Spacecraft Fire Safety: Protecting Vehicles and Crews on Long-Duration Exploration Missions

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Future In-Space Operations (FISO) Seminar

November 15, 2017
NASA’s Risk Management for Spacecraft Fire Safety

Fire Safety Philosophies

- Fire-proof design
- Prevention
  - Fire Triangle
  - Maximize Use of Good Materials
  - Minimize Ignition Mechanisms
  - Utilize Good Practices

- Oxygen
- Heat
- Fuel
NASA’s Risk Management for Spacecraft Fire Safety

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Practically Can’t Be Done

These are the focus of our fire safety activities!
- Tasks “buy-down” the risk of fire for all manned exploration systems
What’s Different in Low-g and Exploration?

**Material Flammability Screening**

- NASA STD-6001 Test 1: Upward Flame Spread Test
- Test is conducted at the worst-case atmospheric conditions in which the material will be used
  - This has historically been 30% O₂, 10.2 psia (shuttle pre-EVA atm)
  - Future exploration atmospheres extend to 34% O₂, 8.2 psia
  - A material fails the test if it burns more than 15 cm (6 inches).
Air Flow is very Important to a Flame

Buoyant or Forced Flow Direction

What does increasing flow do?
- Brings in oxygen
- Removes heat faster
- Reduces time for chemical reactions and heating
- Makes flame closer to the surface (fuel)

Opposed  Concurrent  Opposed  Concurrent
Normal Gravity (Buoyancy)  Microgravity
Material flammability depends on the ambient flow.

In 1-g, the flame determines the flow by buoyancy (natural convection) … … but the material can burn just fine with a lower flow and at a lower oxygen concentration.

The 1-g flammability limit can be determined by NASA-STD-6001 Test 1.

No flow (quiescence) is least flammable but the crew needs fresh air to breathe.

- Environmental control and life support flows are around 15-20 cm/s.
  - Right around the conditions where materials can still burn.

![Typical Flammability Boundary for a Solid Fuel](image-url)
A Lot of Other Low-Gravity Implications!

♦ Where there’s fire, there’s not necessarily smoke.

Candle flame in normal (left) and low-gravity (middle). The low-g flame emits little, if any smoke.

♦ When it’s out, the hazard isn’t necessarily gone.

Cloud of condensed wax vapor after extinction of low-g flame
A Lot of Other Low-Gravity Implications!

- Flames can spread preferentially upstream
  - Into the incoming fresh air
- Ejecta from a melting solid (or firebrands) don’t settle and can travel farther in low-g
- Detection of aerosol or gaseous fire signatures depends on ventilation … which also aids flame spread

Flame spreads preferentially upstream, opposite that in 1g. Paper is centrally ignited in low-speed opposed-air flows (1 and 2 cm/s).

Ejection of burning material
Ambient conditions depend on mission objectives

- The Exploration Atmospheres Working Group convened in 2004 and 2012 to provide recommendations for the cabin atmosphere for exploration vehicles

- Selection attempts to balance competing effects of flammability, decompression sickness, and hypoxia

- Long-distance transport would favor standard atmosphere conditions
  - Known impact on crew and equipment

- Surface operations with frequent EVA would favor higher %O₂ and hypoxic operation
  - Trade crew performance against time for pre-breathe

![Graph showing volume percent oxygen vs. total pressure for various historical designs, with labels for normoxic equivalent, hypoxic boundary, historical designs, decompression sickness on EVA, and flammability.](image-url)
What does NASA do to prevent/respond to fires?

- **Material Flammability**
    - Test 1: Upward Flame Spread Test
  - Materials that fail Test 1 must undergo additional testing and/or configuration control as defined by NASA Materials and Processes personnel

- **Minimize ignition sources**
  - To the extent possible, designs attempt to minimize sources of ignition

- **Fire Detection**
  - On ISS, smoke detectors are positioned near air return vents
  - FGB and SM smoke detectors use different technology (ionization) than US smoke detector (photoelectric)

- **ISS Fire Extinguishers**
  - US: gaseous CO₂, Fine water mist
  - RS: Water-based foam
We can conduct ground tests to assess many of these technologies but the data needs to be anchored using low-g data obtained at relevant length and time scales.

Testing requires:
- Low-g
- Large scale
- Relevant range of conditions including reduced pressure and elevated oxygen
- Large volume

We proposed and developed the concept of conducting a large-scale fire on an ISS resupply vehicle after it left the ISS.
Saffire-I, II, & III 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.

- 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.

