Advanced Exploration Systems Program

Automated Transfer Vehicle Material Flammability Experiment

50th AIAA Aerospace Sciences Meeting and Exhibit
Nashville, Tennessee
January 9 – 12, 2012
Automated Transfer Vehicle Material Flammability Experiment

Authors:
• David L. Urban: NASA Glenn Research Center, Cleveland, OH
• Gary A. Ruff: NASA Glenn Research Center, Cleveland, OH
• A. Carlos Fernandez-Pello: UC Berkeley, Berkeley, CA
• James S. T’ien: Case Western Reserve University, Cleveland, OH
• Grunde Jomaas: Technical University of Denmark, Lyngby, Denmark
• Jose Torero: University of Edinburgh, Edinburgh, Scotland
• Guillaume Legros: University of Pierre and Marie Curie, Paris, France
• Christian Eigenbrod: University of Bremen, Bremen, Germany
• Manfredo Reimert: University of Bremen, Bremen, Germany
• Nickolay Smirnov: Moscow Lomonosov State University, Moscow, Russia
• Osamu Fujita: Hokkaido University, Sapporo, Japan
• Adam Cowlard: University of Edinburgh, Edinburgh, Scotland
• Sebastien Rouvreau, Altran
• Balazs Toth: ESA-ESTEC Project Scientist

Members of the Spacecraft Fire Safety International Topical Team
Automated Transfer Vehicle Material Flammability Experiment

Objective:
Advance spacecraft fire safety technologies through a large-scale fire demonstration in low gravity.

• A large-scale experiment aboard an unmanned re-entry vehicle would investigate important questions about low-gravity material flammability.
• 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.
How different are low-g material flammability limits from those measured in normal gravity?

- Low-gravity oxygen flammability limits are different in low-gravity than in normal gravity
- 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
  - The normal-gravity (and partial-gravity, for that matter) oxygen concentration flammability limit is not necessarily the minimum

What is the fate of a large-scale fire in low-gravity?

- Extrapolation of observed low-g flame behavior to a full-scale spacecraft fire scenario is tenuous
- Fires on-board spacecraft have been few – fortunately
- Experience with “significant” fires is very limited
  - Enhance risk assessments and modeling of fire events

![Diagram of flammability limits](image-url)
• 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: 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
  • Samples are 5 cm wide x 33 cm long and rigidly held in a frame

  ➢ Flammability samples
Low-g Oxygen Flammability Threshold Tests

- Tests conducted in the Zero Gravity Facility at NASA-GRC to quantify the low-g flammability thresholds for typical spacecraft materials

- 5.2-sec limits samples to thin materials
Lunar-g Maximum Oxygen Concentration

- Centrifuge drop rig being prepared for a drop in the Zero Gravity Facility.
- Fuel sample is 5 cm wide by 6 cm long.
Zero-g and Lunar-g MOC Results

- Tests were conducted at WSTF (normal-g) and GRC (Lunar-g) to quantify changes in the MOC for Nomex, Mylar, and Ultem.

- Conditions run in Lunar-g burned at both the normal gravity MOC and at the zero-g convective MOC:
  - Lunar-g flammability appears more like zero-g rather than 1-g.
  - Cessation of ventilation flow is not effective.

- Significant impact on a fire safety strategy, especially if the need for fire detection and suppression is dictated by the difference between the MOC and atmosphere of use.

(MOC: Highest $O_2$ concentration where sample passes Test 1)
How rapidly can a fire spread in low-g?

• This question lies at the heart of the development of a fire safety strategy
  – Terrestrial or spacecraft applications

• Rate of fire growth impacts:
  – Time to detect
    • Early detection reduces impact of fire, response strategy
  – Size of fire
    • Amount of fire suppression agent required
  – Heat release rate, fire spread to surrounding materials
    • Collateral damage
  – Emission of combustion products
    • Post-fire cleanup strategy and consumables

➢ Large-scale *flame spread* sample
  – 0.5 m wide x 1.0 m long
Science Objectives – Fire Safety - 1

• Science objectives developed by the Spacecraft Fire Safety International Topical team
  1. Examine the applicability of upward flammability tests such as NASA STD 6001, Test 1
  2. Observe and quantify the growth and spread of a large-scale fire
  3. Develop an active system based on fire modelling that provides optimised mitigation strategies based on the characteristics of a fire as it occurs.
  4. Quantify the soot concentration field during the growth and spread of a large-scale low-g fire
  5. Determine the impact of fuel surface structure on spread rate and flammability limits of flames
  6. Extend the impact of ground-based testing by comparing flight data with that from Japanese small scale flight experiments.
  7. Quantify the impact of a metallic skeleton of high thermal conductivity in a material on flame spread
  8. Demonstrate the filtering capability of advanced post-fire clean-up system.
  9. Quantify the combustion products of experiment sample materials using a suitable array of gaseous monitors
Experiment Concept

