Large-Scale Spacecraft Fire Safety Experiments in ISS Resupply Vehicles.

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Outline

- Overview of the Spacecraft Fire Safety Demonstration Project
- Science and Technology Demonstration Objectives
  - Details of Sample Selection
- Supporting Ground-based Research
Spacecraft Fire Safety Demonstration

Requirements and Goals

♦ Level 1 Requirements
  • The project shall conduct an experiment on an International Space Station resupply vehicle after it leaves the ISS and before it re-enters the Earth’s atmosphere.
  • The experiment performed on this vehicle shall meet a critical need for developing rational spacecraft fire safety strategy on future exploration vehicles.

♦ Project Goals
  • Conduct a spacecraft fire safety experiment on three flights of Orbital Science’s Cygnus vehicle that investigates large-scale flame spread and material flammability limits in long duration low-gravity.
    — Orb-5: February 2015 probable slip to December 2015
    — Orb-6: September 2015 probable slip to June 2016
    — Orb-7: February 2016 probable slip to October 2016
  • Complete the major experiment development work no later than September 30, 2014.

♦ Needs:
  ♦ Quantify the development and growth of a realistic fire for exploration vehicles
  ♦ Determine low-g flammability limits for spacecraft materials
Objectives:

- **Saffire-I**: Assess flame spread of large-scale microgravity fire
- **Saffire-II**: Verify oxygen flammability limits in low gravity
- **Saffire-III**: Similar to Saffire–I at different air flow

Data:

- Flame size, position, and spread rate (video)
- Flame intensity (radiometer)
- Flame stand-off distance (t/c)
- Flame/plume temperature (t/c)
- O$_2$, CO$_2$ concentrations

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

- Sample card (flame spread sample shown)
- Flow Duct
- Fans
- Power Management
- Cameras
- USB Hub
- Signal conditioning card
- Air flow

Dimensions are approximately 53- by 90- by 133-cm
Operations Concept
Saffire-I, II, & III Schedule & Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTR-1</td>
<td>6/19/13</td>
</tr>
<tr>
<td>FSDP Submit</td>
<td>7/3/13</td>
</tr>
<tr>
<td>ISS Flight Safety Phase I/II Review</td>
<td>8/20/13</td>
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<tr>
<td>Saffire Simulator to Orbital</td>
<td>11/2013</td>
</tr>
<tr>
<td>PTR-2</td>
<td>12/4/13</td>
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<tr>
<td>System AI&amp;T Start</td>
<td>12/12/13</td>
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<tr>
<td>Ground Safety Phase I/II Review</td>
<td>12/12/13</td>
</tr>
<tr>
<td>Verification and Environmental Test Start</td>
<td>3/19/14</td>
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<tr>
<td>Ground Safety Phase III Review</td>
<td>8/21/14</td>
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<tr>
<td>ISS Phase III Review</td>
<td>9/24/14</td>
</tr>
<tr>
<td>SAR</td>
<td>10/17/14</td>
</tr>
<tr>
<td>Saffire-I Ship to WFF</td>
<td>10/24/14</td>
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</tbody>
</table>
Two major stakeholders in sample selection

- Scientific community
  - Address both the “no ignition” and “no flame spread” criteria involved in passing standard material flammability testing
  - Materials can pass NASA-STD-6001 Test 1 because ignition energy is not sufficient to start the flame spread process

- NASA Materials and Processes
  - If a material passes NASA Test 1 on the ground, will it pass the test in microgravity? (i.e. is the ground test the worst case scenario)

The long-term relevance to spacecraft fire safety applications depends on the careful and well-informed selection of the sample materials

- Relevance requires:
  - Scalability
  - Amenable to modeling
Sample Selection Constraints

- **Dimensions and energy release**
  - 1 or 2 flame spread (large) samples (0.5 m x 1.0 m)
  - 9 or 18 material flammability samples (5 cm x 30 cm)
  - Thickness can be a maximum of 10mm
  - Total energy released can be a maximum of 54 grams of fuel (cellulose equivalent)

- **Data Acquisition**
  - Thermocouples (6 total shared by all 9 samples)
  - Radiometer (two sides)
  - Camera (front view)
  - Maximum run time of 6 minutes

- **Flow**
  - Flow rate range is 10-30 cm/s
  - Concurrent or opposed

- **Ignition power and system**

- **Long-term sample storage**
Large-Scale Flame Spread Test

- Upward flame spread test on a fabric sample
  - Solid Inflammability Boundary at Low Speed (SIBAL)
    - Cotton on a fiberglass substrate
    - 75% cotton by weight (18.05 mg/cm²)
  - 0.4 m x 0.94 m

- Saffire-I: 20 cm/s air flow
- Saffire-III: 30 cm/s air flow

Normal gravity test conducted in the VF-13 facility at NASA GRC.
Material Flammability Samples

