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Impact of adopting reduced pressure and oxygen concentration on material flammability: limitations and safety implications

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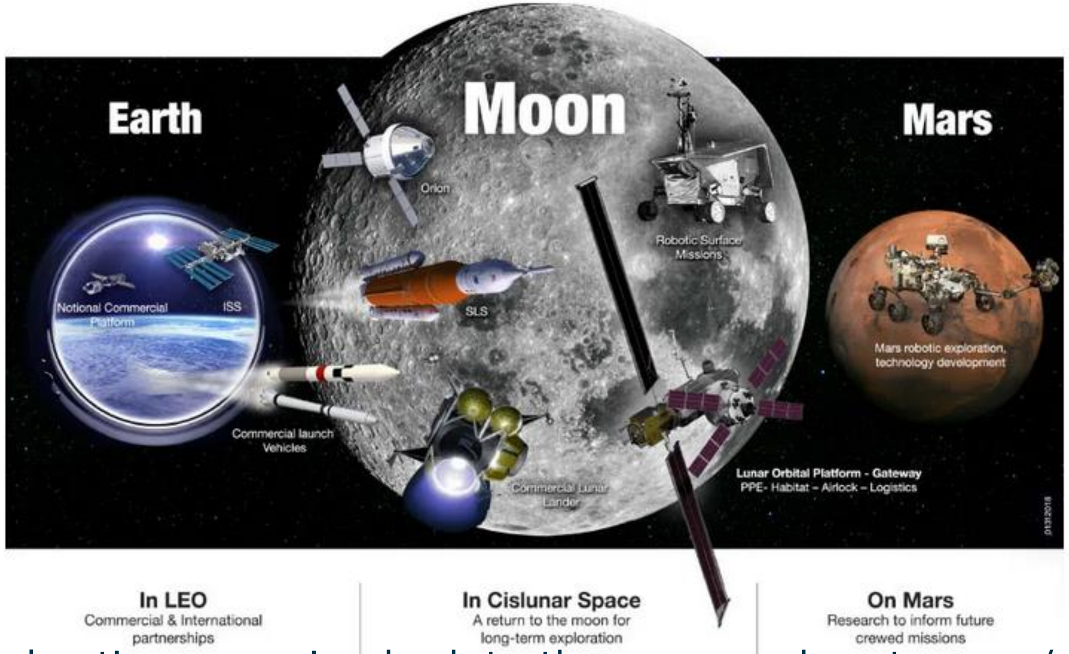
Manned space exploration: Moon To Mars

Materials used for Human Spaceflight spacecrafts must withstand a number of challenging environments and corresponding requirements. Not only the materials should be performing reliably but also not posing hazard concerns for the spacecraft infrastructure and the crew members.

On this regard **materials flammability behavior** receives a high level of attention during mission development and non-flammable materials are selected as part of flammability hazard control.

Human exploration missions in the near future, with Gateway or at the lunar surface, will expose the materials to higher oxygen concentrations than typically found on ISS. Such scenario requires that **flammability testing** is carried out in order to demonstrate suitability under the new mission environments.



https://science.nasa.gov/solar-system/moon/nasas-exploration-campaign-back-to-the-moon-and-on-to-mars/

TRAGICAL FIRST LESSON LEARNED ABOUT FLAMMABILITY

APOLLO 1

During a ground test, an electrical spark ignited a fire, flames and smoke swept through the capsule, and the crew was unable to escape. An investigation later was unable to pinpoint the exact initiation spot of the fire, but determined that the plethora of flammable materials (especially Velcro) and pure oxygen environment inside the capsule were partly to blame.

"*Materials exposed to pure oxygen are just looking for an excuse to burn*." Bill Johns, chief engineer at Lockheed Martin for the Orion capsule.

CAUSE

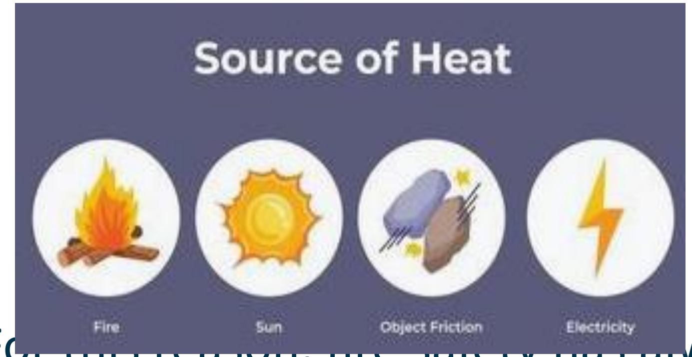
- 100-percent oxygen environment of the capsule;
- Flammable materials;
- hatch opening procedures too difficult and too long. In addition, the inward-opening hatch impossible to open under any pressure higher than normal atmospheric pressure — and the fire had boosted the cabin pressure significantly.