Experiment Configuration and Sequencing:
- Two sets of sample configurations

Flammability Limits: Series of 5 x 30 cm samples selected to test the flammability limit

Flame Spread: Large sample to study fire growth

Concept of Operations:
- Experiment would be launched in soft stowage bags
- Experiment would be assembled by the crew while loading the ATV for undocking
- Tests would be executed sequentially.
- Data to be transmitted to ground.
Experiment Description

Diagnostic Equipment:
- Lights
- Cameras
  - Movie
  - Stills
- Pressure Sensor
- Temperature Sensor
- Oxygen Concentration
- Fire Detection Sensors

Experiment Equipment:
- Fans
- Support Plate
- Smoke Cleaning Material
- Protection Screen
- Ignition System
- Test Material
- Extinguishing Agent
- Command, Control, and Data Computer
- Communication Link (antenna, wiring, interfaces)
CAD Model of Experiment installed in ATV Rack

Filter Module
Test Samples Module
Avionics Module
Fan Module
Battery Module
CAD Model of Experiment - *Protective Nomex Covers*
• Camera array assembly
  – one on each flammability sample
  – three camera array on flame spread sample

• Lights contained in each assembly

• Anemometers

• Gas sensors (O$_2$, CO$_2$, CO)

• Pressure, temperature
Mission Concept

Load onto an ATV in a cargo bag

ATV in shroud on an Ariane V

Ariane V launch
Mission Concept

Dock to ISS

Unpack cargo, reload with trash

Unstow SFS Demo experiment and mount to plates on front of racks
Mission Concept

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

ATV-1 re-entering the atmosphere
Spacecraft Fire Safety Topical Team

Spacecraft Fire Safety

Spacecraft Fire Safety Demo (NASA)
- David L. Urban
- Gary A. Ruff
- James T’ien,
- Carlos Fernandez-Pello

SAFE COSMOS (ESA)
- Grunde Jomaas
- Jose L. Torero
- Adam Cowlard
- Guillaume Legros Sebastien Rouvreau
- Christian Eigenbrod
- Manfredo Reimert
- Nickolay Smirnov
- Olivier Minster
- Balazs Toth

Gravity Impact on Solid Material Flammability
- Osamu Fujita

Project 4 (TBD)

Experiments
- Fire Safety -1
- Experiment 2 (TBD)
- Experiment 3 (TBD)
Project Status

• Primary activities of the international topical team include:
  – Development of the experiment requirements
  – Sample selection and configuration
  – Vehicle pressure control
  – Command, control, and data down-linking

• The European Space Agency kicked off a feasibility study in October 2011
  – Report completed in late December 2011

• Initial draft of the ESA Experiment Science Requirements (ESR) document was completed in early November
  – ESR will continue to be updated as experiment requirements develop
Sample selection – Fire Safety - 1

• Constraints on sample material include (1) material flammability limits (1-g and 0-g), (2) flame propagation rate, (3) material stability, (4) smoke production, (5) heat release, (6) ease of ignition, (7) mounting, ...
  – Material flammability samples: up to 9 samples (5 cm x 30 cm)
  – Flame spread sample (50 cm x 100 cm)

• Sample characteristics
  – cellulose (paper or cotton fabric)
  – Possible additional of an inert support material (fiber glass)

• Density of fuel: no greater than 9 mg/cm² of fuel
  – The inert material would affect the density but will not affect the heat release

• Science team members are investigating other sample configurations
  – corrugated surfaces
  – ridges
  – Corners

• Sample materials and objectives for future flights will be developed based on the results of Fire Safety - 1
Pressure Control in ATV

- ATV maximum pressure is 1048 hPa (mBar)
  - ATV engineering limit is 1035 hPa
  - Assumed initial pressure is 1023 hPa
- Internal pressure can be decreased but ATV engineers estimated that a desired pressure could be achieved only to within +/- 100 hPa
- We have developed a transient lumped-parameter model that accounts for heat release from the sample and heat transfer to the vehicle and contents

