Current Status of the Investigation on Materials Flammability under Microgravity in “FLARE” Project

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Osamu Fujita (Hokkaido Univ.)
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2. Overview of the FLARE Project
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4. Parabolic Flight Experiments
5. Experiments onboard ISS
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Importance of Materials Flammability Evaluation for Fire Safety in Spacecraft

➢ Specific features of fire in spacecraft and/or extra-terrestrial habitats

- Limited options to escape and survive (inside a small volume)
- Quick increase of pressure and temperature inside isolated volume
- Accumulation of toxic products

➢ To ensure fire prevention in spacecraft is very important.

➢ Selection of the materials by screening tests plays a role as the first (and most critical) defense line against fire.

➢ Fire detection and suppression play roles as the second and third defense lines.
Materials flammability screening tests are performed in accordance with NASA-STD-6001 on the ground.

It has been “assumed” that upward flammability test is the worst case to evaluate material flammability.

Many experimental results show materials flammability could be enhanced in microgravity or in partial gravity than that in normal gravity.

In fact, ....

Sketch of NASA-STD-6001 Test 1, Upward Flammability Test※.

※ Flammability, offgassing, and compatibility requirements and test procedures, NASA-STD-6001B, NASA.
The past investigations by many researchers revealed materials flammability could be enhanced in microgravity than that in normal gravity.  

1G test results are not always conservative on materials flammability!

Extinction limit of ETFE insulated copper wire

Effect of Gravity on Combustion Phenomena

Comparison of Candle Flame in Normal Gravity and in Microgravity.

(https://www.nasa.gov/audience/foreducators/microgravity/multimedia/me-candleFlame.html)
Issues of the current flammability test (NASA-STD-6001)

- Extension of flammability region in microgravity is not considered. Conservative results are not always guaranteed.

- It just tells us “pass” or “fail” of the material in the environment exposed in the tests (No quantitative information).
  - If environmental conditions (e.g. oxygen concentration) are changed, the tests shall be performed again.

- Several repetition of the tests are necessary, due to data scattering tendency of upward flame spread.
  - Takes cost and time.

- Chemical igniter is employed for ignition source to the material.
  - Other factor of data scattering and limitation of test conditions.

- Available test apparatus is limited to a few space agencies.
  - Utilization by non-governmental organization is difficult.
Materials flammability evaluation in different ambient conditions (oxygen concentration, pressure, gravimetric acceleration) with the ISS program is required for manned space exploration toward Moon and Mars.

- **Elevated oxygen concentration with lower ambient pressure** is assumed in some system.
- **Partial gravity environment** shall be considered in the Lunar and Martian surface.

https://www.nasa.gov/feature/nasas-exploration-campaign-back-to-the-moon-and-on-to-mars
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Fundamentals on Extinction Boundary of Solid Materials

2 different mechanisms for extinction!!

Flow velocity
- High \(\rightarrow\) Blow-off
- Low \(\rightarrow\) Radiative extinction

**LOC\(_{1g}\)**: Limiting oxygen concentration in normal gravity
**MLOC**: Minimum limiting oxygen concentration in microgravity
**\(V_{\text{cr}}\)**: The flow velocity where MLOC is observed

Schematic on flammability map for flame spread over a solid fuel.

- The gap between **LOC\(_{1g}\)** and the minimum limiting oxygen concentration (MLOC), **\(\Delta O_2\)**, is an **important value** to discuss the flammability of the material in reduced gravity environment.

Prediction of **\(\Delta O_2\)** from **ground-based data** is a key of the project!
Outline of the “FLARE” Project

➢ Objectives
  • Scientific understanding of the gravity impact on materials flammability.
  • Proposal of new international standard on evaluation of solid materials flammability in space for improvement of fire safety.

➢ Approach
  • Establishment of methodology to predict ΔO2 of solid materials in microgravity, through 1G and microgravity experiments.
  • LOI (Limiting Oxygen Index) method (ISO4589-2) is utilized to predict MLOC, since LOI is commercially used in world-wide with high reliability as “eigen-value” of material characteristics.

ISO 4589-2 (LOI Method)※.