EFFECT

- redesigned Apollo to fly with a mix of about 34 percent oxygen in its pressurized modules (including making the spacecraft's walls significantly thicker to handle the increased pressure);
- reduced the amount of flammable and tested many of the capsule's materials for flammability;
- changed Apollo's hatch to an outward-opening design, and that same choice persists today in Orion.

Although they are relatively rare events, fires have occurred in space vehicles and habitats and may occur again.

But fire, as we know, needs three things (and in space missions all three are in spades):



For this reason, fire safety has always been critical to any human exploration of space, because fires can have devastating consequences, including:

- loss of life,
- loss of vehicle or habitat integrity,
- mission failure.

For space exploration, fire safety is based on the principles of fire risk prevention, detection and suppression.

FIRE prevention 1/2

Since the tragic fire in Apollo 1 has been the qualification of materials used in space vehicles and proposed habitats: fundamental requirement is for overall system to be safe from a FLAMMABILITY STANDPOINT

SOME FLAMMABILITY REQUIREMENTs:

1) Acceptable materials/configuration under higher oxygen concentrations are mostly considered acceptable for lower oxygen concentrations

2) Test and evaluation shall be considered in the WORST CASE: most hazardous pressure, temperature, material thickness, and fluid exposure conditions

3) Qualification test shall be based on NASA Standard 6001 / ECSS-Q-ST-70-21, which uses an upward flame spread test in 1 g as a screening test for materials flammability

4) Materials shown to meet the acceptance criteria of the required test(s) are acceptable for further consideration in design

5) Systems containing materials that have not been tested or do not meet the criteria of the required test(s) must be verified acceptable in the use configuration by analysis or testing. In absence of evidence, the material shall be considered FLAMMABLE.

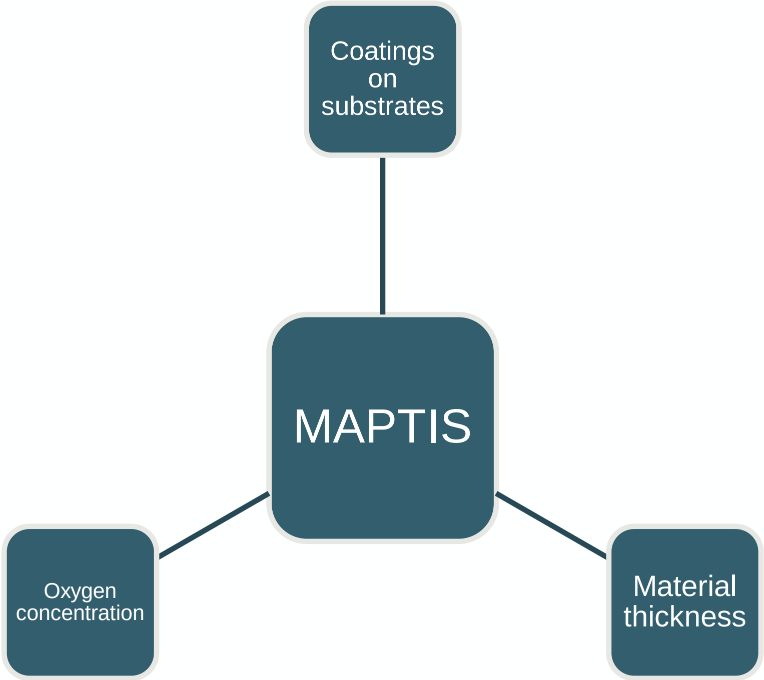
6) Nonflammable is a material that self-extinguishes within 6” when ignited and does not propagate a flame by transfer of burning debris (for at least 5 standard sized samples)

7) An acceptable alternative to flammability testing is to assume material is flammable and demonstrate by analysis that the material configuration cannot propagate fire (e.g. for COTS hardware and electronic equipment) or to propose Configurational test

FIRE prevention 2/2

FLAMMABILITY CONTROLS:

Flammability characteristics of materials evaluated consulting the NASA/MSFC Materials and Processes Technical Information System (MAPTIS) at http://map1.msfc.nasa.gov/WWW_Root/html/page7.html;



- Minimize use of flammable material;
- Eliminate or restrict propagation paths;
- Isolate flammable materials from ignition sources or eliminate ignition sources

Data requirement submittals:

- Materials and Processes Selection, Control, and Implementation Plan
- Materials Usage Agreements (MUAs).
- Materials Identification and Usage List (MIUL).

MAPTIS is the most accredited material assessment tool, continuously updated based on oxygen percentages and required pressure.

FIRE detection

TECHNOLOGIES FOR FIRE DETECTION:

- ionization technology in Space Shuttle;
- photoelectric detection technology based on the belief that smoke particles in low-gravity environments would be large (>1 µm) for ISS.