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.
Sample Card Holder Configurations

- Sample card and samples are the only differences between the three flight units

**Saffire-I, -III Sample Card**
Composite fabric (SIBAL cloth)
(75% cotton – 25% fiberglass by mass)
(0.4 m x 0.95 m)

**Saffire-II Sample Card**

* Saffire-II Samples (5 cm x 29 cm)
  - PMMA (flat and structured)
  - Silicone (3 thicknesses, different ignition direction)
  - SIBAL
  - Nomex (with PMMA ignition)
Operations Concept

Pre-Launch

- Saffire Post Ship Checkout & Cygnus Interface Testing
- Saffire Hand-Over for Cygnus Integration
- Cygnus Integration & Power Continuity and Safety Inhibit Checks
- Saffire Unpowered

Unpowered
Inhibits Open

- Cygnus Departs ISS
- Saffire Unpowered

Powered
Inhibits Closed

- Cygnus Berthed to ISS
- Saffire Unpowered

- Cygnus in Free Flight Outside ISS
- Safety Corridor
- Saffire powered ON. Autonomous Experiment Sequence Initiated

- Hawaii
- WGS

- ISS Rendezvous, Pre Ops, and SSRMS Capture
- Saffire Unpowered

- Cygnus Destructively Re-enters Atmosphere With Saffire

- Antenna Launch
- Saffire Unpowered
## Saffire Operations

<table>
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<tr>
<th>Mission</th>
<th>Launch Site</th>
<th>Launch Vehicle</th>
<th>Integration</th>
<th>Launch</th>
<th>Mission Ops</th>
</tr>
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- **Operations received considerable coverage on social media**
  - NASA GRC and AES

*Above: Saffire-II Mission Support Teams at NASA-GRC; Left: Saffire-II Flight Operations Team at Mission Control Dulles (backroom data assessment); Far Left: Saffire and Orbital ATK Flight Operations Teams at Mission Control-Dulles*
Images were taken 20 sec after ignition

Both samples are 40 cm wide

Two of the most important factors for crew safety during on-board fires are:
1. How bad can the cabin conditions get during a fire?
2. How quickly can they get bad?

Fire is only the beginning – combustion products (smoke, CO, acid gases, …) also contribute to the hazard.
Saffire-I and III Results

- **Left:** Sequence of concurrent flame images from Saffire-I and III.
  - Each image is 40-sec apart.
  - Saffire-I burned for 400 sec
  - Saffire-III burned for 320 sec
  - The flame speed is proportional to the air flow velocity

- **Below:** Comparison of the opposed (upper) and concurrent (lower) flames from Saffire-III.
  - The flame images were taken at different times (near the end of each burn) and superimposed.
Saffire-II Summary

- **Samples 1-4**: Silicone sheets of varying thickness (*0.25 mm, 0.61 mm, 1.03 mm, 0.36 mm respectively*)
  - Samples ignited but flame did not propagate
- **Samples 5-6**: SIBAL cloth (*20 cm/s and 25 cm/s - same as Saffire-I and III*)
  - Burned to completion
- **Sample 7**: Nomex with PMMA igniter (*1 mm thick PMMA*)
  - PMMA burned; flame did not propagate into Nomex
- **Sample 8-9**: Structured and Flat PMMA (*10 mm thick*)
  - Burned for the entire duration (6; 12 min); extinguished when flow ceased

Composite picture of samples 1-9 at end of experiment. *Streaks are soot from Samples 7-9 deposited on card.*
Saffire-I-III Results

Measurements of flame base, pyrolysis tip, and pyrolysis length from concurrent and opposed burns from Saffire-I. The flame base is the most upstream portion of the flame and is bright and well-defined. The pyrolysis tip is the most downstream portion of the blackened (charred) fuel. The fuel was a 40.6-cm-wide cotton-fiberglass fabric. Air flow speed was 20 cm/s.

Spread rate summary for Cotton/Fiberglass fabric burning in microgravity
Summary of Saffire Results…So Far!

**Saffire-I & III**

- Flame reaches a limiting length in forced convective concurrent flow even for very wide sample
  - Implies a steady spread rate and a limiting heat release rate
  - *A fire on a spacecraft vehicle may reach a steady size?*

- Concurrent flame spread is proportional to the flow velocity

- Concurrent flame spread rate was much slower than expected from previous space experiments
  - 65% less than observed in Burning and Suppression of Solids experiment on ISS
  - *What is the impact of slower growth on release of combustion products? On fire detection? How does this depend on flow velocity?*

- Proximity to and interaction with side walls appears to impact the flame more than expected
  - *Needs to be better understood through computational models; Review results of previous microgravity experiments*

- Opposed flames spread at about the same rate as concurrent flames
  - *How does this depend on flow velocity?*
  - *Are concurrent flames always the worst case for microgravity fires?*

- We need to make a bigger fire to impact the vehicle
Summary of Saffire Results…So Far!

