Fire Safety in Space –
Beyond Flammability Testing of Small Samples

GRUNDE JOMAAS
ASSOCIATE PROFESSOR
DTU CIVIL ENGINEERING
Goals for ISS and Space Design

• Safety for launch, personnel, hardware, uninvolved public
• Identify, control and document hazards
• Enable informed programmatic decisions
• Handle situations and continue successfully
• Redundancy
  • CO₂ removal system
  • Atmosphere Control System(ACS)
  • Oxygen supply system
• Robust, yet versatile
• Historical approach falls short (limited data)
It is only going to get more challenging!

“We have not even begun to comprehend the complexities of fire safety in commercial space travel”

NASA Decadal Review, National Academy of Sciences, 2010
Progress related challenges

- Governmental Programs
  - SOYUZ - launch of crew
  - Exploration
    - Beyond LEO (Low Earth Orbit), 2013-2021
    - Into the Solar System, 2021-2027
    - Exploring Other Worlds, 2027-2033
    - Planetary Exploration, 2033-

- Commercial Programs
  - Space X - Dragon (w/ return)
  - Orbital – Cygnus (COTS program)
  - Virgin Galactic (400+ have signed up)
    - Numerous other private enterprises

- Safety design becomes disconnected from the operator
  - Relies on fire safety test procedures from NASA
    - Spacecraft fire safety emphasizes fire prevention, which is achieved primarily through the use of fire resistant materials.
    - Materials selection for spacecraft is based on conventional flammability acceptance tests, along with prescribed quantity limitations and configuration control for items that are non-pass or questionable.
NASA-STD-6001 describes the test methods used to qualify materials for use in space vehicles.

The tests cover flammability, odor, off-gassing, and compatibility.

The primary test to assess material flammability is Test 1 (based on ASTM test): 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 O₂ at which material passes Test 1.
- Flammability limits determined by this test are strongly influenced by natural convection.
- Drop tower data shows that flammability limits are lower in low- and partial-gravity!
- Do NASA’s flammability standards result in higher flammability limits than actually found in low-gravity?
Material Flammability

- Mostly based on a “Worst Case Scenario” Test
- NASA Test 1
Challenges

- Fires in micro-gravity will burn with a very different flow field:
  - Affects heat transfer
  - Affects mass transfer
  - Affects combustion chemistry
Can it be “Worse” than Test 1?


Differences
Understanding Flammability – Co-current flame spread

\[ \dot{q}_e \quad \dot{q}_L \quad \dot{q}_f \quad \dot{m}_F \quad y_F(x) \]

\[ U_{\infty} \quad x = 0 \quad X_P \quad V_{C,S} \quad \delta_C \]

\[ L_f \]

\[ \equiv \]

\[ \text{eq} \]
Relevant Parameters

Material Parameters

- $\dot{m}''_F$
- $Y_F$
- $X_P$

Flame Length ($L_f$)

Flow Parameters

- $U_\infty$
- Turbulence
- Buoyancy
- Composition
- Combustion
- ...

Flame Spread Velocity ($V_{C,S}$)

Flammability
The Emmons Solution (I)

\[ f = \frac{\psi}{(x / \text{Re})^{1/2}} \quad \beta = \frac{Z_i - Z_i,0}{Z_i,\infty - Z_i,0} \quad \eta = \frac{1}{2} \left( \frac{\text{Re}}{x} \right)^{1/2} \int_{0}^{y} \rho dy \]

\[
\begin{align*}
\dot{m}'' + f \cdot f'' &= 0 \\
\beta'' + f \cdot \beta' &= 0
\end{align*}
\]

\[
\begin{align*}
\eta = 0 & , \quad f' = 0 & , \quad \frac{f}{f''} = -\frac{B}{2} & , \quad \beta = 0 \\
\eta \rightarrow \infty & , \quad f' = 2 & , \quad \beta = 1
\end{align*}
\]

The Emmons Solution (III)

\[ B = \frac{\Delta H_C Y_{O,\infty} - C(T_S - T_\infty)}{\Delta H_P + Q} \]

The Mass Transfer Number

Adiabatic

$$B_A = \frac{\Delta H_C Y_{O_2,\infty} - C_p \infty (T_W - T_\infty)}{\Delta H_P}$$

Combustion Efficiency

$$B_T = \frac{(1 - \chi)(\Delta H_C Y_{O_2,\infty}) - C_p \infty (T_W - T_\infty)}{\Delta H_P + Q}$$

Property of the fuel and oxidizer, therefore easy to evaluate

Variable, depending on the specific burning conditions, therefore difficult to evaluate

