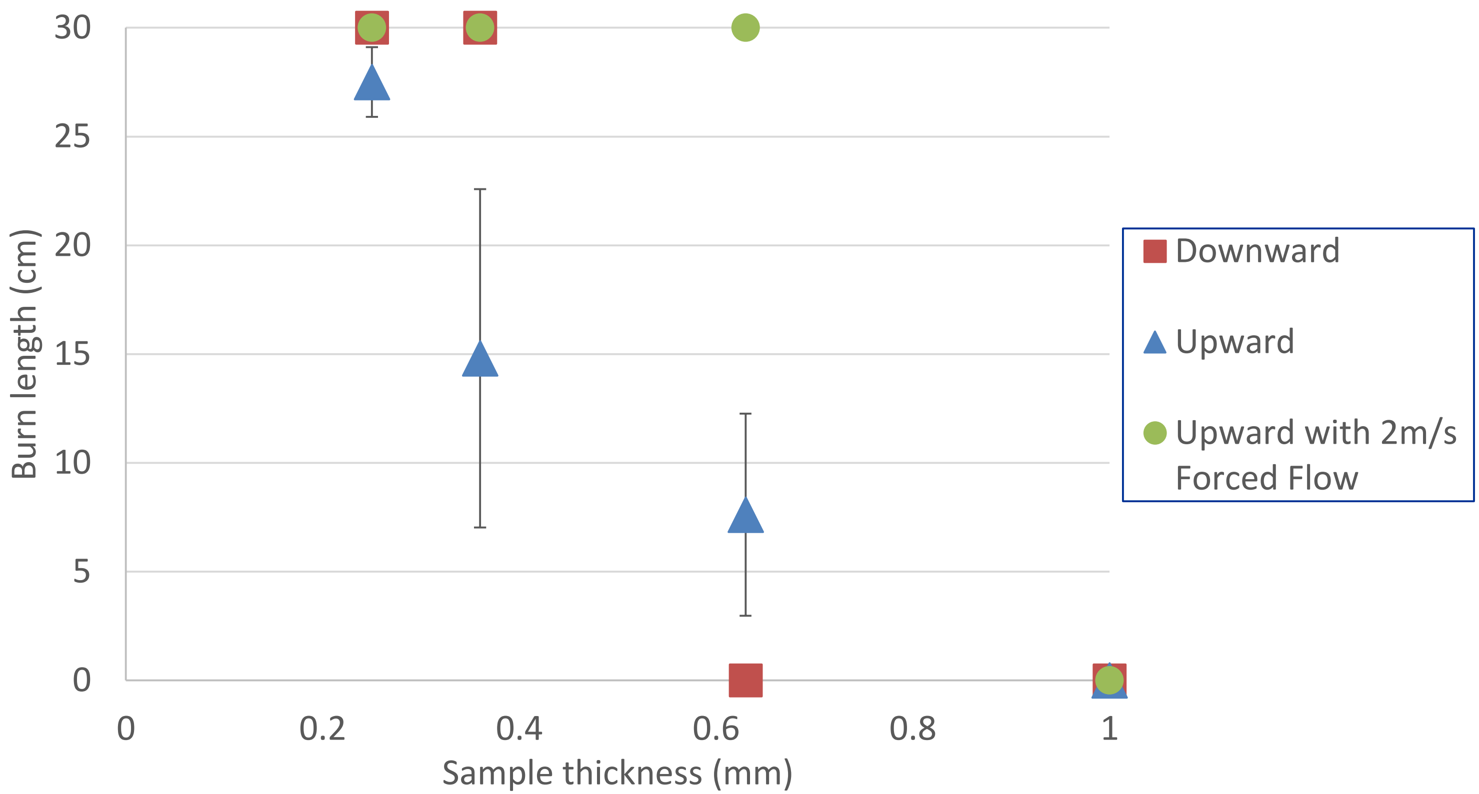
Results: Forced Flow

- Forced flow enhanced flame spread
- Samples could not ignite in the downward configuration under forced flow
- For samples ignited downward without flow, the flames were blown off almost immediately when forced flow was applied

Thickness (mm)	Burn Length (cm)	Burn Time (s)	Burn Velocity (mm/s)
0.36	30.0	88.6	3.4
0.61	30.0	198.9	1.5

* Values represent the average of 6 tests for each thickness

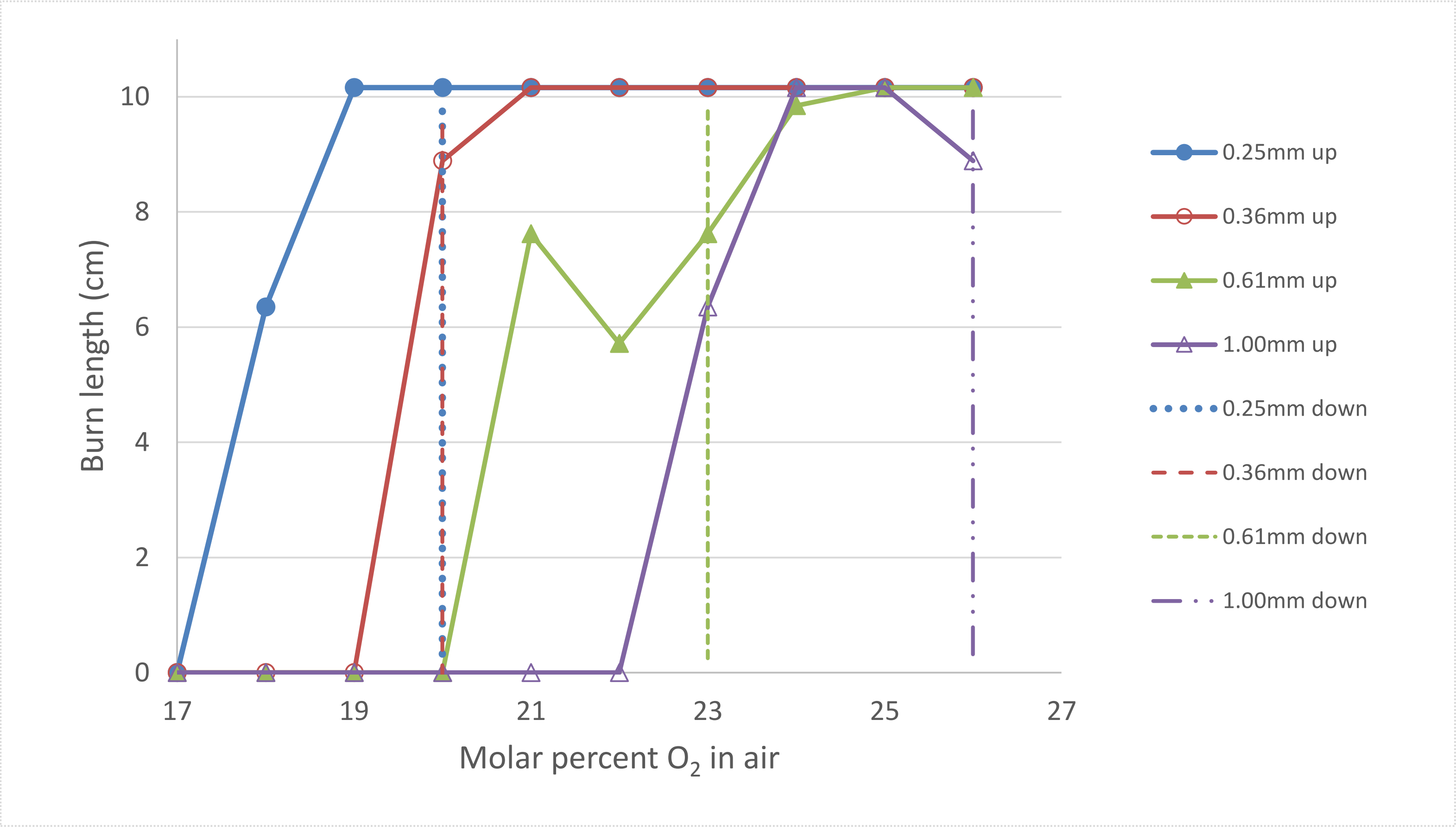
Results: Upward, Downward and Forced Flow