Where there are particles, there is smoke, and where there is smoke, there is fire: this assumption is wrong.

Particles generated from many other sources that are free to float about in a microgravity environment have the potential to generate false alarms from such smoke detectors.
In addition, sizes from smoldering materials may actually be too small (<0.3 µm) to be detected by photoelectric smoke detectors.

RECOMMENDED IMPLEMENTATIONs:
- Combination of detection sensors (e.g. several fire signature sensors in addition to the smoke particle detector for faster and more reliable response);
- Evaluation by computer-based fire models to integrate sensor data;
- Crew training to manage any hazard.

FIRE suppression

Lack of qualified testing leaves room for many questions:

- Do gravity tests remain reliable in micro-partial gravity?
- Is the extinction time the same with different atmospheres/relevant gravities?
- Which agent is better?

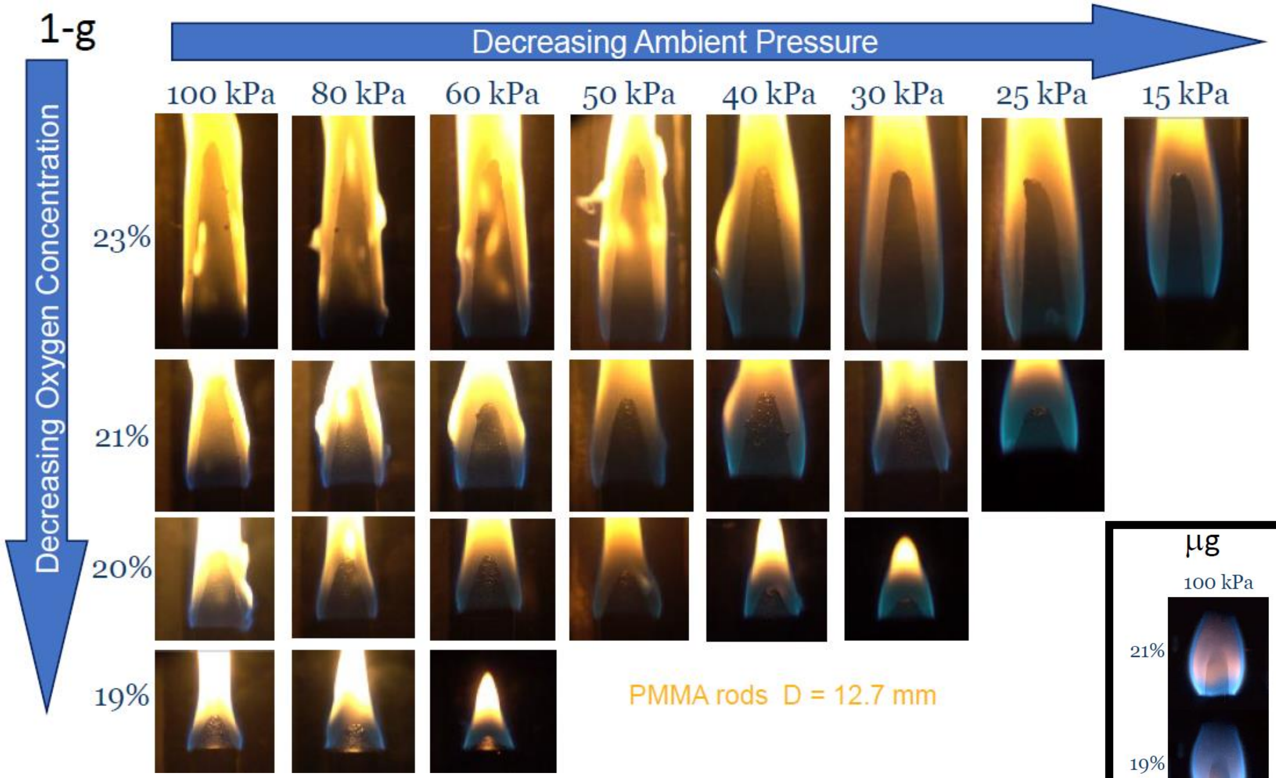
AGENTS CURRENTLY USED:

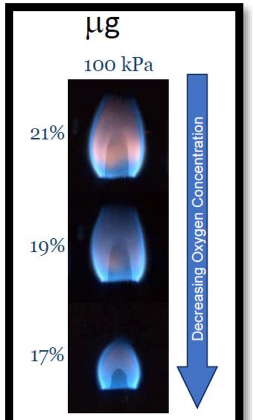
- NASA currently relies on CO_2 for the ISS and/or water mist for Columbus (water mist might be effective in various gravities, but it is necessary to specify their impact on droplet size, size distribution, and injection method)
- halon for the Space Shuttle;

Note: Fire does not equal Explosion.