Losses
Losses

- $Q$ decreases with the free stream velocity
- $Q$ increases with “x”

\[
Q = \frac{\left( \dot{q}_{L,C}'' + \dot{q}_{L,sr}'' - \dot{q}_{fr}'' \right)}{\dot{m}_f''}
\]

\[
\dot{m}_f'' = (\rho_\infty U_\infty) \frac{(\eta f' - f)}{2(\text{Re}.(x/L))^{1/2}}
\]
SPACECRAFT FIRE SAFETY DEMONSTRATION
Project Objective:
• Advance spacecraft fire safety technologies identified as gaps by the Constellation Program and in the Exploration Technology Roadmaps
• Demonstrate performance of these technologies in a large-scale, low-gravity spacecraft fire safety test aboard an unmanned re-entry vehicle
  – Demonstration of this operational concept could allow future experiments to investigate additional fire safety technologies and protocols

Experiment Objective:
Determine the fate of a large-scale microgravity fire
1. Spread rate, mass consumption, and heat release
   • Is there a limiting size in microgravity?
2. Confirm that low- and partial-g flammability limits are less than those in normal gravity
   • Are drop tower results correct?

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
- Naval Research Laboratory Ex-USS Shadwell
- ESA’s ATV approaching the ISS
- Orbital Science’s Cygnus approaching ISS
- Controlled burns of structures
Saffire

- Validation at realistic time and length scales with materials relevant to spacecraft
  - Flammability analysis
  - Forecasting by data assimilation

International Team:
- Coordinator: Grunde Jomaas: Technical University of Denmark, Kgs. Lyngby, Denmark
- Nickolay Smirnov: Moscow Lomonosov State University, Moscow, Russia
- David L. Urban and Gary A Ruff: NASA Glenn Research Center, Cleveland, OH, USA
- A. Carlos Fernandez-Pello: UC Berkeley, Berkeley, CA, USA
- James S. T’ien: Case Western Reserve University, Cleveland, OH, USA
- José L. Torero University of Queensland, Brisbane, Australia
- Adam Cowlard: University of Edinburgh, Edinburgh, UK
- Sebastien Rouvreau: Belisama R&D, Toulouse, France
- Olivier Minster and Balazs Toth: ESA ESTEC, Noordwijk, Netherlands
- Guillaume Legros: Université Pierre et Marie Curie, Paris, France
- Christian Eigenbrod: University of Bremen (ZARM), Bremen, Germany
- Osamu Fujita: Hokkaido University, Sapporo, Japan
Spacecraft Fire Safety Demo Experiment Concept

• "Simple" modular test facility that can be replicated and fly on multiple Cygnus flights
  ➢ Only the sample card and test conditions are different in the three flights

• Multiple, single-objective experiments that address spacecraft fire safety gaps
  1. Single, large sample → large-scale flame spread (flame spread samples)
  2. Six to twelve flammability limit samples → evaluate NASA-STD-6001 Test 1 and verify oxygen flammability limits in low gravity
  3. Repeat 1. or 2. at different conditions

• No safety-critical software; heritage based
• No crew interaction; fully assembled experiment
• Unpowered while attached to ISS
• Commanding originates from Orbital Sciences

Details of experiment flow duct approximate size: 20” x 20” x 44”

Design choices driving simplified concept
Spacecraft Fire Safety Demonstration
Experiment Design

◆ Two major assemblies
  - Avionics Bay
  - Flow Duct

◆ Nine separate hardware “products”
  - Sample card
  - Flow control
  - Power management system
  - Igniter
  - Signal conditioning
  - Cameras/vision
  - Instrumentation
  - Processor stack
  - Data Acquisition

◆ Hardware Products evaluated by Tabletop Reviews prior to hand-off to Assembly, Integration, and Test
Saffire Flight Unit Structure

Products
1. Primary Structure
2. Sample Card
3. Flow Control
4. Thermal/Fluids
5. Power
6. Igniter Control
7. Processor
8. Instrumentation
9. Signal Conditioner
10. Vision system
11. DAQ
12. USB
13. Cables/connectors
14. Software

- Maximum mass: 375 lbs
- Maximum power: 309 W continuous; 547 W (peak)
- Dimensions: 35.3” x 21.0” x 52.5”
Saffire Avionics Plate

Products
1. Primary Structure
2. Sample Card
3. Flow Control
4. Thermal/Fluids
5. Power
6. Igniter Control
7. Processor
8. Instrumentation
9. Signal Conditioner
10. Vision system
11. DAQ
12. USB
13. Cables/connectors
14. Software
Assembly and Integration Status
Avionics Panel Assembly

- Assembly and functional testing of Saffire-I, II, and III avionics panels completed in July 2014
- Tests of the low and high speed serial Cygnus interface showed compliance with our Saffire-Cygnus serial communications interface requirements.

