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

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Zhuhai, China

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Osamu Fujita (Hokkaido Univ.)

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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.
⇨ different concept with fire on earth !!

◆ Fire detection and suppression play roles as the second and third defense lines.

Fire accident on the ground test in "Apollo 1" in 1967.

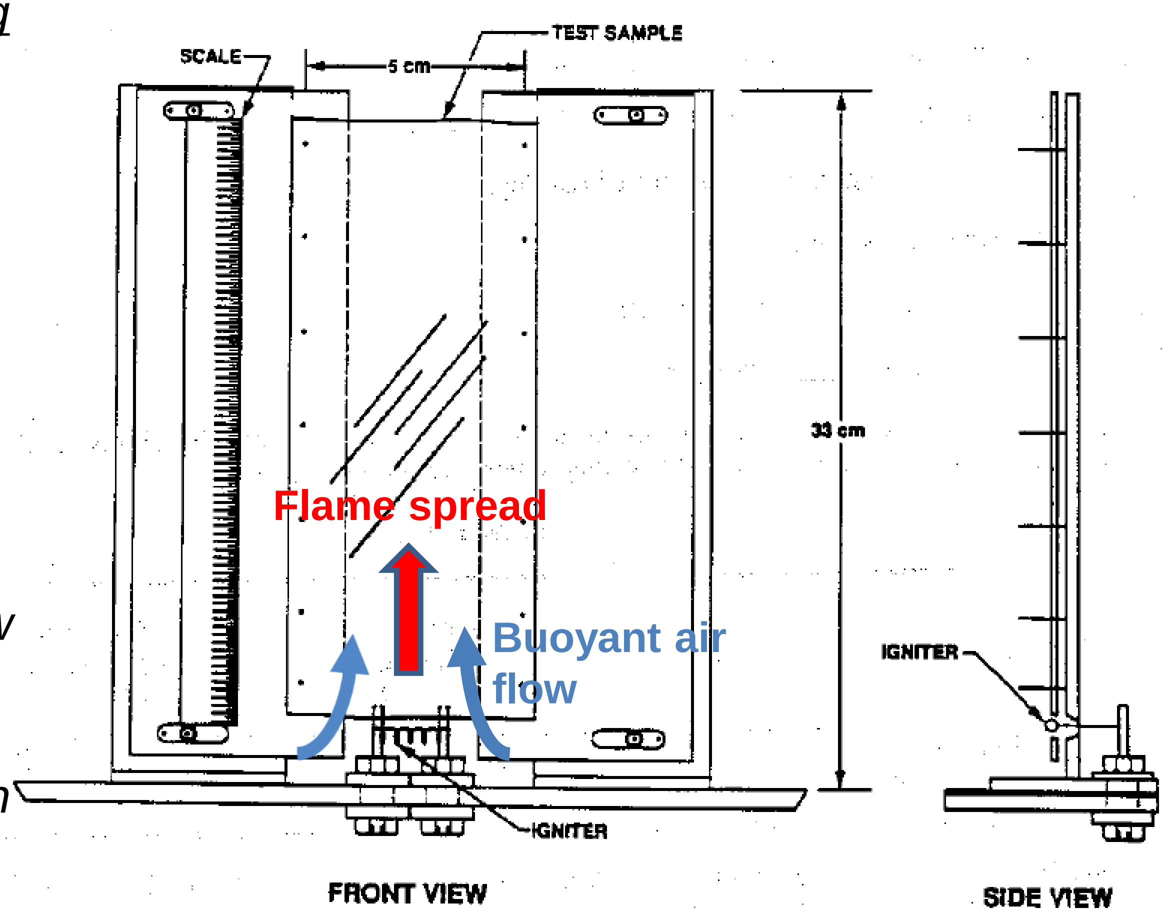
Oxygen candle fire in Russian space station "Mir" in 1997.

Materials Flammability Screening Test ~ NASA-STD-6001 ~

- *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.*

In fact, ….