- 1-mm thick sample did not ignite in air
- Forced flow increased burn length and upward spread rate for 0.61, 0.36 and 0.25-mm samples
- Samples in upward configuration that were burning under forced flow self extinguished after forced flow was shut off

Results: Maximum Oxygen Concentration

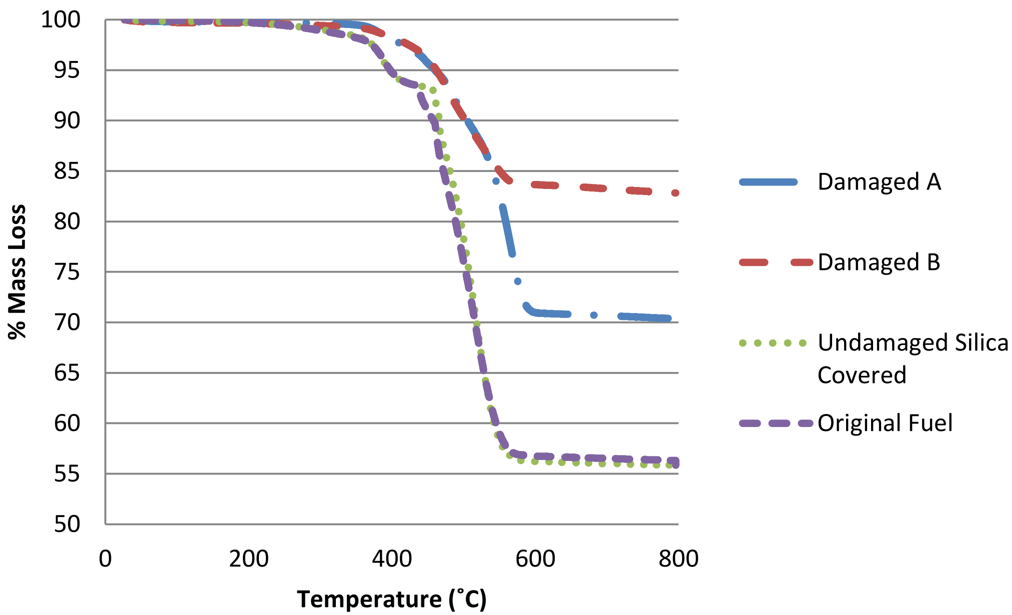
- Oxygen concentrations from 17% to 26% were examined