Research Promotion Structure

Research Director (Prof. A. Sawaoka)

Discipline Advisor (Vacant)

Scientific Advice

Direction on the Project

Project Manager
Ms. S. Ogawa

JAXA

Project Management

Principal Investigator
Prof. O. Fujita

Research Team

Co-Investigators
4 Research Sub-Groups (Co-Is from Japan, U.S., and Europe)

User Integration
Mr. T. Sakashita

• Planning, promotion, coordination for the project.

Project Scientist
Dr. M. Kikuchi

• Coordination and promotion on scientific aspects.

H/W Development
Mr. Y. Nakamura

• Development of the experimental apparatus for the ISS experiment.
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<th>Research Sub-group</th>
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<th>Role of each investigator</th>
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<tr>
<td><strong>Group 1</strong>&lt;br&gt;Flammability limit of flat sheet ($\Delta O_2$)</td>
<td>© Shuhei Takahashi (Gifu Univ.)&lt;br&gt;Yoshinari Kobayashi (Gifu Univ.)</td>
<td>Dominant parameter to control limiting condition in microgravity, Applicable thickness limit of Takahashi’s model</td>
</tr>
<tr>
<td></td>
<td>Hiroyuki Torikai (Hirosaki Univ.)</td>
<td>Charred material in microgravity,</td>
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<tr>
<td></td>
<td>Yuji Nakamura (TUT)</td>
<td>Advise on discussion of the applicable thickness limit of Takahashi’s model</td>
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<td></td>
<td>Sandra L. Olson (NASA GRC)</td>
<td>Flammability of fabric clothes material</td>
</tr>
<tr>
<td></td>
<td>Christian Eigenbrod (Univ. Bremen)</td>
<td>Analysis of IR camera data from the parabolic flight experiments</td>
</tr>
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<td><strong>Group 2</strong>&lt;br&gt;Flammability of electric wire and cylindrical material</td>
<td>© Carlos Fernandez-Pello (UC Berkeley)</td>
<td>External radiation effect on material flammability in cylindrical shape.</td>
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<td></td>
<td>Osamu Fujita (Hokkaido U.)&lt;br&gt;Nozomu Hashimoto (Hokkaido U.)</td>
<td>Flammability limit of wire insulation in microgravity, Effect of core material and flow direction</td>
</tr>
<tr>
<td></td>
<td>Guillaume Legros (Univ.Pierre-et-Marie Curie-Paris6)</td>
<td>Soot formation in microgravity flame and its radiation characteristics. Microgravity tests in CNES flight.</td>
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# Research Sub-group 3

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<th>Research Sub-group</th>
<th>Investigator name (affiliation)</th>
<th>Role of each investigator</th>
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<tr>
<td>Group 3 Ignition of overloaded wire</td>
<td>📚 Mitsuhiro Tsue (U. Tokyo)</td>
<td>Effect of gravity and flow conditions on the growth limit of initial flame kernel generated in the flammable mixture.</td>
</tr>
<tr>
<td></td>
<td>Osamu Fujita (Hokkaido U.)</td>
<td>Ignition of overloaded wire, Effect of sample geometry.</td>
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◎ Group leader
### Research Sub-group 5

<table>
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<tr>
<th>Research Sub-group</th>
<th>Investigator name (affiliation)</th>
<th>Role of each investigator</th>
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</table>
| Group 5 (Discussion on new standard recommendation and its consistency with present method) | © Harold D. Beeson (NASA WSTF) | • Comparison of the result of material safety evaluation between an existing NASA test method and a new test method.  
• Discussion with JAXA and ESA on correlation and appropriateness of the test method.  
• Acquisition of ULOI and MOC data on the selected materials. |
| | David Hirsch (NASA WSTF) | |
| | Kana Kowatari (JAXA Human Space Safety and Mission Assurance Office) Osamu Fujita (Hokkaido U.) | • Study of fire safety standard and discussion on appropriateness of the test method with NASA and ESA from Japan’s standpoint.  
• Acquisition of LOI (HOI), ULOI and MOC data on the selected materials. |
| | Kaoru Wakatsuki (Shinshu U.) | • Advise on sample choice for μG tests, Advise on new ISO development |
| | Michal Malicki, Mauricio Portaluppi, Cathal Mooney (ESA ESTEC) | • Study of fire safety standard and discussion on appropriateness of the test method with NASA and JAXA from European standpoint.  
• Acquisition of ULOI and MOC data on the selected materials. |