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



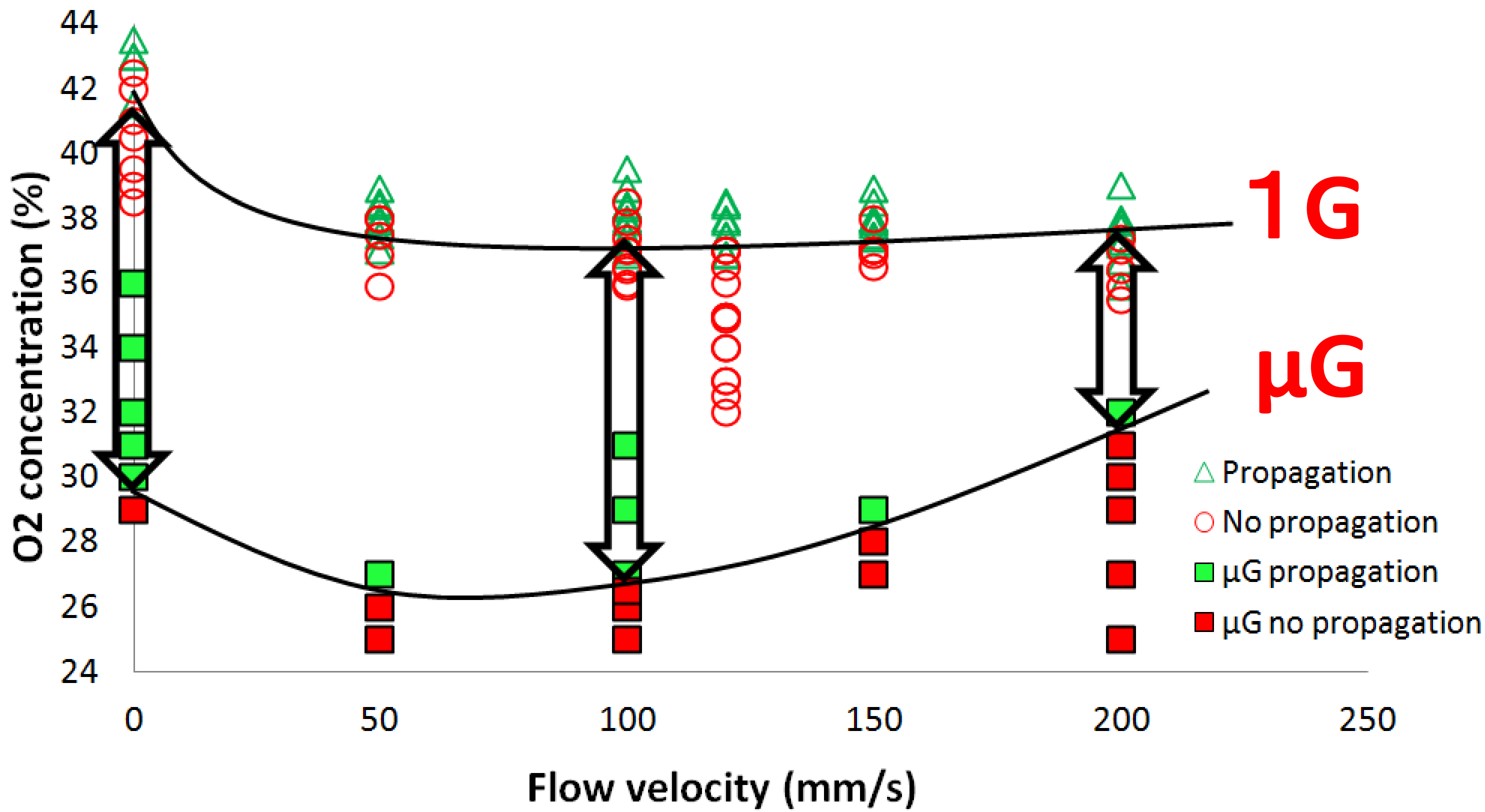
Sketch of NASA-STD-6001 Test 1, Upward Flammability Test※.

※ Flammability, offgassing, and compatibility requirements and test procedures, NASA-STD-6001B, NASA.

Extension of Materials Flammability in μG

- *The past investigations by many researchers revealed materials flammability could be enhanced in microgravity than that in normal gravity.*