* Values represent the average of 3 tests for each thickness

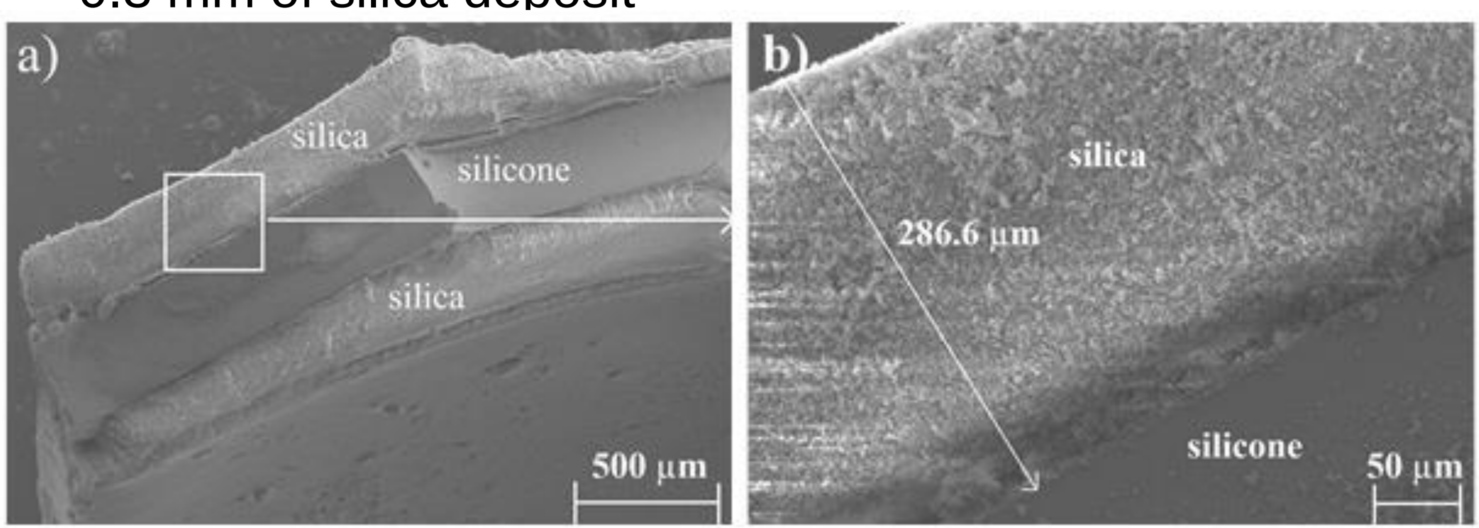
Residue Analysis: TGA

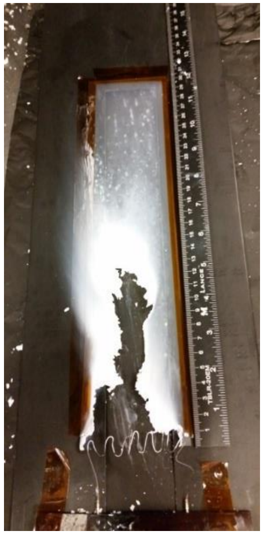
- Thermo-Gravimetric Analysis
- 10° C increase per minute
- Post burn analysis of 0.61-mm sample
- Mass loss in 4 different areas
- Original fuel and undamaged silica covered fuel produced same mass loss curve



Residue Analysis: SEM and EDS

- Energy Dispersive X-ray Spectroscopy (EDS) performed on the deposit from an upward burning 0.36-mm sample post test
- Only silicon and oxygen detected leading to assumption the deposit was SiO_2 (silica)
- Scanning Electron Microscope (SEM) image of same sample post burn
- ~ 0.3 mm of silica deposit

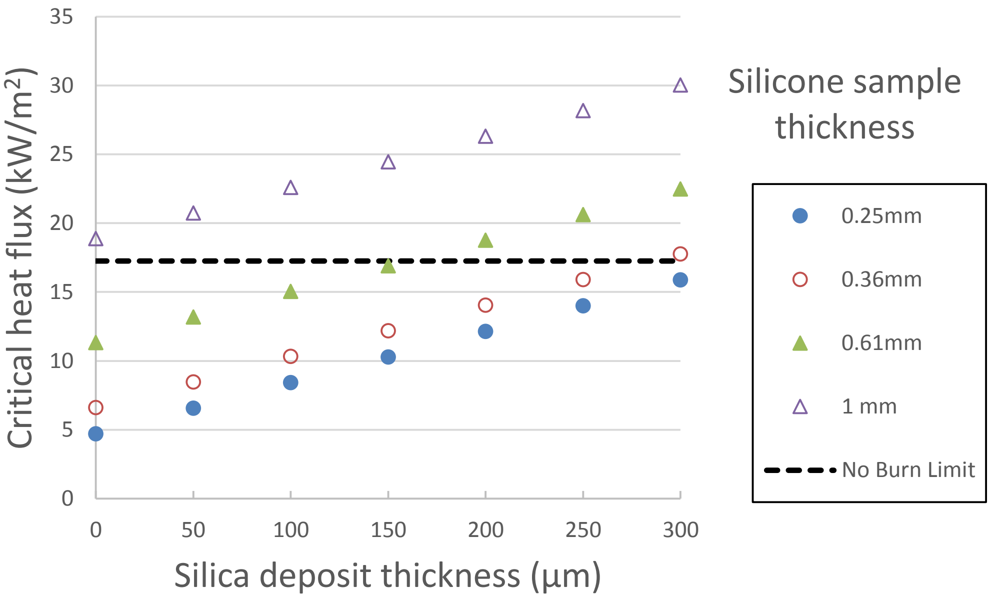




SEM images. (a) SiO_2 layers formed on both sides of the originally 0.36-mm-thick silicone sample after an upward burn. (b) SiO_2 layer 286 µm thick was formed over the silicone sample.

Discussion and Model

- Flame spread model from Markstein and de Ris
- Critical heat flux needed to raise thermal inertia of half the thickness of a sample plus silica deposit
- Dashed line represents half 0.36-mm sample with 286 µm of silica deposit



ρ_s (kg/m³)z	970
$C_{p,s}$ (J/kg-K)	1050
ρ_{SiO2} (kg/m³)	2600
$C_{p,SiO2}$ (J/kg-K)	1591
T_{ign} (K)	673
T_∞ (K)	293
τ (s)	55

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

Analysis Conclusions

- There is a critical heat flux needed to raise the temperature of silicone to the pyrolysis temperature and continue flame spread
- Silica deposits downstream onto silicone sample
- Flame uses energy to heat silica, has less energy for pyrolysis of sample
- Angled configuration and forced flow tests results support this hypothesis
- Other possible mechanisms for extinction:
  - Deposit layer could be acting as a physical barrier to mass transfer
  - Could affect flame stabilization zone or flame standoff distance
  - Emissivity of silica layer could be higher than silicone producing greater heat loss

Summary and Conclusions

- As silicone burns upward, silica deposits downstream
- If the silicone is ignited in the downward configuration, it burns the entire length of the sample
- Burning upward at an angle increases the burn length in some cases possibly due to less silica deposition
- Forced flow in the upward burning case increases flammability, likely due to an increase in convective flow preventing silica from depositing
- Samples in upward configuration burning under forced flow self extinguish after forced flow is removed

Questions

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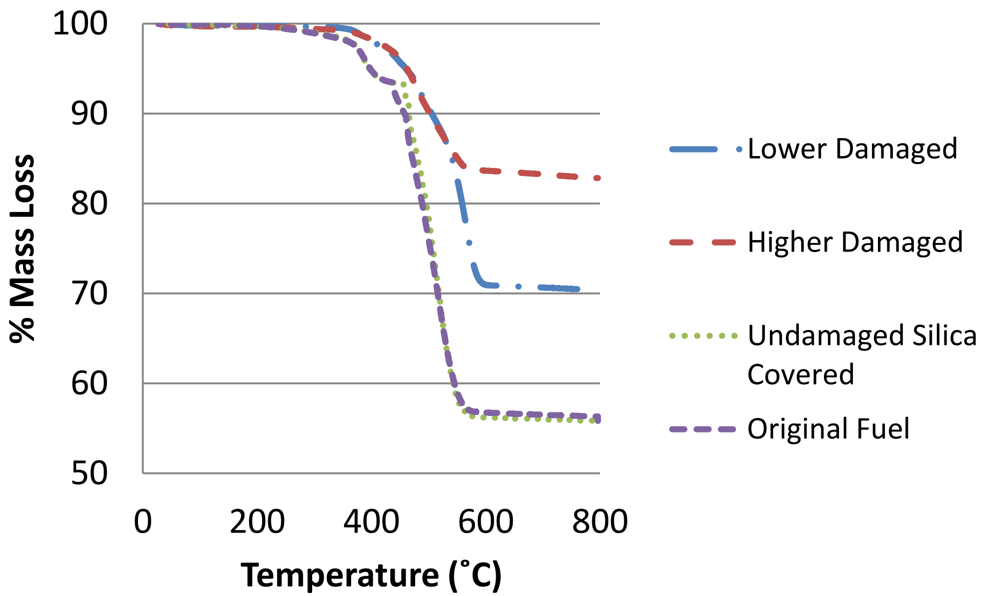
Results: Angled Spreading Buoyant Flow