High O_2 environments and reduced gravity affect flammability limits; therefore, materials such as various types of hydrocarbon liquids (e.g., oils and greases) and some metals can become explosive.

WHAT HAPPENS?



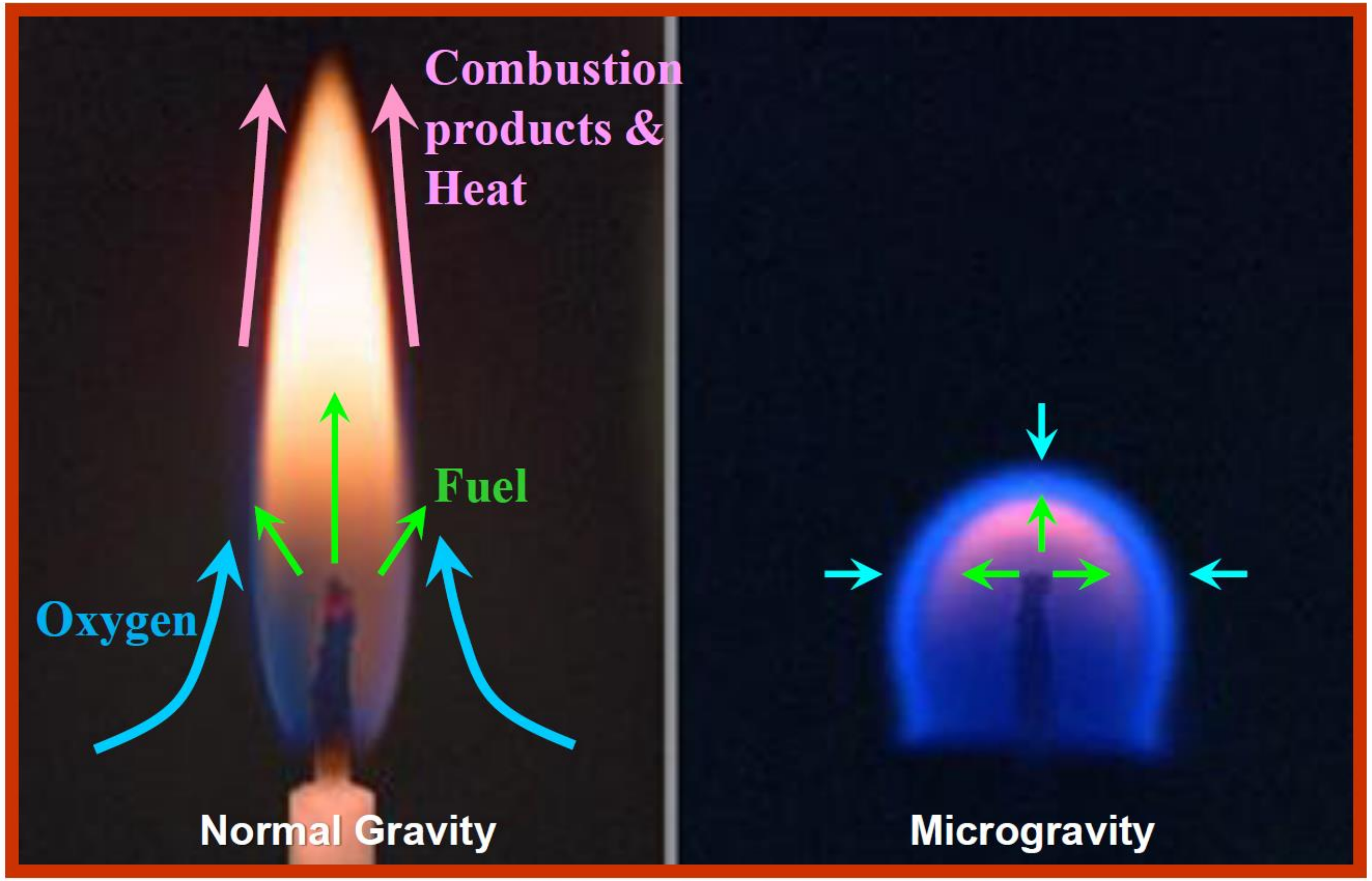


Micro-g images obtained from the Microgravity Science Glovebox on ISS

Impact of Lunar Gravity on Material Flammability
Gary A. Ruff
Spacecraft Fire Safety Demonstration Project Manager
NASA John H. Glenn Research Center
Cleveland, Ohio

- Increasing the oxygen concentration dominates the effect of reducing pressure
- The microgravity flame is weaker but can still propagate and at lower $\%O_2$ than in 1-g

WHAT HAPPENS?



Comparison of Candle Flame in Normal Gravity and in Microgravity.
(https://www.nasa.gov/audience/foreducators/microgravity/multimedia/me-candleFlame.html)

1. Extension of flammability region in microgravity is not considered.

Conservative results are not always guaranteed.