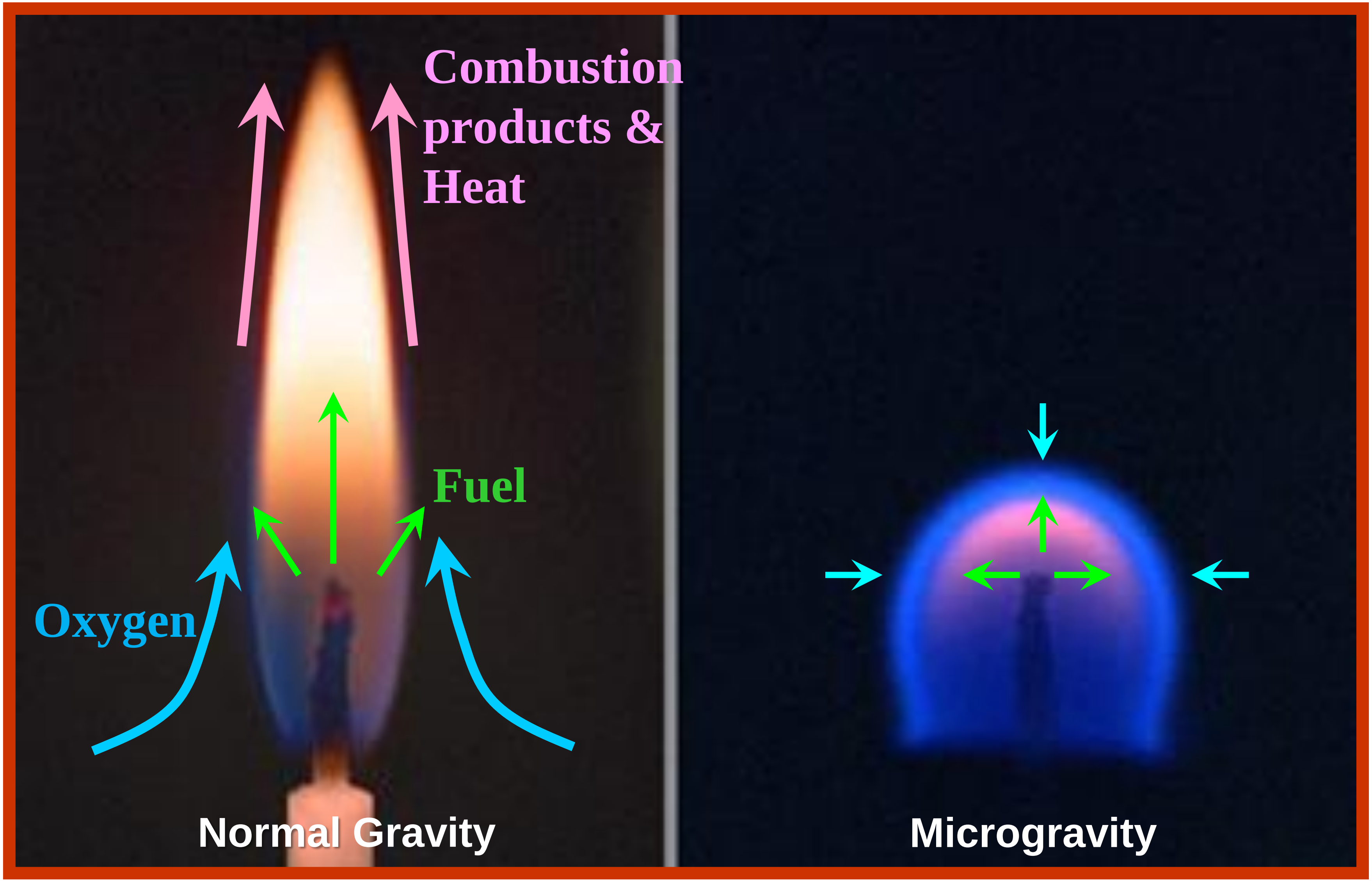
1G test results are not always conservative on materials flammability!



Extinction limit of ETFE insulated copper wire

1) A. Osorio, et al., *Proc. Combust. Inst., 35* (2015), 2683-2689.
2) K. Mizutani, et al., *Int. J. Microgravity Sci. Appl.*, 35 (1), 2018.

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)

Motivations of New Approach for Materials Flammability Evaluation

➢ ***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.*

▼

New Method on Materials Flammability Evaluation

Materials Flammability Evaluation in the Post ISS Era

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.