- Horizontal flame spread burned similar to downward flame spread
- Some angles for the 0.36 mm aloud the sample to burn to completion

Test Name	Thickness (mm)	Burn Length (cm)	Burn Time (s)	Burn Velocity (mm/s)
Horizontal	0.25	30.00	287.34	1.04
Horizontal	0.36	30.00	530.87	0.57
Horizontal	0.61	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	103.00	2.91
75 degree upward	0.61	9.86	83.00	1.19
80 degree upward	0.36	15.80	55.00	2.87
80 degree upward	0.61	9.43	72.94	1.29

Residue Analysis: TGA

- Thermogravimetric Analysis
- Post burn analysis of 0.61 mm sample
- Mass loss in 4 different areas
- Original fuel and undamaged silica covered fuel produced same mass loss curve
- 10 degrees a minute



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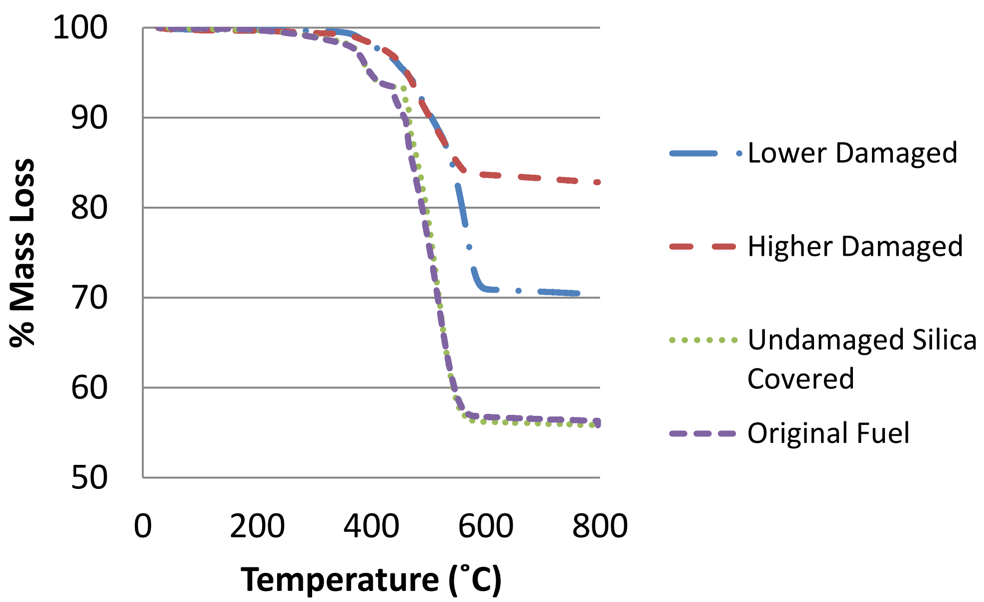


Saffire-IV, V, and VI Development Path

- **Conduct stakeholder review of the objectives and mission concept**
  - March 2015
- **Evaluate design concepts to define science requirements**
  - Interim Concept Review in November 2015
- **Develop breadboards and final design**
  - December 2015 – September 2016 (re-use of Saffire-I, II, III)
- **Manufacturing**
  - October 2016 – May 2017
- **Assembly and Test**
  - June 2017 – May 2018 (staggered test of IV, V, and VI)
- **Launches**
  - Saffire-IV: September 2018
  - Saffire-V: March 2019
  - Saffire-VI: September 2019
- **Plans will be submitted in PPBE17**

Prioritization of Objectives

	Objective	Est Priority	Comment	Stakeholder Priority?
9	**Post-fire monitoring**: Demonstrate performance of prototype Orion and ISS CPM	1	Demo of prototype flight hardware; specified in Program Resource Guidance	5
11	**Fire behavior/modeling:** Quantify growth and end state of realistic fires in spacecraft and their influence on vehicle habitability	2	Require to validate model development	1
12	**Fire behavior/modeling:** Obtain data required to validate spacecraft fire scenario models	2	Required for model development	1
2	**Fire growth/dynamics:** Flame behavior in complex geometries	3	More realistic configurations	2
3	**Fire growth/dynamics:** Flame behavior for planar and complex geometries in exploration atmospheres	4	Elevated O_2, lower P; compare with Saffire-I, II, III; supplement small-scale tests in CIR	3
1	**Fire growth/dynamics:** Measure flame behavior over planar surfaces	5	Continue Saffire-I and III	4
4	**Fire detection:** Obtain data to validate transport and detection models	6	Required for model development	5
5	**Fire detection:** Demonstrate fire detection with multi-moment sensors	6	Reject nuisance alarms	5
6	**Fire detection**: Evaluate performance of hybrid fire detection (smoke and gaseous products)	6	Combustion product detection by prototype CPM	5
10	**Post-fire monitoring:** Quantify rate of decay of gas species	6	Required for model development; get with Objective 9 but only natural decay	5
8	**Post-fire cleanup:** Quantify atmosphere cleanup rate with prototype smoke-eater	7	Demo of prototype flight hardware	6
7	**Fire suppression:** Performance of low-momentum water mist suppression	8	Effectiveness of fire ports	7