2. NASA-STD-6001 is only “pass” or “fail” criteria of the material in the environment exposed in the tests.

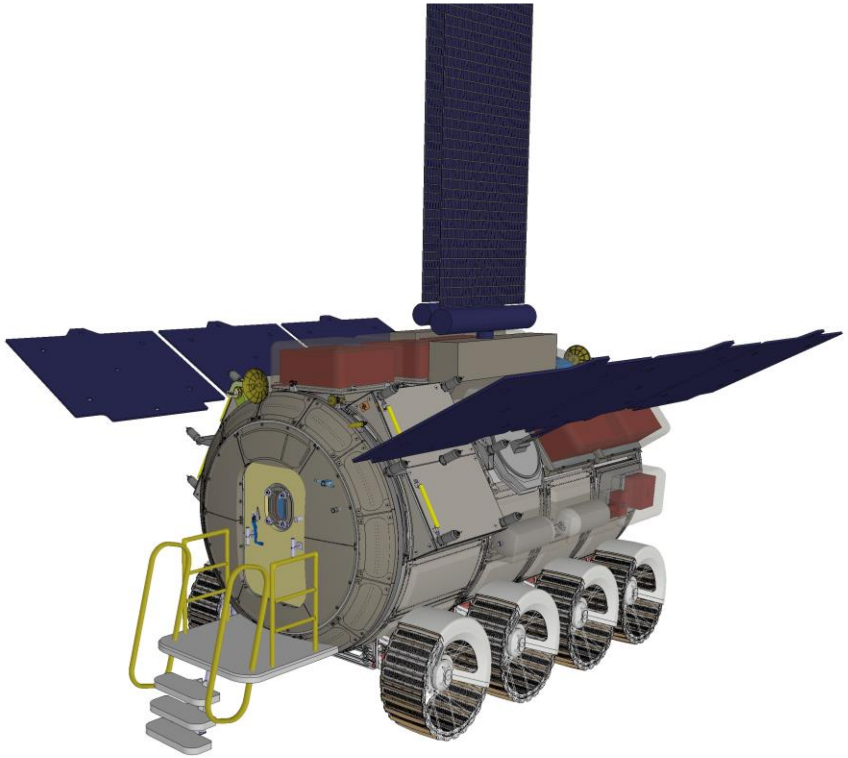
If environmental conditions (e.g. oxygen concentration) are changed, the tests shall be performed again: MAPTIS update.

Current Status of the Investigation on Materials Flammability under Microgravity in “FLARE” Project
Masao Kikuchi, Tomoyuki Nukui, Yasuyuki Hanaki, Takuma Suzuki, Yuji Kan, Tetsuya Sakashita, Yasuhiro Nakamura (JAXA)
Osamu Fujita (Hokkaido Univ.)

Multi Purpose Habitat (MPH)

The Italian Space Agency, in collaboration with NASA and Thales Alenia Space, is taking steps to establish a permanent base on the Moon as part of its **Artemis** mission.

The **Multi-Purpose Habitation Module (MPH)** is being developed to support long-term human presence on the moon, allowing astronauts to conduct scientific experiments, test new technologies, and explore potential risks.



The concept showed in renders includes :

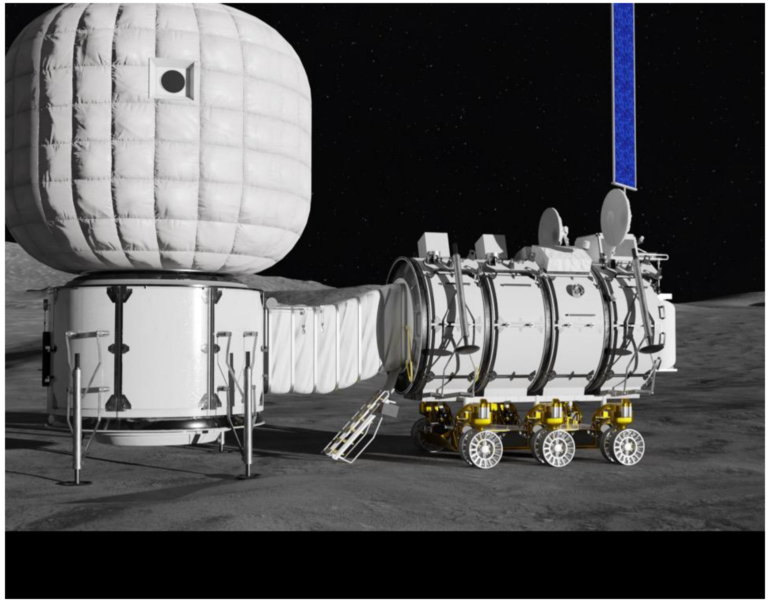
- a metallic cylinder
- on integrated mobility
- solar panels,
- radiators
- an extended airlock.