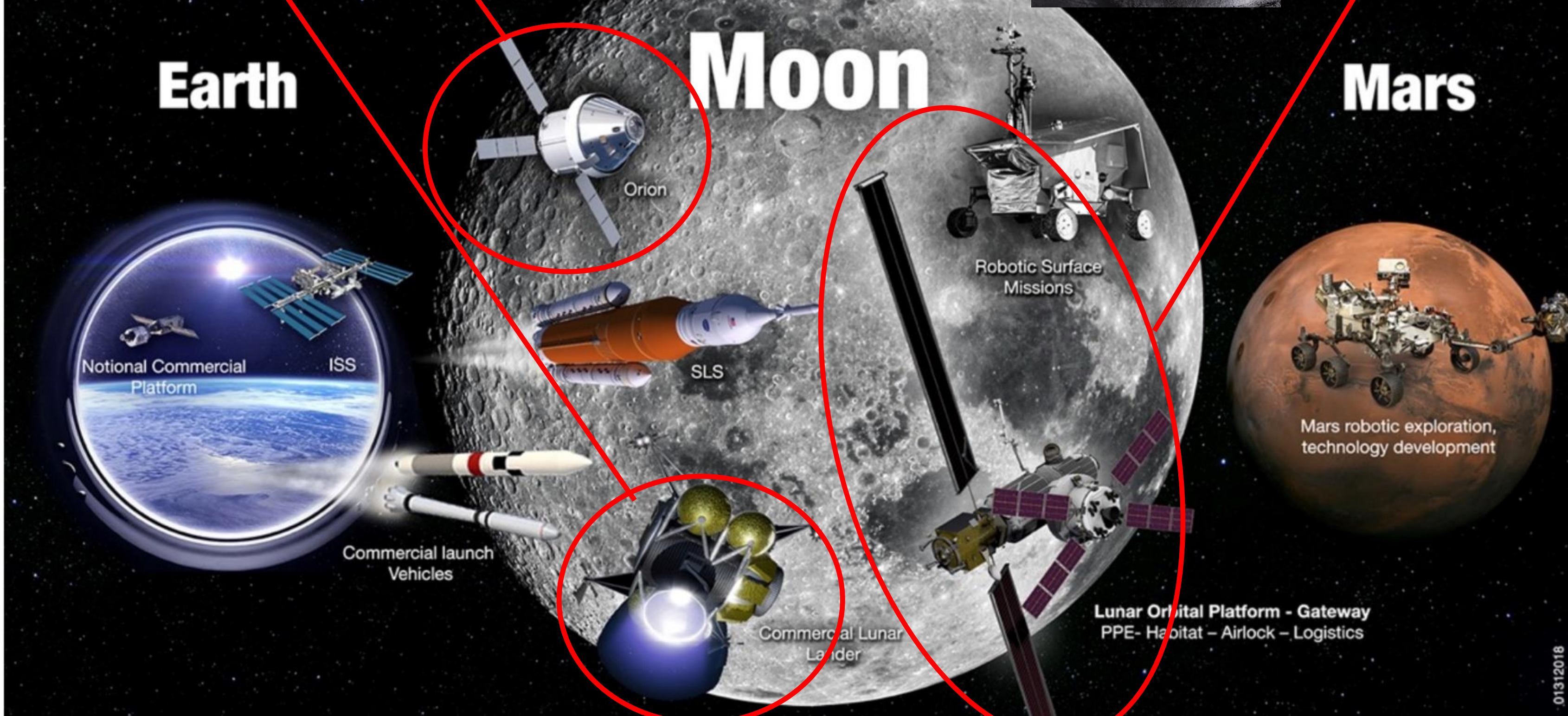
- Elevated oxygen concentration with lower ambient pressure is assumed in some system.
- Partial gravity environment shall be considered in the Lunar and Martian surface.

Lander to Moon/Mars

Orion space vehicle

Habitat module on the lunar surface

Deep Space Gateway around the Moon



https://www.nasa.gov/feature/nasas-exploration-campaign-back-to-the-moon-and-on-to-mars