<table>
<thead>
<tr>
<th>Condition</th>
<th>Large Sample</th>
<th>Small Sample</th>
<th>Number of Small Samples</th>
<th>Fuel mass (g)</th>
<th>$T_o$ (K)</th>
<th>$P_o$ (hPa)</th>
<th>Conductive loss area (cm x cm)</th>
<th>$T_{\text{max}}$ (K)</th>
<th>$P_{\text{max}}$ (hPa)</th>
<th>Average Rate of Pressure Rise (hPa/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>100</td>
<td>10</td>
<td>30</td>
<td>9</td>
<td>69.3</td>
<td>294</td>
<td>1023</td>
<td>N/A</td>
<td>313</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>100</td>
<td>10</td>
<td>30</td>
<td>9</td>
<td>69.3</td>
<td>294</td>
<td>1023</td>
<td>50 x 20</td>
<td>299</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>100</td>
<td>10</td>
<td>30</td>
<td>9</td>
<td>69.3</td>
<td>294</td>
<td>950</td>
<td>N/A</td>
<td>314</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>50</td>
<td>5</td>
<td>30</td>
<td>4</td>
<td>16.7</td>
<td>294</td>
<td>1023</td>
<td>N/A</td>
<td>300</td>
</tr>
</tbody>
</table>
Estimation of Pressure Rise

<table>
<thead>
<tr>
<th>Condition</th>
<th>Large Sample width (cm)</th>
<th>Large Sample length (cm)</th>
<th>Small Sample width (cm)</th>
<th>Small Sample length (cm)</th>
<th>Number of Small Samples</th>
<th>Fuel mass (g)</th>
<th>$T_0$ (K)</th>
<th>$P_0$ (hPa)</th>
<th>Conductive loss area (cm x cm)</th>
<th>$T_{\text{max}}$ (K)</th>
<th>$P_{\text{max}}$ (hPa)</th>
<th>Average Rate of Pressure Rise (hPa/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>100</td>
<td>10</td>
<td>30</td>
<td>9</td>
<td>69.3</td>
<td>294</td>
<td>1023</td>
<td>N/A</td>
<td>313</td>
<td>1089</td>
<td>0.63</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>100</td>
<td>10</td>
<td>30</td>
<td>9</td>
<td>69.3</td>
<td>294</td>
<td>1023</td>
<td>50 x 20</td>
<td>299</td>
<td>1039</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>100</td>
<td>10</td>
<td>30</td>
<td>9</td>
<td>69.3</td>
<td>294</td>
<td>950</td>
<td>N/A</td>
<td>314</td>
<td>1014</td>
<td>0.61</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>50</td>
<td>5</td>
<td>30</td>
<td>4</td>
<td>16.7</td>
<td>294</td>
<td>1023</td>
<td>N/A</td>
<td>300</td>
<td>1043</td>
<td>0.40</td>
</tr>
</tbody>
</table>

• Rate of pressure rise for Condition 1
  – Transient, lumped-parameter model
• Assumes a constant burning rate based on low-g data
• Burning rate and heat release data will be required for any sample material
Full-Scale Environment Effects

- Conduct tests in a vacuum chamber at GRC on full-scale demonstration using candidate materials and configurations
- Characterize the transient pressure and temperature environment
- Compare data with estimates and modeling results

VF-13 Pressure Vessel (5’ diameter x 11’ tall) that allows testing of full-scale samples

CAD model of ATV interior to be used in detailed modeling of the Fire Safety – 1 experiment. (Internal racks are not filled in this image.)
Command, Control, and Data Down-link

- Options range from minimal C&C to having the ability to review data between runs
- Experiment communications to remain isolated from vehicle command and control
- S-band suggested by ESA
  - Antenna and location available
  - Longest contiguous downlink is ~22 minutes
  - Data could be packaged into files, each download initiated with a “start” command
- X-band options are being investigated by NASA
- Availability of a transponder is an issue
Summary

• A Spacecraft Fire Safety International Topical Team has been formed and is developing requirements for a unique large-scale fire safety experiment to be performed on the Automated Transfer Vehicle
  – Tests planned for ATV-5 (March 2014) pending the results of the ESA ATV Feasibility Study
  – NASA Project Team is developing and building the experiment
    • Advanced Exploration Systems Program, Spacecraft Fire Safety Demonstration Project

• Initial tests will focus on material flammability
  – Low-g flammability limits
  – Large-scale flame spread

• Current activities of the science team include evaluation of pressure rise and control options in the ATV, selection of sample materials, and development of alternative for communications

• Long lead time items include:
  – S- or X-band transmitter
  – International agreements