When the MPH is operational, it will protect its inhabitants from intense cosmic radiation and extreme temperatures on the lunar surface. Additionally, the MPH will have a life support system that can provide air, water, and stable, livable temperatures for beyond a few days.

MPH Challenging scenario

While the human need for oxygen depends on the partial pressure of oxygen, ignition and fire spread on materials depend on the absolute concentration of oxygen. So, MPH Program is investigating possible alternative atmospheres to reduce flammability risks concerns but allow increased EVA pre-breathe times.

At the moment, design requirements for MPH moves to environments with higher concentrations of oxygen and this could be in conflict with the current understanding of fire behavior in these atmospheres.



CURRENT BASELINE	
PRESSURE	**%O2**
8.2 psi	34%

Flammability testing ongoing (trade-off)

- For 37% O2 and the gap area between 30% to 37%
- 1/6g characterization

Available test equipment in TAS-I TURIN: FIAMMA facility

In the frame of a joint activity with ESA, Thales Alenia Space Italy – Turin conceived a high-volume flammability chamber **FIAMMA** (Flammability facility for Future HuMan Missions SpAceflight) with tunable oxygen concentration and total pressure.

The FIAMMA facility is connected to vacuum pumps with air, oxygen, and nitrogen supplies able to perform standard and R&D tests **in quiescent environments**, for the understanding of flammability material behavior up to **50% oxygen** concentration.

Furthermore the facility total pressure range from 0.7 bar to 2.0 bar . **Lower pressure and higher content in O_2** can be **achieved** if requested by implementing dedicated set-up.

Different **ignition** sources, **electrical and chemical**, can be also used.

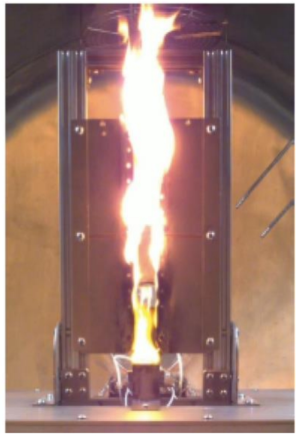
FIAMMA facility

FIAMMA is equipped by 4 windows and a video system to observe and recording burning behavior of flame. Two video cameras for front and back view has been designed to be integrated on the flammability chamber and, if needed, a third video camera for side view is also available. The versatile sample holder allow to execute test **in not-standard conditions** and videorecorders system are used to evaluate the flame behaviors.

Available test equipment in TAS-I TURIN: FIAMMA facility

The FIAMMA facility, apart from testing at materials level, is the only facility in Europe which can perform flammability testing at component level e.g as COTS (commercial-off-the-shelf), following the configurational test according to the ECSS-Q-ST-70-21 flammability standard.

The FIAMMA chamber is adaptable to various flammability test methods, not only capable of performing the Upward Propagation Test (**UPT**) and the Maximum oxygen concentration (**MOC**) tests, but is also capable of performing the Upward limiting oxygen index test (**ULOI**)

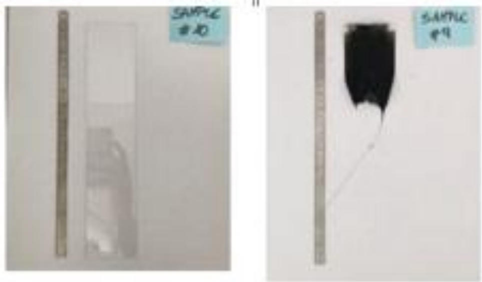


Configurational test : Action camera pre (L) and after test (R)

The definition is hereafter reported :

- Upward limiting oxygen index ULOI : oxygen concentration where approximately 50 % of samples fail the test

- Maximum oxygen concentration MOC: highest oxygen concentration where all samples tested (at least five) pass the test



O X

Usually more then 15 samples have to be tested to obtain ULOI values

FIAMMA facility capability

FIAMMA facility key figures

Chamber volume	Appx. 1500 L
Maximum operating pressure	2 bar
Minimum operating pressure	0,70 bar(*) (*) 0,5 bar if requested
Inlet ports	2 (one for pure oxygen and one for pure nitrogen)
Oxygen concentration	Tunable from 0% to 50%
Oxygen analyzer accuracy	0,5%
Viewports	4
Video recording system	2 video cameras for front and back views, and 1 for side view.