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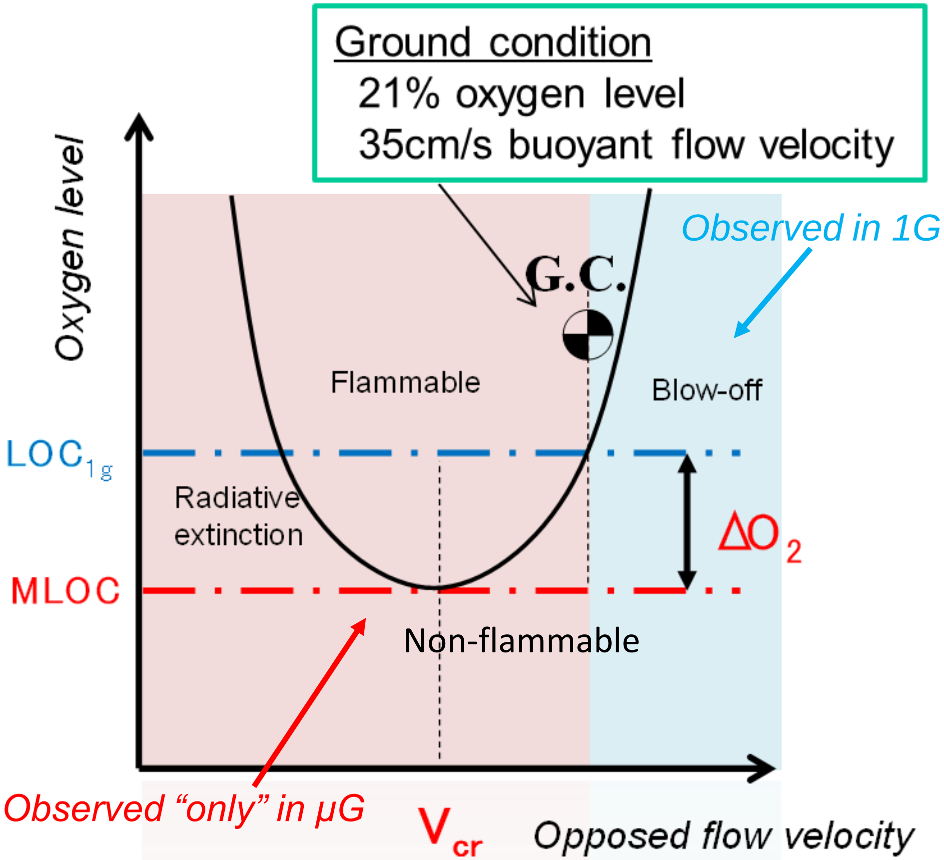
Fundamentals on Extinction Boundary of Solid Materials



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

2 different mechanisms for extinction!!

Flow velocity		
High	⇨	**Blow-off**
Low	⇨	**Radiative extinction**

LOC_{1g}: Limiting oxygen concentration in normal gravity
MLOC: Minimum limiting oxygen concentration in microgravity
V_{cr}: The flow velocity where MLOC is observed

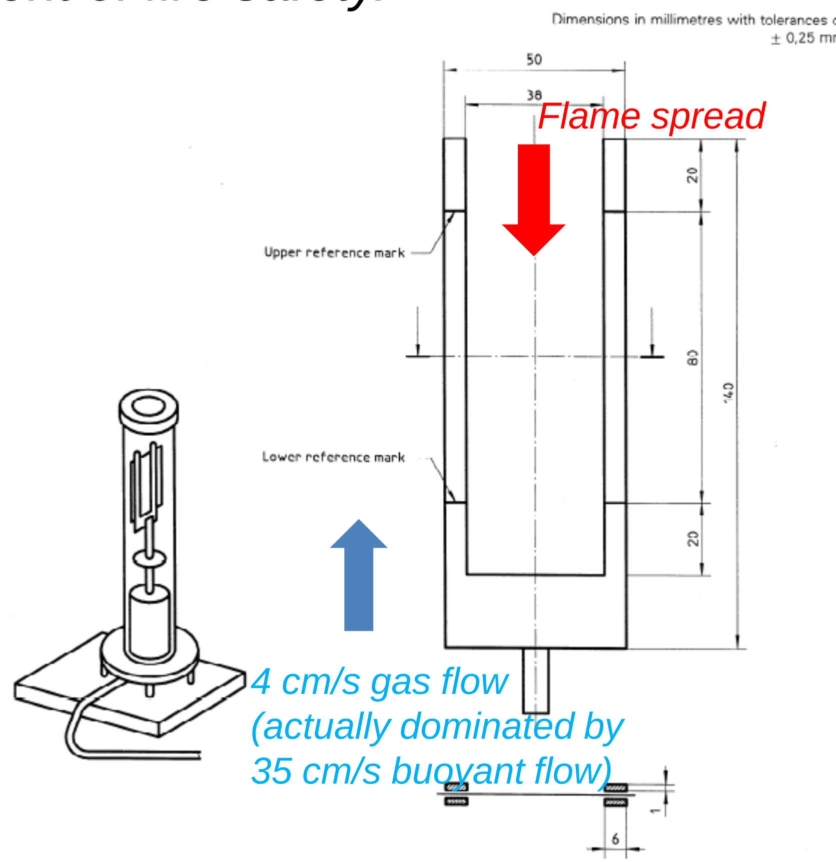
- The gap between LOC_{1g} and the minimum limiting oxygen concentration (MLOC), **ΔO_2, is an important value** to discuss the flammability of the material in reduced gravity environment.