RSG 4 was abolished, and its members and roles were re-arranged into RSG 1 and 5, in 2017.
**Current Location in Whole Project Schedule**

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<th>April</th>
<th>March</th>
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<td>Selection</td>
<td>Preparation of Project Plan</td>
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<tr>
<td>- Selection Review</td>
<td>- Project Transition Review (MDR/SRR)</td>
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<tr>
<td>Science Review</td>
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- H/W Development/Exp. Preparation & Execution/Analysis
- On-orbit Experiments
- Development Completion Review
- Science Review
- Project Completion Review

*The future project schedule is current plan and subject to change.*
Comparison of the materials flammability thresholds by three different methods

**ISO/TC61/SC4**

**LOI based method**
(ISO 4589-4 (1G test) + \(\alpha\) (theory))

- OI, HOI (experimental)
- OI\(_{mg}\) (theoretical)

**Experimental Results on Flammable Limits in \(\mu G\) (Parabolic flight & ISS tests)**

**NASA-STD-6001B**
(ISO 14624, ISO/TS 16697)

- ULOI, MOC (experimental)

**Comparison, inter-relation**

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Scale analysis of flame spread with opposed flow

\[ V_r = V_f + V_g \sim V_g \]

\[ V_{g,\text{eff}} \sim \frac{V_g}{\text{Pr Re}_{x}^{1/2}} \]

Heat balance with including radiative heat loss and finite kinetic effect

\[ V_f \rho_s c_s L_{sy} W (T_v - T_\infty) + \varepsilon (1 - \alpha_{abs}) \sigma (T_v^4 - T_\infty^4) L_g W \sim \left( 1 - \frac{1}{Da} \right) \lambda_g \frac{(T_f - T_v)}{L_{gy}} L_g x W \]

\[ \eta + R_{\text{rad}} + \frac{1}{Da} = 1 \]

where \( \eta \equiv \frac{V_f}{V_{f,\text{th}}} \)

\[ R_{\text{rad}} = B_2 \cdot \frac{\varepsilon (1 - \alpha_{abs}) \sigma (T_v^4 - T_\infty^4)}{\rho_g c_g V_r (T_f - T_v)} \]

\( B_1 \) and \( B_2 \) is constant

Opposed flow velocity: low

\( Da \sim \frac{\alpha_g}{V_r^2} \rho_g Y_o A \exp(-E / RT_f) \)

Opposed flow velocity: high

Applying BL model

\( \frac{\alpha_g}{V_r} \rho_g Y_o A \exp(-E / RT_f) \)

Estimation of MLOC from ground tests

1. Measure the LOC$_{1g}$ of the downward spread. (similar to ISO4589-2)
2. Measure the LOC at a certain high opposed velocity, ex. Vg=80cm/s (Blow-off test as ISO4589-4)
3. Draw blow-off limiting line. (Empirical A and E for blow-off are obtained.)
4. Draw radiative extinction line with Tv and other gas properties.
5. Draw the limiting line on which $\eta + R_{rad} + 1/Da = 1$.

\[ Da = B_1 \cdot \frac{\alpha_g}{V_r^2} \rho_g Y_o A \exp(-E/RT_f) \]
\[ R_{rad} = B_2 \cdot \frac{\varepsilon(1-a_{abs})\sigma(T_v^4-T_\infty^4)}{\rho_g c_v V_r (T_f-T_v)} \]

Test Apparatus to Measure HOI

HOI test apparatus.

Contracted flow nozzle.

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Parabolic Flights in the Project

In Japan (operated by Diamond Air Service Inc., in Nagoya)

Gulfstream-II (G-II) (https://www.das.co.jp/)
MU-300 (https://www.das.co.jp/)

In France (operated by Nova Space Inc., in Bordeaux), under support by CNES

A-310 (http://www.novespace.fr/)
**Noble Ability of the New Method**

The new method enables us to predict the materials flammability in microgravity environment:

- The predicted results have good quantitative agreements with the results by the parabolic flight experiments.
- It is possible to predict MLOC as well as $V_{cr}$, where MLOC occurs.