Advanced Exploration Systems

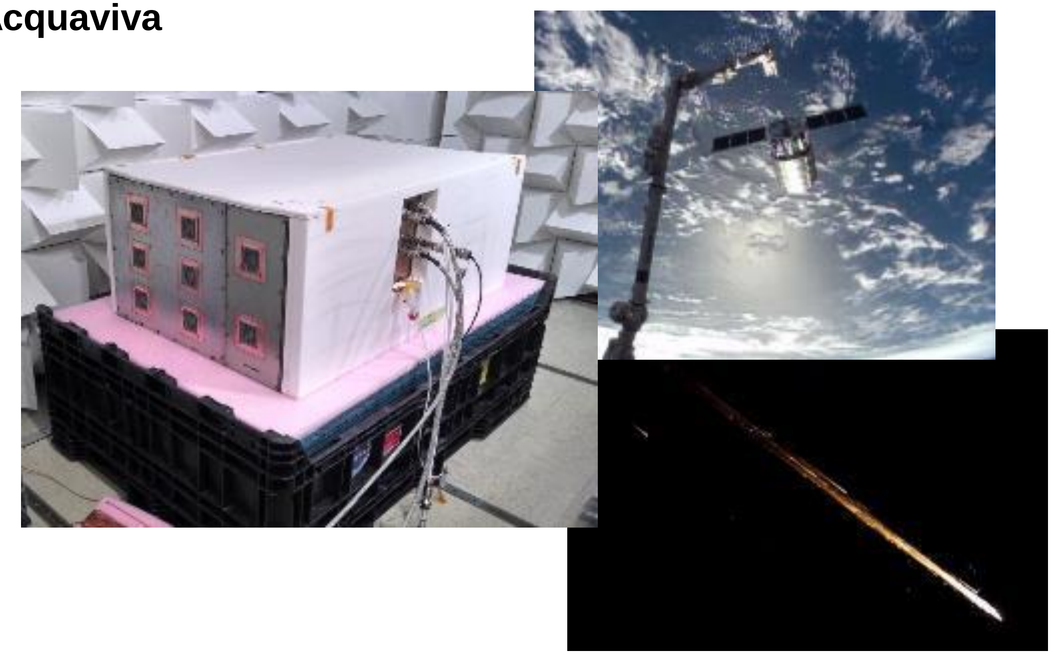
WBS 067463 - Spacecraft Fire Safety Demonstration

GRC Project Manager: MX/Gary A. Ruff
GRC Chief Engineer: LA/Lynn Capadona
GRC Chief Safety Officer: QER/ Bill Schoren
GRC Lead System Engineer: LSB/Karen Weiland
GRC Resource Integration: MX/Thomas Acquaviva

FY15 Budget ($K): $7,308
FY15 FTEs/WYEs: 32.3/14.0
Phase: D (System AI&T, Launch, and Check-out)
Project start/end: 10/1/2011 – 9/30/2017

Project Mission Statement:

Develop and conduct a large-scale fire safety experiment on an International Space Station resupply vehicle after it leaves the ISS and before it re-enters the Earth's atmosphere.



GRC Scope:

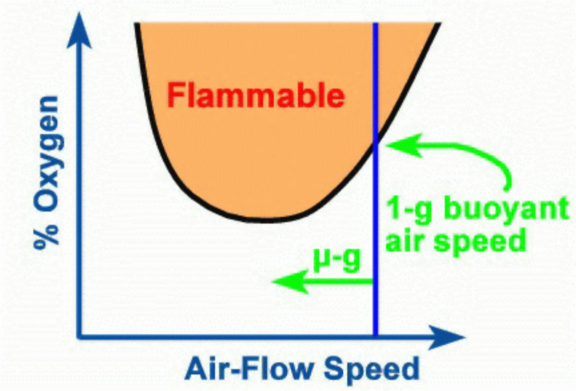
- Project leadership
- Design, fabricate, and operate the large-scale low-gravity fire safety experiment

Project Life Cycle Schedule

Milestones	Continuation Review	ATP	MCR/SRR (Unit 1,2,3)	PTR-1 (Unit 1,2,3)	Safety ϕ I / II (Unit 1,2,3)	Continuation Review	PTR-2 (Unit 1,2,3)	Continuation Review	Safety ϕ III (Unit 1)	SAR (Unit 1)
Actual/ Baseline	09/18/2012	10/01/2012	11/2012	7/2013	08/2013	09/2013	2/2014	9/2014	3/2015	7/2015
Milestones	**Continuation Review**	**ORR (Unit 1)**	**Launch (Unit 1)**	**Safety ϕ III (Unit 2)**	**ORR (Unit 2)**	**Launch (Unit 2)**	**Safety ϕ III (Unit 3)**	**ORR (Unit 3)**	**Continuation Review**	**Launch (Unit 3)**
Actual/ Baseline	9/2015	*3/2016*	*3/2016*	2/2016	6/2016	6/2016	6/2016	9/2016	9/2016	10/2016

Combustion

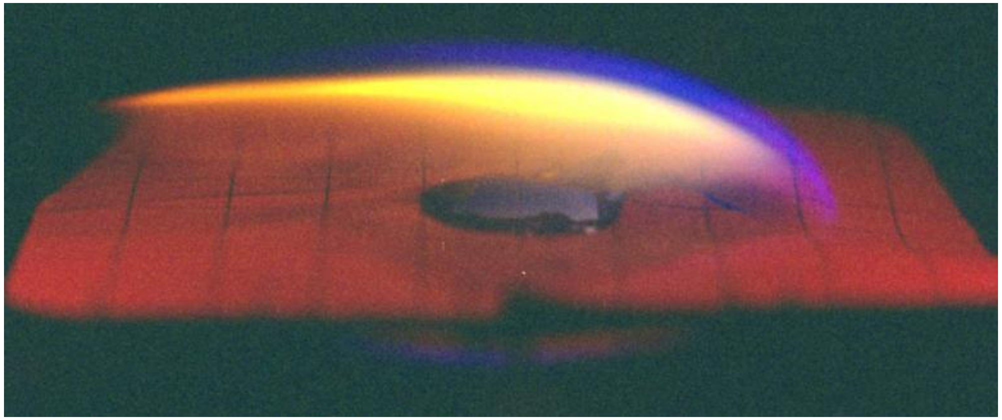
- Our primary energy source (85%)
- A catastrophic hazard for the manned space flight program
- The reality is that substantial improvements in the quality of life in space or here on earth will require improvements in our ability to predict and control combustion.
- **High-efficiency, low-emission flames can be near limit, which are unstable, where kinetics are important**
- **Demonstration that flame spread behavior in low-gravity is substantially different from 1-g**
- Invalidation of the prevalent assumption that 1-g is always a worse case than low-g
- **Demonstration of the significance of low speed air flows on material flammability.**
- **Materials Combustion**
  - Burning and Suppression of Solids (BASS), 2012, MSG
  - Flammability Assessment of Materials for Exploration (FLAME), CIR