Prediction of ΔO_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.*

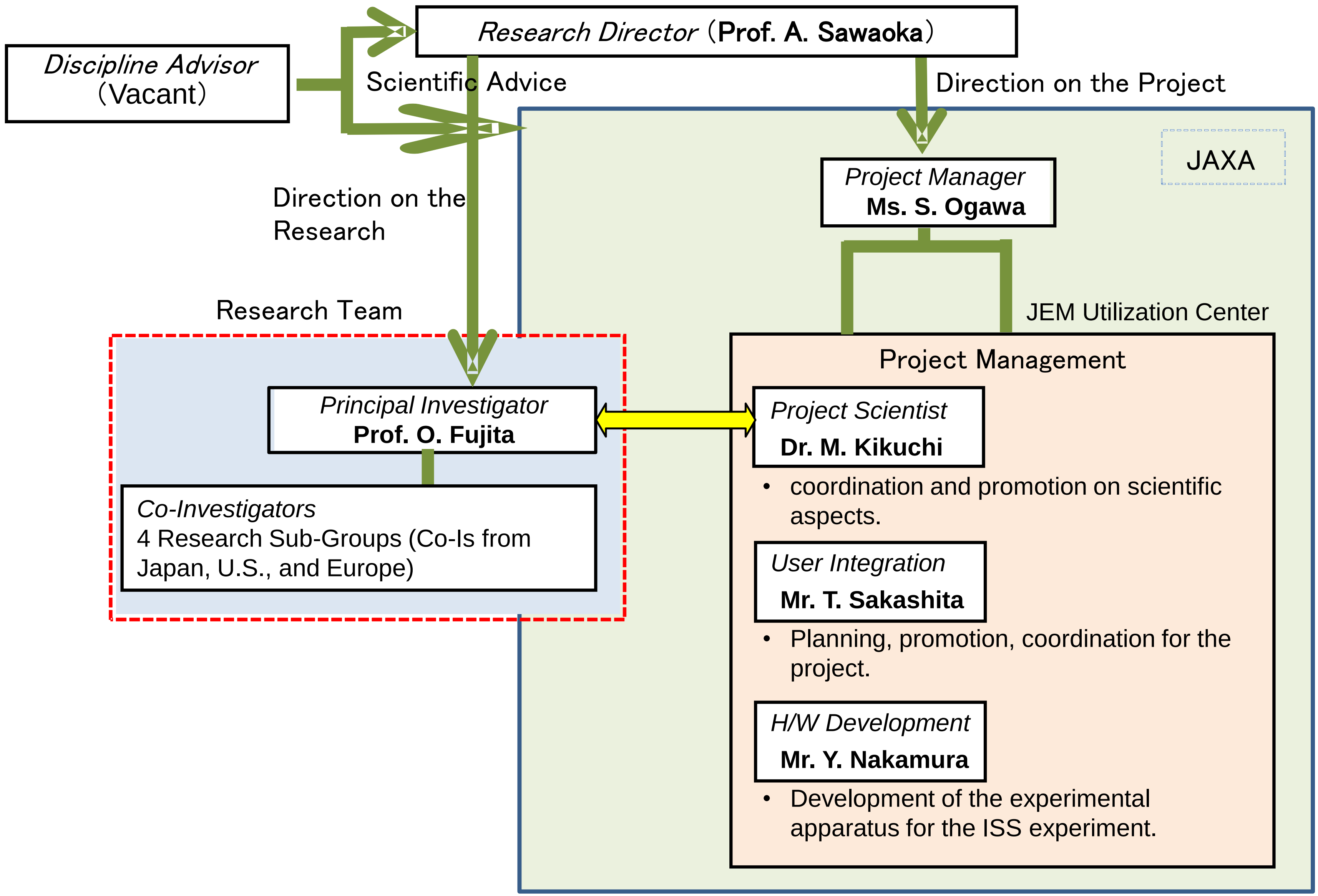
- *Approach*
  - *Establishment of methodology to predict ΔO2 of solid materials in microgravity, through 1G and microgravity experiments.*
  - *LOI (Limiting Oxygen Index) method (ISO4589-2) is utilized to predict MLOC, since LOI is commercially used in world-wide with high reliability as "eigen-value"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



ISO 4589-2 (LOI Method)※.