Saffire-II

- Materials that burned all had slower spread rates than expected
  - Composite fabric, PMMA
- Flame spread rates on composite fabric were similar to those seen in Saffire-I
  - Rapidly reached a steady spread rate and a limiting heat release rate
- Examining material flammability limits in microgravity using a limited number of experiments is difficult
  - Repeat cases are required to understand the competing phenomena
Saffire-IV, V, and VI Summary

Needs:
- Demonstrate spacecraft fire monitoring and cleanup technologies in a realistic spacecraft fire scenario
- Characterize fire growth in high O$_2$, low pressure atmospheres
- Provide data to validate models of realistic spacecraft fire scenarios

Objectives:
- **Saffire-IV:** Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release) in exploration atmosphere
- **Saffire-V:** Evaluate fire behavior on realistic geometries
- **Saffire-VI:** Assess existing material configuration control guidelines
- All flights will demonstrate fire monitoring and response technology

**Saffire Flow Unit**
Approx. 53x90x133 cm. New features include 2 side view cameras, acid gas, O$_2$, heat and byproduct release to cabin

**Remote Sensors (6)**
Measure temp & CO$_2$ in standoffs, hatch and end cone

**Far Field Diagnostics (in Mid Deck Locker)**
Avionics, CO$_2$ scrubber, Smoke Eater, Combustion Products Monitor, particulate monitors (DustTrack & Ion Chamber)
Saffire-IV, V, and VI Experiment Concept

- Concept consists of three distinct hardware locations
  - Saffire flow unit
  - Far-field diagnostic
  - Distributed sensors

- Far-field diagnostic module
  - Combustion product monitor
  - CO and CO₂ sensors
  - Post-fire cleanup module

- Distributed sensor network
  - Temperature
  - CO₂
Expected Results of the Saffire-IV, V, and VI Experiments

- Flammability in normal and exploration atmospheres
  - Traceability to Saffire-I, II, and III
- Oxygen calorimetry for a large-scale microgravity fire
  - Rate of heat release for fire scenario modeling
- Rate of change of cabin pressure and temperature during a large-scale fire
- Transport and mixing of an inert gas (CO$_2$)
  - Fire detection
  - Fire scenario modeling
- Demonstration of advanced combustion product monitor to quantify CO, CO$_2$, and acid gases (HF, HCl)
- Transport/decay of acid gases in a post-fire environment
- Demonstration of advanced sorbents for cleanup of CO and CO$_2$
  - Sizing of smoke-eater for exploration applications
Other Considerations for Exploration

- **Dormancy**
  - Many of the mission scenarios include vehicles that are uncrewed and in a dormant state for extended periods of time.
  - Dormancy impacts protocols for detection, suppression and cleanup
    - Dormancy before crew arrives
    - Dormancy between crew visits

- **Partial Gravity**
  - Habitats on a anticipated planets, moons, or asteroids will have buoyant convection but at a smaller flow velocity than Earth
  - There are limited facilities on Earth in which we can conduct partial-gravity flame spread tests

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Fire Safety Strategy Depends On Vehicle State During Dormancy

- **Is there ECLSS ventilation?**
  - **Pro:** can use ventilation for fire detection
  - **Con:** first response is to terminate ventilation after a fire alarm
  - **Impact:** When can ventilation be re-initiated?

- **What is the atmospheric composition?**
  - **Pro:** can make the atmosphere unable to support combustion
  - **Con:** must increase $O_2$ mole fraction before crew returns
  - **Impact:** Does increasing $O_2$ for a “short” time increase risk significantly?

- **What systems are powered during dormancy?**
  - **Pro:** can monitor system state for abnormal current draw; terminate power if an electrical short is detected
  - **Con:** powered systems are the most likely ignition source
  - **Impact:** When can power be restored?
Fire Safety Strategy Depends On Vehicle State During Dormancy

♦ Is there gravity?
  - Pro: In microgravity, termination of ventilation and power will most likely be effective for fire suppression
  - Con: In a gravity field, propagation of fire is uncertain even if ventilation and power is removed
  - Impact: When can power and ventilation be re-initiated?

♦ If a fire is detected, at what point do you initiate an active response?
  - How do you confirm that any passive responses were not effective?
    • Monitoring is effective but takes time
    • Visual confirmation of the vehicle state would be effective
  - Pro: An active response can assuredly extinguish a fire
  - Con: (1) An active response changes the state of the vehicle
    (2) Active response during dormancy requires a fixed fire suppression system; mass, risk of failure (on or off)
  - Impact: Clean-up of the suppression agent. When can power and ventilation be re-initiated?
Summary

♦ Low- and partial-gravity impacts many areas of the combustion process and, therefore, spacecraft fire safety

♦ Mission scenarios play a major role in determining the fire hazard… …and fire safety is never the driving factor!

♦ The Saffire missions were developed to investigate many of the knowledge gaps in spacecraft fire safety
  • Saffire-I-III primarily investigated flame spread and material flammability limits

♦ Future Saffire missions will investigate advanced material flammability questions as well as fire/vehicle interactions
  • Missions will also demonstrate technologies needed to protect the spacecraft and crew

♦ Periods of spacecraft or habitat dormancy pose unique hazards for fire safety
  • Primarily operational issues rather than new technology development
  • Need to have data in hand so that the operational environment and configuration can be appropriately analyzed