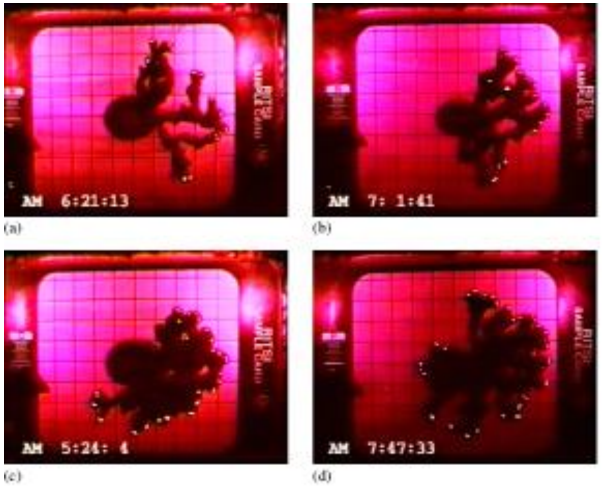


Flight results: Flame Spread

Ignition at the middle of the sample:

- **Flame spreads upstream, however, in the shape of a fan.**
- **With an increase in the incoming air flow velocity, the fan angle increases due to an increase in oxygen supply rate.**
- **This is completely contrary to normal gravity**
- **An unpredicted and presently unexplained smoldering pattern was observed in thin cellulose.**





ISS Results Solid Fuel Combustion-Material Flammability

The Burning and Suppression of Solids Experiment (BASS) – 2012 in process now

Recent Results:

With BASS we can measure material flammability in microgravity to compare with normal gravity flammability NASA-STD-6001 Test # 1. Results to date indicate that Test 1 is not conservative, and materials can burn at lower oxygen levels in microgravity than on Earth.

BASS also assesses the effectiveness of N_2 inert extinguishing agent in putting out flames over different materials, geometries, and flow. Results to date indicate that local application of suppressant is not adequate to fully extinguish the flames. The local jet entrains air and sustains the flame even when the ambient air flow is turned off.

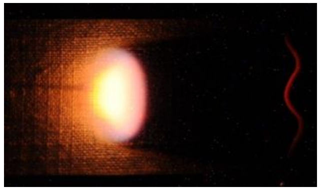
Relevance/Impact:

Spacecraft fires are a significant risk factor for human exploration.

Understanding material flammability and suppression in actual spacecraft environments relative to 1g materials screening is needed to mitigate this risk.

The PMMA material burned in BASS is being considered for MPCV windows. JSC was surprised that this thick sample ignited easily and burned well in air.

Ground-based drop tower testing provides some data, but long-duration microgravity data is needed to study flammability limits for all but the thinnest films.



Nomex III burning in BASS in air. This material will not burn in air on earth.

BASS in MSG

Don Pettit running BASS

Spherical PMMA sample in BASS. N2 Jet does not extinguish flame, only blows out stagnation region. Wake region continues to burn.

N_2 flow makes candle flame longer, it does not put it out.

Image analysis

Flammability Assessment of Materials for Exploration (FLAME)

FLAME PI's:
Subrata Bhattacharjee, San Diego State University
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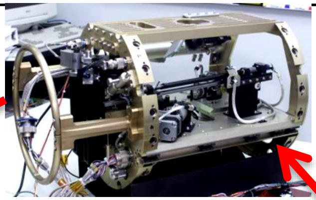
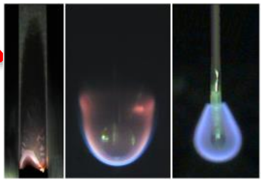
Carlos Fernandez-Pello, University of California, Berkeley
Fletcher Miller, San Diego State University
PS: Paul Ferkul, NCSER
PM: Mark Hickman, GRC
Engineering Team: GRC in-house team



CIR Insert – FLEX (Similar to anticipated FLAME insert)

Flat, Spherical, and Cylindrical samples (L to R) burning in 1-g



Objective:

- **To study and characterize ignition and flammability of solid spacecraft materials in practical geometries and realistic atmospheric conditions**

Relevance/Impact:

- **Improve EVA suit design**
- **Determine safer selection of cabin materials and validate NASA materials flammability selection 1-g test protocols for low-gravity fires**
- **Improve understanding of early fire growth behavior**
- **Validate material flammability numerical models**
- **Determine optimal suppression techniques for burning materials by diluents, flow reduction, and venting**

Development Approach:

- **Develop FLAME facility (CIR insert and avionics) to support multiple solid-material combustion and fire suppression studies**
- **Utilize Combustion Integrated Rack (CIR)**
- **Support multiple investigations using common infrastructure:**
  - Common interfaces and flow control
  - Removable test sections and sample holders
  - Removable ignition system

ISS Resource Requirements

Accommodation (carrier)	CIR
Upmass (kg) (w/o packing factor)	250 kg
Volume (m^3) (w/o packing factor)	0.50 m^3
Power (kW) (peak)	0.75 kW
Crew Time (hrs) Crew Time (hrs) - Initial configuration of CIR Rack - Change-outs during experiment	8 hrs 8 hrs
Autonomous Ops (hrs)	200 hrs
Launch/Increment	Inc. 55

Project Life Cycle Schedule

Milestones	Kickoff	SCR	RDR	PDR	CDR	VRR	Safety	SAR	Ship	Launch	Ops	Ops End	Report
Baseline	Oct 2012	May 2013	May 2014	Jun 2015	Sep 2016	Sep 2017	Dec 2017	Mar 2018	Apr 2018	Jul 2018	Aug 2018	Nov 2019	Dec 2020

Spacecraft Fire Safety Demonstration Flight

Objective:

- Advance spacecraft fire safety technologies identified as gaps by the Constellation Program and in the Exploration Technology Roadmaps
- Demonstrate their performance in a large-scale, low-gravity spacecraft fire safety test aboard an unmanned re-entry vehicle
  - Demonstration of the operational concept could allow future experiments to investigate fire detection and suppression equipment and protocols.