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

Research Promotion Structure



Research Sub-group 1&2

Research Sub-group	Investigator name（affiliation）	Role of each investigator
Group 1 **Flammability limit of flat sheet (ΔO2)**	**◎ Shuhei Takahashi (Gifu Univ.)** Yoshinari Kobayashi (Gifu Univ.)	Dominant parameter to control limiting condition in microgravity, Applicable thickness limit of Takahashi's model
	Hiroyuki Torikai (Hirosaki Univ.)	Charred material in microgravity,
	Yuji Nakamura（TUT）	Advise on discussion of the applicable thickness limit of Takahashi's model
	Sandra L. Olson（NASA GRC）	Flammability of fabric clothes material
	Christian Eigenbrod (Univ. Bremen)	Analysis of IR camera data from the parabolic flight experiments
Group 2 **Flammability of electric wire and cylindrical material**	**◎ Carlos Fernandez-Pello（UC Berkeley）**	External radiation effect on material flammability in cylindrical shape.
	Osamu Fujita (Hokkaido U.) Nozomu Hashimoto (Hokkaido U.)	Flammability limit of wire insulation in microgravity, Effect of core material and flow direction
	Guillaume Legros（Univ.Pierre-et-Marie Curie-Paris6）	Soot formation in microgravity flame and its radiation characteristics. Microgravity tests in CNES flight.

◎ Group leader

Research Sub-group 3

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

◎ **Group leader**

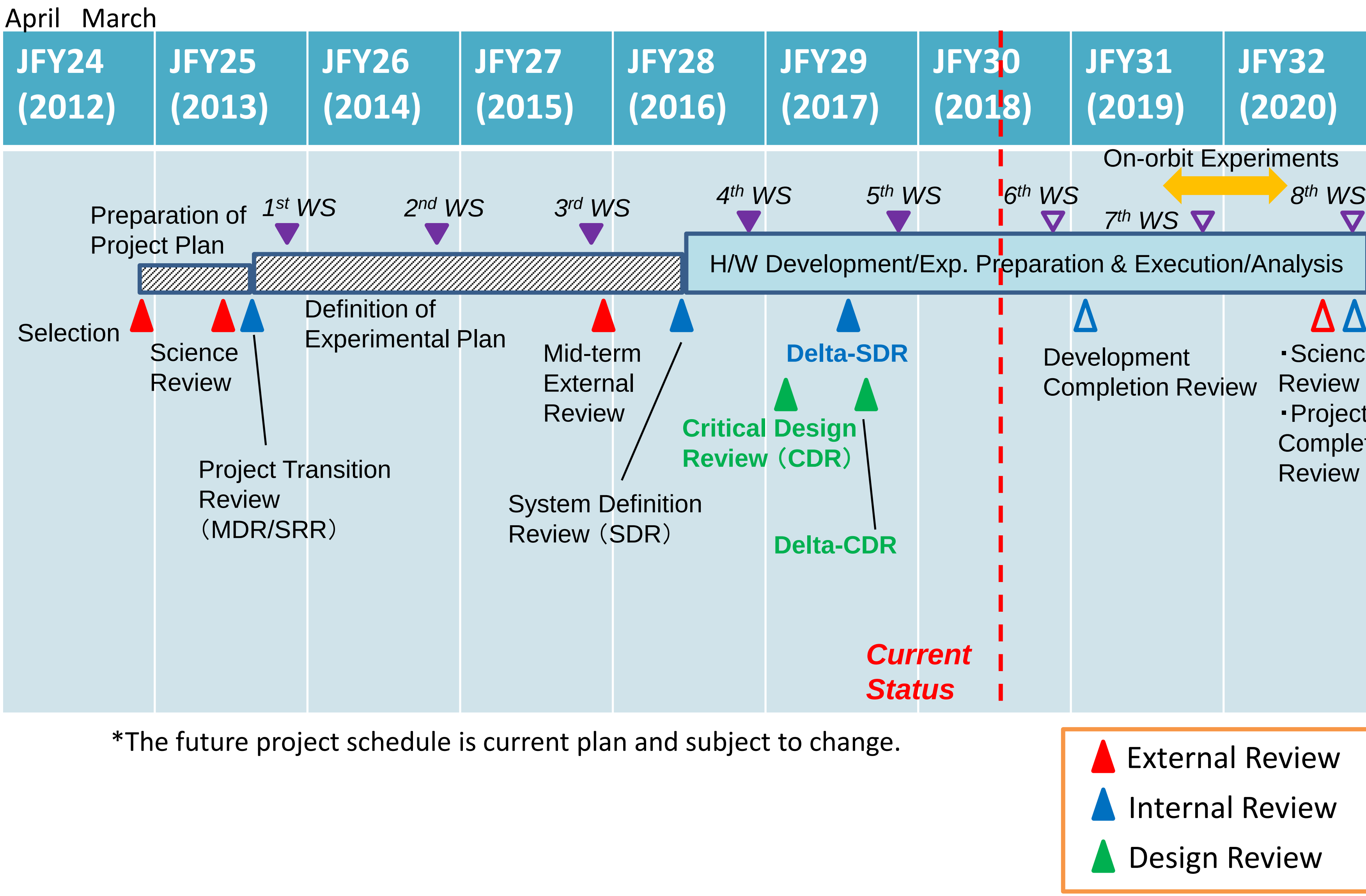
Research Sub-group 5

Research Sub-group	Investigator name (affiliation)	Role of each investigator
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.