<u>Tested materials:</u> Film (PC; FEP; PMMA), sheet (PC), foam (PEI/PU/PP),
textile (Aramidic/paramidic), adhesive (epoxy..), COTS (Monitor, camera, air diffusion)

UPT facts

Tests	ULOI and MOC according to ISO/TS 16697:2012; Upward propagation test (UPT) according to ECSS-Q-ST-70-21 and ISO 14624-1
Sample dimensions	5 samples per material are tested Each sample must be in the form of rectangles 300 mm x 64 mm
Test conditions	For UPT test pressure and atmosphere condition will be the most hazardous atmosphere in the spacecraft. Ignition source standard : chemical ignition by use of a chemical igniter
Acceptance conditions	Materials shall be classified non-combustible, or self-extinguishing if the burn length is less than 150 mm and the time of burning doesn't exceed 10 minutes

Configurational test facts

Test lifecycle	20 days as test life cycle including test preparation, test plan, setup, and execution, after receiving the "questionnaire for flammability" from Customer.
COTS dimensions	The possibility to remove or adapt holder as needed doesn't pose limitation to sample size. In case of irregular shape, special holder are present
Test conditions	Test pressure and atmosphere conditions as the most hazardous atmosphere in the spacecraft. Ignition source standard: chemical ignition by use of a chemical igniter If requested, also hot wire technology is available

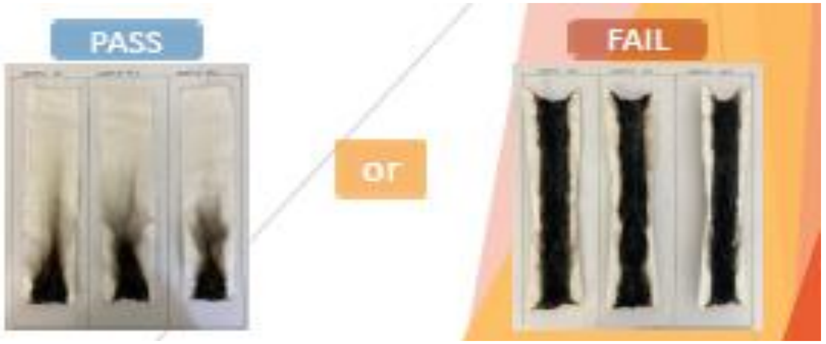
FIAMMA facility applications

An **UPT** test provide the following steps:

- Pre- conditioning of the samples: 24 hours before testing at 22 °C and 55% relative humidity
- Weight the sample and measure the thickness
- Evacuate the chamber and fill it with test atmosphere
- Start video recording
- Proceed with the test applying current to the ignition source
- Weight the sample post-test

Parameters taking into account to determine the test results:

- **Burn length:** distance from bottom of the specimen to the furthest evidence of damage to the test specimen due to flame impingement.
- **Burn propagation time:** time that elapses from ignition of the specimen until vertical flame propagation stops.
- **Weight loss:** confronting the pre-test mass and post-test mass of the samples.



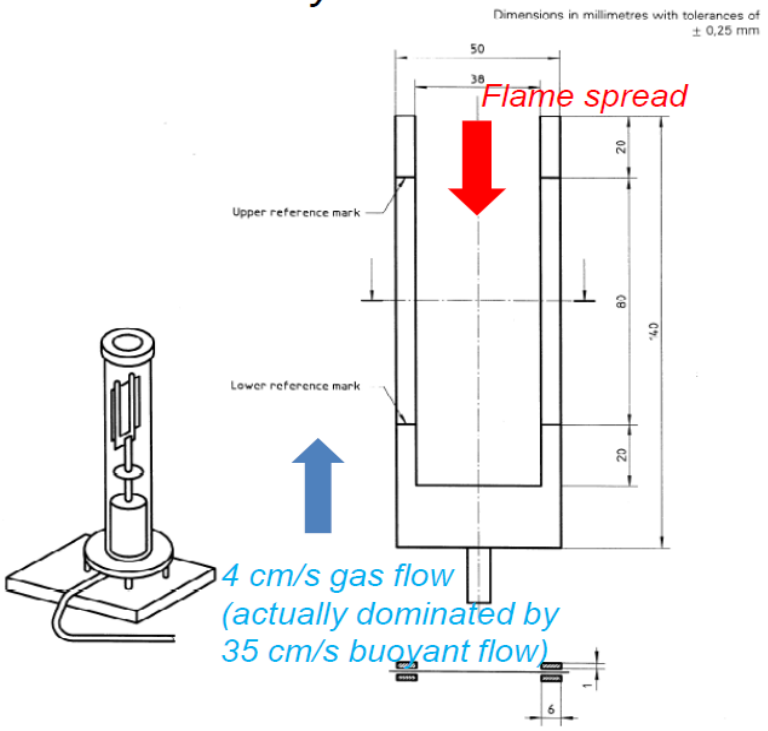
FIAMMA has been used for ESA projects Stefania/Cecilie, Cygnus tests

Waiting Micro-partial gravity studies (Jaxa)

Outline of the “FLARE” Project

- Objectives
  - Scientific understanding of the <u>gravity impact on materials flammability</u>.
  - Proposal of <u>new international standard</u> on evaluation of solid materials flammability in space for improvement of fire safety.