Relevance to Human Space Flight:

The material flammability questions to be addressed in this experiment were identified during the design of the ECLS system for Orion, Altair, and Lunar Surface Systems

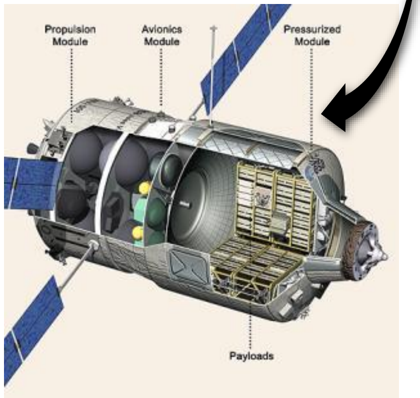
- Addresses knowledge gaps that must be resolved for assured protection of a spacecraft from fire hazards

Most U.S. agencies responsible for large transportation systems conduct full-scale fire tests to address gaps in fire safety knowledge and prove equipment and protocols.

FAA full scale aircraft test

ESA ATV approaching the ISS

Naval Research Laboratory Ex-USS Shadwell



Cut-away of the Automated Transport Vehicle (ATV). The large-scale experiment could be conducted in one of the standard payload racks.

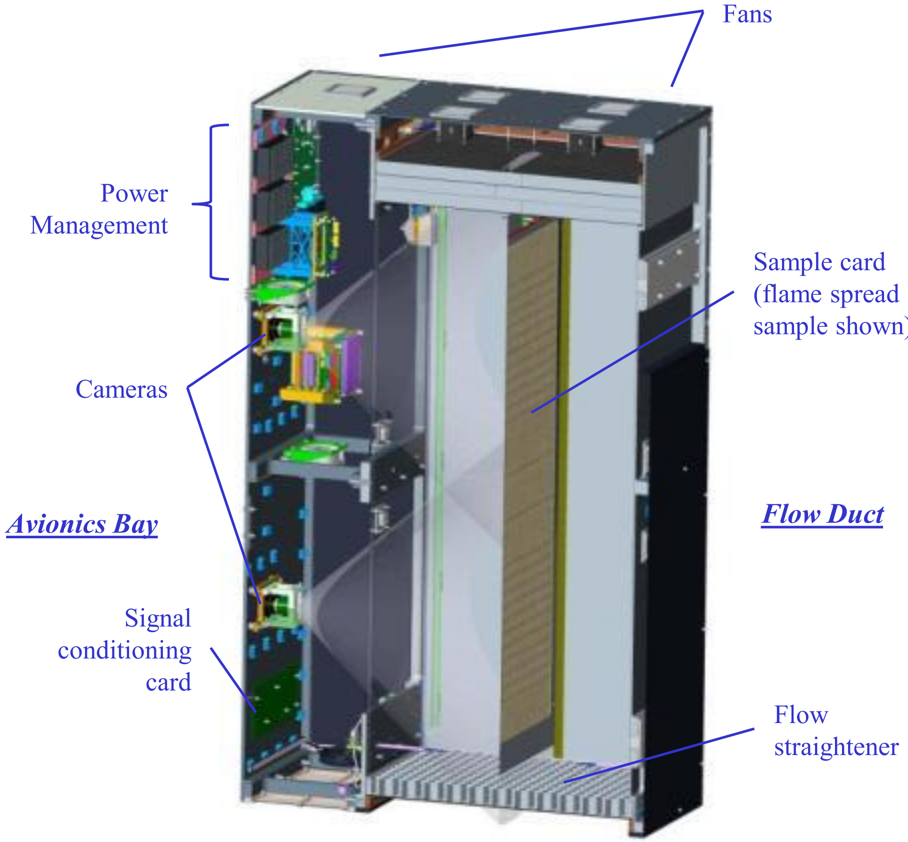
Saffire Overview

Needs:

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

Objectives:

- *Saffire-I*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release)
- *Saffire-II*: Verify oxygen flammability limits in low gravity
- *Saffire-III*: Same as Saffire-I but at different flow conditions.



Saffire module consists of a flow duct containing the sample card and an avionics bay. All power, computer, and data acquisition modules are contained in the bay. Dimensions are approximately 53- by 90- by 133-cm

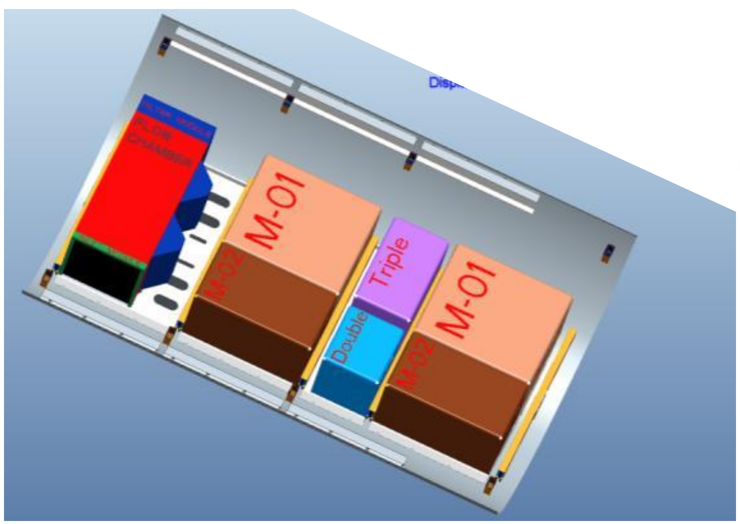
- *Data obtained from the experiment will be used to validate modeling of spacecraft fire response scenarios*
- *Evaluate NASA's normal-gravity material flammability screening test for low-gravity conditions.*

SFSD Concept

Cygnus approaching ISS

Unpack cargo, reload with trash

Proposed location of the SFS Demo experiment (back of vehicle)