- Avionics panel is 1.3 m long by 0.5 m wide
Flight tests

1. Large Flame Spread sample
   • Orbital-5: July 24, 2015

2. Material Flammability samples
   • Orbital-6: January 4, 2016

3. Large Flame Spread Sample
   • Orbital-7: June 19, 2016
Assembly and Integration Status

**Flow Duct Assembly**

- Flow duct instrumentation
  - Radiometers
  - O₂ sensor
  - CO₂ sensor
  - Pressure Transducer
  - Anemometers
  - Thermocouples

**Fan Panel**
### Saffire-2 Sample Details

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Material</th>
<th>Sample Thickness</th>
<th>Air Flow (cm/s)</th>
<th>Igniter Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saffire-2-S1</td>
<td>Silicone (Flammability limit 1)</td>
<td>0.25 mm (0.010&quot;)</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S2</td>
<td>Silicone (Flammability limit 2)</td>
<td>0.61 mm (0.024&quot;)</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S3</td>
<td>Silicone (Flammability limit 3)</td>
<td>1.02 mm (0.040&quot;)</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S4</td>
<td>Silicone (Downward burn 1)</td>
<td>0.36 mm (0.014&quot;)</td>
<td>20</td>
<td>Top</td>
</tr>
<tr>
<td>Saffire-2-S5*</td>
<td>SIBAL fabric (SIBAL 1)</td>
<td>0.33 mm (0.013&quot;)</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S6*</td>
<td>SIBAL fabric (SIBAL 2)</td>
<td>0.33 mm (0.013&quot;)</td>
<td>30</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S7*</td>
<td>PMMA to Nomex (Transition 1)</td>
<td>0.33 mm (0.013&quot;)</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S8**</td>
<td>Structured PMMA (Thick 1)</td>
<td>10 mm with tapered edge for ignition</td>
<td>20</td>
<td>Bottom</td>
</tr>
<tr>
<td>Saffire-2-S9</td>
<td>Flat PMMA (Thick 2)</td>
<td>10 mm with tapered edge for ignition</td>
<td>30</td>
<td>Bottom</td>
</tr>
</tbody>
</table>

* Samples S5, S6, and S7 get two thermocouples each; see pp. 2-3
** See detailed drawing on p. 4
Science Status
Saffire-II Sample Card

- Populated and wired sample card for Saffire-II
- Igniter wire “loops” on a silicone sample
  - Space upstream of sample allows edge ignition
Saffire-2 Sample 5 and Sample 6 Details

Air Flow

Igniter

SIBAL Fabric

30 cm overall length

15 cm width

7.5 cm
Saffire-2 Sample S7 (Transition: PMMA to Nomex) Details
Xiaoyang Zhao and Prof. James T’ien (Case Western Reserve University) are expanding the capability of an existing flame spread model to simulate Saffire test conditions.

- Model is for flame growth on samples similar in length and same material as Saffire-I and –III
- Data from Saffire-I, -II, and –III experiments will be compared to extended versions of these models.

Buoyant flow sample is 5 cm wide by 30 cm long, sandwiched by metal plates.

Temperature along center plan (colors) vs. time (top to bottom) for a buoyant flow condition. (In low-g, Saffire conditions will be in forced flow.)
Saffire Development Schedule

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software TTR #1 – Environmental Test S/W (UID 4752)</td>
<td>7/28/14</td>
</tr>
<tr>
<td>Saffire-I Assembly Complete (UID 4123)</td>
<td>10/2/14</td>
</tr>
<tr>
<td>Saffire-III Assembly Complete (UID 4151)</td>
<td>10/14/14</td>
</tr>
<tr>
<td>Saffire-II Assembly Complete (UID 4137)</td>
<td>10/23/14</td>
</tr>
<tr>
<td>Ground Safety Data Package Submit (UID 2884)</td>
<td>10/31/14</td>
</tr>
<tr>
<td>Saffire-III Offgas Testing Complete (UID 4211)</td>
<td>11/18/14</td>
</tr>
<tr>
<td>Saffire-I Environmental Testing Complete (UID 4177)</td>
<td>12/17/14</td>
</tr>
<tr>
<td>Software TTR #2 – Final SW Version (UID 4751)</td>
<td>1/2/15</td>
</tr>
<tr>
<td>Saffire-I Phase II Functional Testing Complete (UID 4179)</td>
<td>1/28/15</td>
</tr>
<tr>
<td>Saffire-I ISS Phase III Flight Safety Review (UID 2882)</td>
<td>2/27/15</td>
</tr>
<tr>
<td>Cygnus Interface Testing at Orbital Start (UID 4186)</td>
<td>3/2/15</td>
</tr>
<tr>
<td>Saffire-I SAR (UID 2883)</td>
<td>3/25/15</td>
</tr>
<tr>
<td>Saffire-I Ship to Wallops (UID 6257)</td>
<td>5/1/15</td>
</tr>
<tr>
<td>Saffire-I Cygnus Integration Testing at Wallops Start (UID 6258)</td>
<td>5/4/15</td>
</tr>
<tr>
<td>Saffire-I Launch minus 70 day Turnover (UID 6259)</td>
<td>5/15/15</td>
</tr>
</tbody>
</table>
Orbital Cygnus
Orbital Cygnus
Orbital Cygnus
Orbital Cygnus
Astronaut View Looking Inside a Loaded Pressurized Cargo Module (PCM)