We can predict the material is more flammable in microgravity, or not. Also, increase of the materials selection for space use would be possible with reasonable rationale.

Results of the Parabolic Flight Experiments (Flat Samples)

Flammability map of various materials.

- a) NOMEX HT90-40 (meta-aramid fabric: DuPont, t=0.3mm)
- b) Kevlar KE5847 (para-aramid fabric: DuPont, t=0.35mm)
- c) Kapton 500H (polyimide film: DuPont, t=0.125mm)
- d) CARBOGLASS C110C (polycarbonate: Asahi Glass, t=0.25mm)


Set-up and some results on the wire samples by the parabolic flight experiments in France.

Typical frame showing the shape of the flame spreading in a concurrent flow (velocity: 150 mm/s; O₂ concentration: 18%).

Frames showing the evolution of the visible flame shape for increasing concurrent flow velocity.

Frames with backlighting on (NiCr core wire; concurrent flow velocity: 150 mm/s; O₂ concentration: 18%).

NiCr core wire
Cu core wire

Results of the parabolic flight experiments (LDPE Insulated Wire Samples)
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### Overview of the ISS Experiments

- Flame spread experiments are performed in **both opposed and concurrent flow conditions** to explore the lower LOC.
- Both flat samples and wire/rod samples are burned in the ISS experiments.

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<th>Exp. No.</th>
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<th>Test Samples</th>
<th>Experiment Outline</th>
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<td>1-1</td>
<td>S. Takahashi (Gifu Univ.)</td>
<td>PMMA sheet &amp; plate</td>
<td>Flame spread experiment to find the extinction limit (inc. <strong>sample thickness</strong> effect)</td>
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<td>1-2</td>
<td>H. Torikai (Hirosaki Univ.)</td>
<td>Filter paper sheet</td>
<td>Flame spread experiment to find the extinction limit (inc. <strong>sample width</strong> effect)</td>
</tr>
<tr>
<td>1-3</td>
<td>S. L. Olson (NASA GRC)</td>
<td>Cotton fabric sheet</td>
<td>Flame spread experiment to find the extinction limit</td>
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<tr>
<td>1-4</td>
<td>S. Takahashi (Gifu Univ.)</td>
<td>NOMEX® sheet</td>
<td>Flame spread experiment to find the extinction limit</td>
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<tr>
<td>2-1</td>
<td>C. Fernandez-Pello (UC Berkeley)</td>
<td>Polyethylene insulated wire &amp; rod</td>
<td>Flame spread experiment to find the extinction limit</td>
</tr>
<tr>
<td>2-2</td>
<td>O. Fujita/ G. Legros (Hokkaido Univ./UPMC)</td>
<td>Polyethylene &amp; ETFE insulated wire</td>
<td>Flame spread experiment to find the extinction limit (inc. the effects of <strong>diameter, core wire material, and pressure</strong>)</td>
</tr>
<tr>
<td>3-1</td>
<td>O. Fujita (Hokkaido Univ.)</td>
<td>Polyethylene insulated wire</td>
<td>Self-ignition experiment of wire to find the ignition limit by excess electric current</td>
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Schematics of the experimental apparatus for the experiments onboard the ISS/Kibo※.
Overview of SCEM

Schematics of the Solid Combustion Experiment Module (SCEM)※.
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Summary

• To clarify gravity impact on materials flammability, and to establish new international standard on the evaluation method of materials flammability in space, JAXA promotes “FLARE” project with international partners, as the Strategic Research in “Kibo”.

• In the new method, it is possible to predict the OI_{mg} (MLOC) of the materials in microgravity, based on 1G test data.

• Development and preliminary verification of the OI_{mg} prediction model have been performed by using the parabolic flight experiments.

• Also, development of ISO 4589-4, as the international standard to define test apparatus and test method to measure HOI, is on-going at ISO/TC61/SC4.

• The Solid Combustion Experiment Module (SCEM) is developed and employed for the on-orbit combustion experiments on the ISS/Kibo.