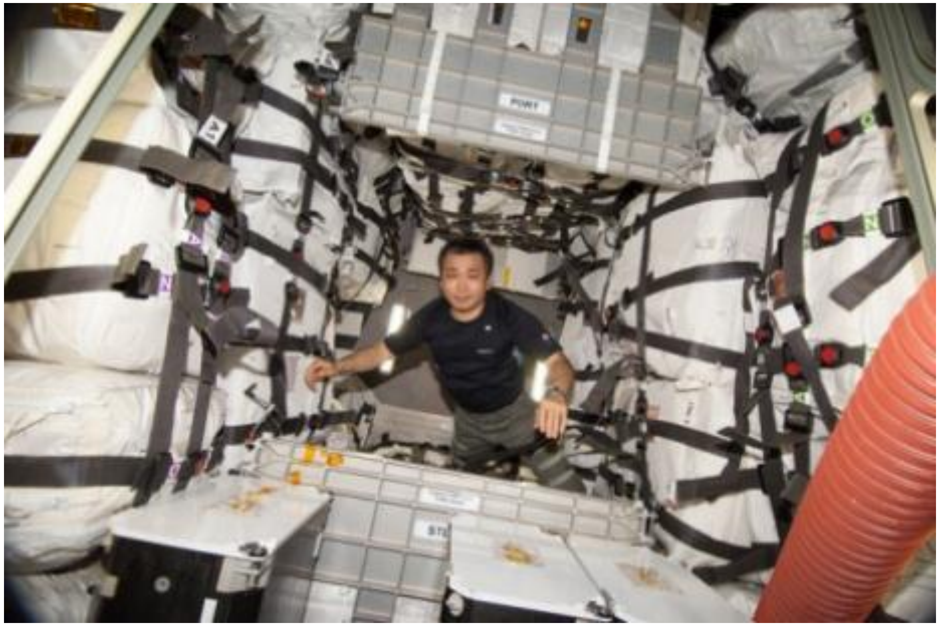


Check-out SFS Demo experiment

Issues

Trash packing

- Based on input from Orbital, we anticipated that Cygnus packing for re-entry would be similar to launch
  - Developed a Payload Integration Agreement to prevent stowage near the Saffire inlet and outlet



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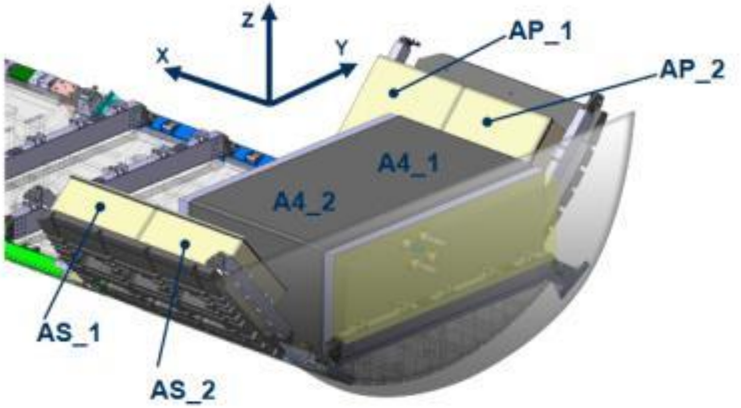


Issues
Trash packing

- Actual trash packing is not quite so organized
  - Impacts air mixing and oxygen availability for Saffire

- Project has discussed this with Orbital and begun discussions with our Payload Integration Manager with ISS

Orb-2 Trash Packing

Silicone Samples

- 4 of 9 small samples on Saffire will be Silicone
- Silicone is a very simple option for burning on the second flight of the Saffire project. It has practical application in space such as covering for camera microprocessors and for grips for space suit gloves. The silicone samples that are being proposed are readily available in various thicknesses which will make it easy to test thickness effects on flammability in microgravity. It has been studied extensively on the ground, with a thickness that is right on the border of passing NASA Standard 6001 Test 1 (self-extinguish before 6 inches)[1]. It is solid and non-porous, giving it great structural integrity. The MSDS and material properties are readily available and understood.

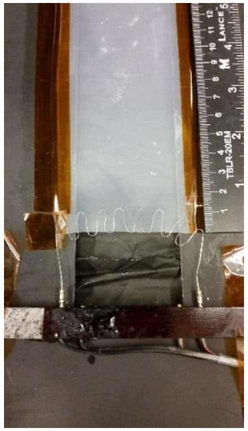
- Silicone has been tested in a 1-G environment using the NASA STD-6001 Test #1 experiment. Five thicknesses have been testing and three thicknesses are close to the limit. The .04’’ thickness does not ignite, while the .024’’ and .014’’ on average pass Test 1. .01’’ and .004’’ thicknesses do not pass Test 1 in any of the trials. Figure 1 demonstrates an “S” curve, which gives the probability of a sample to pass Test 1 against a certain variable. Tables 1 through 4 show the specific results below.

- If the Silicone, especially the .014’’ thickness, burns greater length in microgravity, it could prove that Test 1 is not a conservative test and needs to be re-evaluated. The MOC for the same thicknesses of silicon has been tested by Hirsch [2]. It would be interesting from a scientific point of view to see if the MOC changes once in microgravity. The .014’’ thick Silicone sample also burns downward without self-extinguishment, showing it could possibly be more flammable in microgravity than 1-G.

- The purpose of the experiment will be to test silicone thicknesses that are near the limit of passing NASA STD-6001 Test 1 in air at 1-G. Then by picking a thickness above the flammability limit and below the flammability limit, the effect of 0-G on thickness of material can be determined. The length of the burn, and whether the material passes Test 1 can be compared for 1-G vs. 0-G, along with the burn rate. The proposal is to burn a sample of the .024’’, .14’’ and .01’’ thicknesses of the silicone samples.

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

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. The chemical igniter provides approximately 3000 J for a duration of 25 ± 5 s.



Silicone Samples

- 4 of 9 small samples on Saffire will be Silicone
  - An effort to determine the thinnest sample that can pass Test 1 has been complete and the data is shown below. Testing that thickness and others near the limit will help determine the conservatism of Test 1 in microgravity. The samples take approximately 1 minute to burn in 1-G so microgravity results using drop towers and parabolic flights would not be an option. MOC and ULOI data for these samples exist, which can be compared to the results obtained in microgravity.
  - The samples to be tested are thermally thin, meaning the thickness of the material determines its flammability. The silicone samples are simple in nature, making it easy to find their thermophysical properties, and the MSDS from the supplier is readily available.
  - The stakeholders for this experiment are the scientific community that researches combustion and flammability, along with the spacecraft engineers who determine which materials are safe for microgravity. This experiment can satisfy both types of stakeholders by comparing ground data to microgravity data, and by testing the conservatism of tests used to select spacecraft materials.

Thickness	MOC	ULOI
1.00 mm	22	23.4
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