Proposed location of SFS Demo Experiment

- Experiment would use standard straps and replace cargo bags.
Experiment Configuration

- Experiment replaces an M-01 and M-02 bag
- Fully assembled and installed into the PCM at Wallops Flight Facility (WFF)
  - Power and communication cables
- System check-out when attached to Service Module at WFF
- No crew interaction with the experiment
  - Experiment does not need to be moved during unloading or loading

- Experiment remains on AFT wall but rotated to lie between the rails
- Sample spacing requirements met
- Length of flow chamber reduced from 48” to 44”
- Camera enclosures facing M-01/M-02 bags on AFT wall
Mission Concept

Load experiment into Cygnus PCM

Cygnus mounted in the shroud of the Antares vehicle

Antares Launch

Wallops
Mission Concept

Cygnus approaching ISS

Unpack cargo, reload with trash

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

Check-out SFS Demo experiment
Mission Concept

CAD model of SFS Demo in Cygnus

Side view of a low-g flame on a thin paper sample in a convective flow

S-Band Antenna

X-Band Antenna

Cygnus Comm

TDRSS

Ground Stations

Data Receiving and Analysis
GRC Operations

Cygnus Ops Center

NASA Ops Engr.

Cygnus Ops Engr.

VOICE
Operations Concept

- Saffire Arrives at H100
  - Saffire Post Ship Checkout & Cygnus Interface Testing
  - Cygnus Integration & Power Continuity and Safety Inhibit Checks
  - Saffire Unpowered
  - Cygnus Berthed to ISS
  - Cygnus Departs ISS
  - ISS Rendezvous, Prox Ops, and SSRMS Capture
  - Cygnus in Free Flight Outside ISS Safety Corridor
  - Cygnus in Orbit up to 8 days to downlink Saffire Data.
  - Cygnus Destructively Re-enters Atmosphere With Saffire
  - Santiago, Chile
  - Fucino, Italy
  - WGS

- Antares Launch
  - Saffire Unpowered
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 at a different flow condition

• 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.
Future Flight – Wire array concept?

Typical arrangement of wire spreading test. Air flow is given from right to left.

Limiting oxygen concentration of PE wire with different core material in 1G and 0G.
Specification of sample (PE#2): Outer diameter 0.8mm, inner core diameter 0.5mm, insulation thickness 0.15, insulation material is polyethylene.
Cygnus Vehicle Capability

- Airflow for Mid-Deck Lockers is part of the cabin (fire detection and suppression) airflow system

- Area smoke detector in Cygnus
  - Appears similar to the ISS detector

![Diagram of Cygnus Vehicle with labeled components: IMV fan, Silencers, and identified airflow paths.](image-url)
Summary of Spacecraft Fire Safety Needs

◆ Material Flammability
  • Low- and partial-g flammability limits for spacecraft materials
  • Material flammability at high %O₂ and reduced pressure
  • Realistic fire challenges

◆ Fire Detection
  • Hybrid gas and particulate sensors for fire detection
    ▪ Knowledge of spacecraft fire signatures

◆ Fire Suppression
  • Common portable fire extinguisher for exploration
    ▪ Relevant for elevated oxygen conditions, varying size of vehicle

◆ Post-fire response
  • Hybrid gas and particulate sensors for post-fire monitoring
  • Post-fire cleanup technology (Smoke-Eater)
  • Combustion Product Monitor

◆ System Demonstration
  • Demonstration of end-to-end fire detection, suppression, and post-fire cleanup technologies
Conclusions

◆ Microgravity fire behavior remains poorly understood and a significant risk for spaceflight

◆ An experiment is under development that will provide the first real opportunity to examine this issue focusing on two objectives
  • Material Flammability
  • Flame Spread

◆ This experiment has been shown to be feasible on both ESA’s ATV and Orbital Science’s Cygnus vehicles with the Cygnus as the current base-line carrier.

◆ An international topical team has been formed to develop concepts for that experiment and work towards its implementation.
  • Pressure Rise prediction and Modeling
  • Sample Material Selection
  • Supportive Experiments – Ground, Drop-Tower, Parabolic Flights, ISS

◆ This experiment will be a landmark for spacecraft fire safety with the data and subsequent analysis providing much needed verifications of spacecraft fire safety protocol for the crews of future exploration vehicles and habitats.