- NASA-STD-6001 describes the test methods used to qualify materials for use in space vehicles.
- The primary test to assess material flammability is Test 1: Upward Flame Propagation
- Materials “pass” this test if the flame self-extinguishes before it propagates 15 cm
  - Maximum oxygen concentration (MOC) is defined as the highest $O_2$ at which material passes Test 1

![Test 1 Apparatus](image)
Low-g Maximum Oxygen Concentration

- Flammability limits determined by this test are strongly influenced by natural convection
  - Normal gravity flames induce a natural convective flow that transports oxygen to the flame but also removes heat
  - Forced convection in low-g transports oxygen to the flame but rate of heat removal is reduced

Sample Selection Goals

- **Build data sets on scalability of low-g fires**
  - Materials that have been tested in low-g at different length scales

- **Amenable to modeling**
  - Large, vehicle scale fire modeling
    - Impact on vehicle
    - Real-time modeling of fire response
  - Details of low-g flame spread

- **Conclusive low-g flammability limit (Maximum Oxygen Concentration) data**
  - Flammability limit sample materials must cross the flammability limit in 21% O₂
    - Requires approaches to alter flammability including: material thickness, heat loss (metal backing/matrix), radiative feedback (surface variation (grooves), inert (non-flammable) coatings

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**Burning and Suppression of Solids (BASS)**

- **2cm and 1cm Flat Samples**
  - SIBAL - cotton-fiberglass fabric
  - Nomex - flame resistant material related to nylon
  - Ultem - thermoplastic resins used in medical and chemical instrumentation

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**Three-dimensional, time dependent upward flame spread in buoyant flows**
Candidate Samples

- Nomex (HT90-40, Combo)
- Mylar
- Ultem
- SIBAL cloth
  - Solid Inflammability Boundary at Low Speed (SIBAL)
    - Cotton on a fiberglass substrate
    - 75% cotton by weight (18.05 mg/cm²)
- Silicone (2-3 thicknesses, concurrent/opposed spread)
- PMMA
  - Straight, tapered, or structured
- Cellulose (with backing/metal matrix)
- Fire-resistant coating
- Wires

PMMA-samples shaped at University of Bremen with grooves parallel or perpendicular to the flame propagation direction
### MOC and ULOI of Potential Saffire Samples

<table>
<thead>
<tr>
<th>Material Description</th>
<th>MOC</th>
<th>ULOI</th>
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</thead>
<tbody>
<tr>
<td><strong>Composites and Laminates</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy/Glass laminate NEMA G-11, H-23842</td>
<td>23</td>
<td>23.6</td>
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<tr>
<td><strong>Rigid Plastics</strong></td>
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<tr>
<td>P1700 polysulfone</td>
<td>25</td>
<td>27.5</td>
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<tr>
<td>Zytel 42 from 93-27463</td>
<td>24.1</td>
<td>24.5</td>
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<tr>
<td><strong>Fabrics</strong></td>
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<tr>
<td>Nomex HT 90-40, L/N 7254</td>
<td>24</td>
<td>24.8</td>
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<tr>
<td>Nylon Tricot ST11N791-01</td>
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<td>24.3</td>
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<tr>
<td>TCU Bottom, P/N SKD38114488-01</td>
<td>21</td>
<td>22.8</td>
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<td>Nomex Webbing P/N 9981</td>
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<tr>
<td><strong>Foams</strong></td>
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<tr>
<td>L-200 Minicel Foam</td>
<td>20</td>
<td>21.7</td>
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<tr>
<td>TA-301 Polyimide foam</td>
<td>25</td>
<td>27.3</td>
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<tr>
<td><strong>Films</strong></td>
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<tr>
<td>Ultem 1000 Film, P/N DLI1648</td>
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<td>22.1</td>
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<td>PEEK Victrex Film, 10-mil</td>
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<tr>
<td>Kapton HN Film</td>
<td>26</td>
<td>27.2</td>
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<tr>
<td>SSP-M823 Silicone membrane, 0.004&quot;</td>
<td>17</td>
<td>17.5</td>
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<tr>
<td>SSP-M823 Silicone membrane, 0.010&quot;</td>
<td>18</td>
<td>19.7</td>
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<tr>
<td>SSP-M823 Silicone membrane, 0.014&quot;</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>SSP-M823 Silicone membrane, 0.024&quot;</td>
<td>20</td>
<td>22.8</td>
</tr>
<tr>
<td>SSP-M823 Silicone membrane, 0.040&quot;</td>
<td>22</td>
<td>23.4</td>
</tr>
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</table>
Selected Samples

- Nomex (HT90-40) with PMMA promoter (1 sample)
- SIBAL cloth (2 samples at the same flow rates as Saffire 1 & 3)
- Silicone (3 thicknesses for concurrent spread and 1 thickness for opposed spread)
- PMMA 10 mm thick
  - Flat sample
  - Structured sample