- Approach
  - <u>Establishment of methodology to predict ΔO2</u> of solid materials in microgravity, through 1G and microgravity experiments.
  - <u>LOI (Limiting Oxygen Index) method (ISO4589-2)</u> 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)※.

※Plastics-Determination of burning behavior by oxygen index- Part 2: Ambient temperature test, ISO 4589-2.

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Osamu Fujita (Hokkaido Univ.)

Future perspectives and research

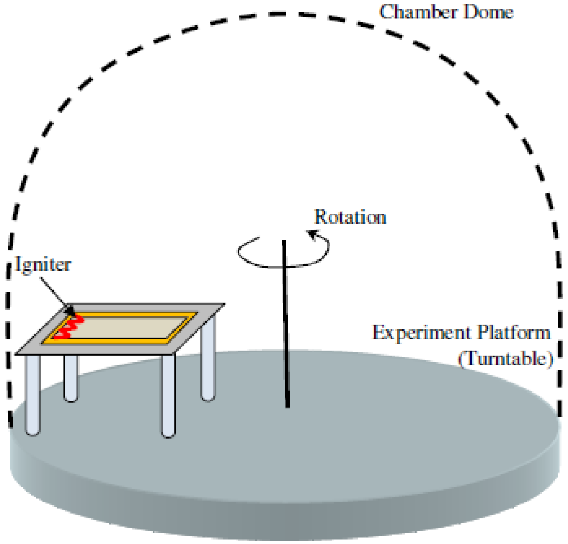
- Increase experimental data set on material flammability suitable for upcoming deep space exploration missions
- Progress of study to define testing opportunities in partial-gravity, extended duration, complex geometries/configurations, fire growth
- Design and validation of fire prevention, detection technologies/systems to the specific space vehicle/infrastructure
- The MPH module shall be designed to avoid flammability hazards to the crew, both during intra-vehicular and extravehicular activities, able to detect and act against the occurrence of accidental fires onboard. Upon the detection, the system shall initiate immediate actions to stop and extinguish the fire.

Back-up:

ADDITIONAL ATMOSPHERE STUDY (GRAVITY IMPACTS)

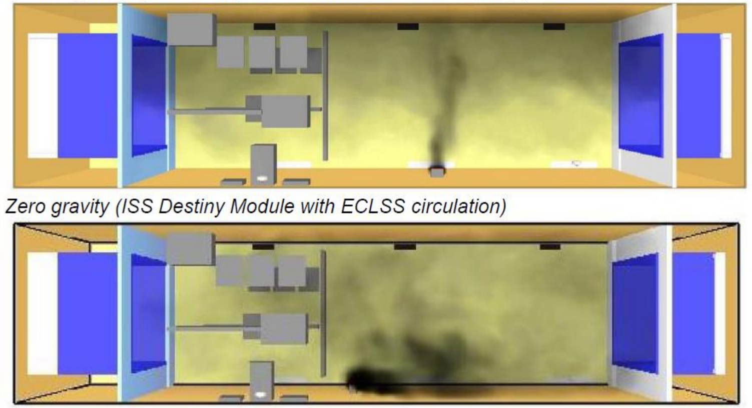
Waiting Micro-partial gravity studies (NASA)

Reduced Gravity Flammability Threshold Tests

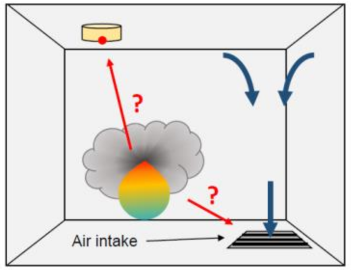


- Partial-g flames propagated at the normal-g MOC for all materials (charring and non-charring)
- Lunar-g MOC can be lower than either zero-or Martian-g levels
- Variation of MOC with gravity level is dependent on the material

Fire Detection in Zero-Gravity



Brooker, J.E., Urban, D.L. and Ruff, G.A. "ISS Destiny Laboratory Smoke Detection Model," Paper No. 2007-01-3076, 37th International Conference on Environmental Systems, Chicago, Illinois, July 9-12, 2007.



Partial gravity

Modeling has shown that in zero-g with forced convection, the spacecraft volume must reach the alarm level before an alarm will sound:
•Unless the smoke production rate is large
•If the smoke production rate is too low, smoke is scrubbed by air circulation before it can reach alarm levels

Impact of Lunar Gravity on Material Flammability Gary A. Ruff Spacecraft Fire Safety Demonstration Project Manager NASA John H. Glenn Research Center Cleveland, Ohio

THANK YOU FOR THE ATTENTION

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