Top view of PMMA sample - edges have different radii
PMMA / Nomex

- Example with 4 inch SIBAL cloth promoter
- 8 inch Nomex
Downward Silicone

- Average ~ 5 minutes to burn 30 cm
- 0.014” thick Silicone will burn downward but not upward

.01” down burn
## Flight 2 Sample Selection

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Material</th>
<th>Sample Thickness</th>
<th>Flow (cm/s)</th>
<th>Igniter Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saffire-2-S1</td>
<td>SIBAL</td>
<td>N/A</td>
<td>20</td>
<td>Bottom</td>
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<tr>
<td>Saffire-2-S2</td>
<td>Silicone down</td>
<td>0.36 mm (0.014&quot;) Silicone</td>
<td>20</td>
<td>Top</td>
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<tr>
<td>Saffire-2-S3</td>
<td>SIBAL</td>
<td>N/A</td>
<td>30</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S4</td>
<td>Flam limit 1 Silicone</td>
<td>0.25 mm (0.010&quot;) Silicone</td>
<td>20</td>
<td>Bottom</td>
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<tr>
<td>Saffire-2-S5</td>
<td>Flam limit 2 Silicone</td>
<td>0.36 mm (0.014&quot;) Silicone</td>
<td>20</td>
<td>Bottom</td>
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<tr>
<td>Saffire-2-S6</td>
<td>Flam limit 3 Silicone</td>
<td>0.61 mm (0.024&quot;) Silicone</td>
<td>20</td>
<td>Bottom</td>
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<td>Saffire-2-S7</td>
<td>PMMA 2 sided burning</td>
<td>10 mm with tapered edge for ignition</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S8</td>
<td>Transition 1: PMMA to NOMEX</td>
<td>N/A</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S9</td>
<td>PMMA 2 sided burning</td>
<td>10 mm with tapered edge for ignition</td>
<td>30</td>
<td>Bottom</td>
</tr>
</tbody>
</table>
The outcomes of this experiment are multiplied by tasks performed by contributing team members (and the funding from other organizations)

- **Sample Selection**
  - Structured materials:
    - Nickolay Smirnov, *Moscow Lomonosov State University*, Moscow, Russia
    - Christian Eigenbrod, *University of Bremen (ZARM)*, Bremen, Germany
  - Wires: Osamu Fujita, *Hokkaido University*, Sapporo, Japan
  - Coated materials: James S. T’ien, *Case Western Reserve University*, Cleveland, OH, USA
  - Nomex: Carlos Fernandez-Pello, *UC Berkeley*, Berkeley, CA, USA

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**Guanylurea Phosphate (GUP) (g) in 25 mL water (samples are 2 cm x 18 cm)**

The outcomes of this experiment are multiplied by tasks performed by contributing team members (and the funding from other organizations)

- **Modeling**
  - Low-g Fire Dynamics
    - James S. T’ien, Case Western Reserve University, Cleveland, OH, USA
  - Real-time fire response:
    - Jose L. Torero, University of Queensland, Brisbane, Australia
    - Adam J. Cowlard, University of Edinburgh, Edinburgh, UK
  - Vehicle-scale fire scenario modeling
    - Sebastien Rouvreau, Belisama R&D, Toulouse, France
    - Dan Dietrich, NASA GRC, Cleveland, OH
    - Suleyman Gokoglu, NASA GRC, Cleveland, OH

Three-dimensional, time dependent upward flame spread in buoyant flows

Schematic for a concurrent spread over the flat surface of a solid combustible

Fluent model calculation of velocity magnitude in ATV configuration after 1 minute of heat release.
The outcomes of this experiment are multiplied by tasks performed by contributing team members (and the funding from other organizations)

- **Diagnostics**
  - Fuel Characteristics: Adam J. Cowlard, *University of Edinburgh, Edinburgh, UK*
    - *Flame Propagation Apparatus: Heat release rate of materials to support detailed modeling of fire response*
  - Soot Volume Fraction in Low-g: Guillaume Legros, *Université Pierre et Marie Curie, Paris, France*
    - *Laser extinction technique to measure soot volume fraction in large-scale normal- and low-g flames*
Summary

• The Saffire experiment (Spacecraft Fire Safety Demonstration Project) is in development to address knowledge gaps in low-g material flammability.

• Sample were selected to meet stakeholder requirements and to ensure the long-term impact of the project on the spacecraft fire safety protocol.

• Samples will address both flame spread and material flammability understanding.

• Recent studies and analyses have confirmed the fire safety needs for long-term exploration missions. Spacecraft fire safety technologies have been identified as enabling for some exploration missions, enhancing for others.
  • The Saffire experiments address several of these but lack fire detection, suppression, and post-fire cleanup.

• An end-to-end demonstration of a fire detection, suppression, and clean-up scenario would verify hardware and the ability to properly size fire response hardware.