◎ Group leader

Current Location in Whole Project Schedule



*The future project schedule is current plan and subject to change.

Group Photo at the FLARE Workshop

January 24, 2018, 5th FLARE International Workshop
@Tsukuba Space Center, Tsukuba, Japan

Comparison of the materials flammability thresholds by three different methods

ISO/TC61/SC4

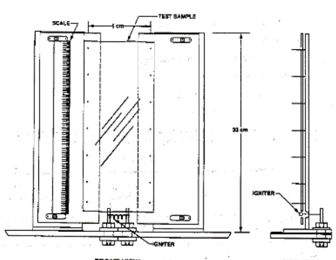
OI, HOI (experimental)
OI_mg (theoretical)

LOI based method
(ISO 4589-4 (1G test) + α (theory))

Experimental Results on Flammable Limits in µG (Parabolic flight & ISS tests)

ULOI, MOC (experimental)

MLOC (experimental)



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

ISO/TC20/SC14

⟷ Comparison, inter-relation

※ Overview of the Investigation on Fire Safety in Space (FLARE) and the Latest Progress, M. Kikuchi, et al., Proceedings of JASMAC-30, 31A10, 2018.

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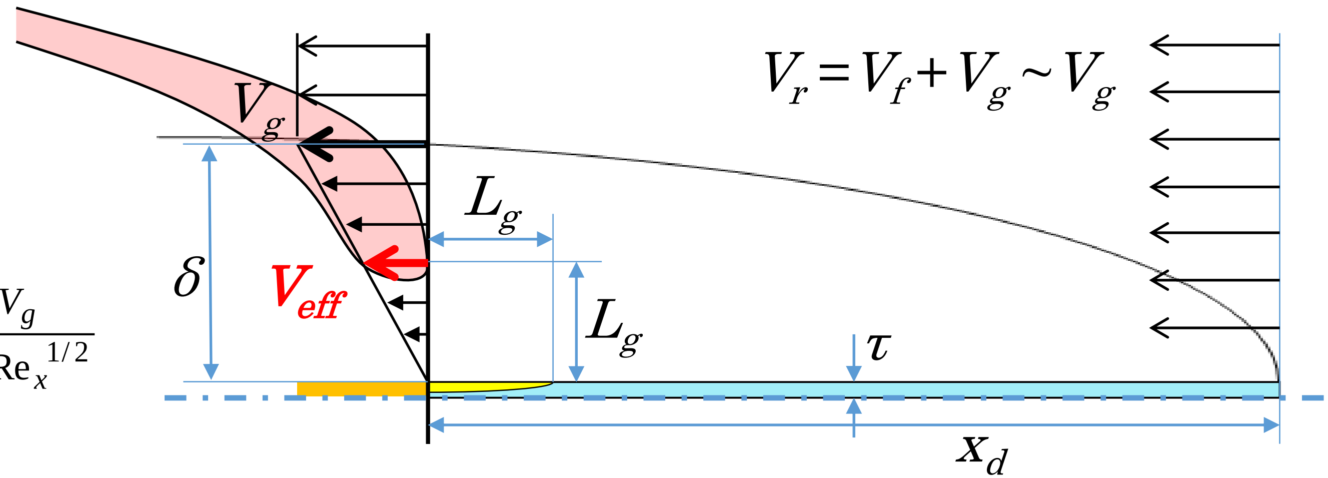
Scale analysis of flame spread with opposed flow

$$V_{g,eff} \sim \frac{V_g}{\Pr \mathrm{Re}_x^{1/2}}$$



Heat balance with including radiative heat loss and finite kinetic effect

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

Radiative heat loss

Finite kinetic effect

$$\eta + R_{rad} + \frac{1}{Da} = 1$$

where $\eta \equiv V_f / V_{f,th}$

Opposed flow velocity: low

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

B_1 and B_2 is constant

Opposed flow velocity: high

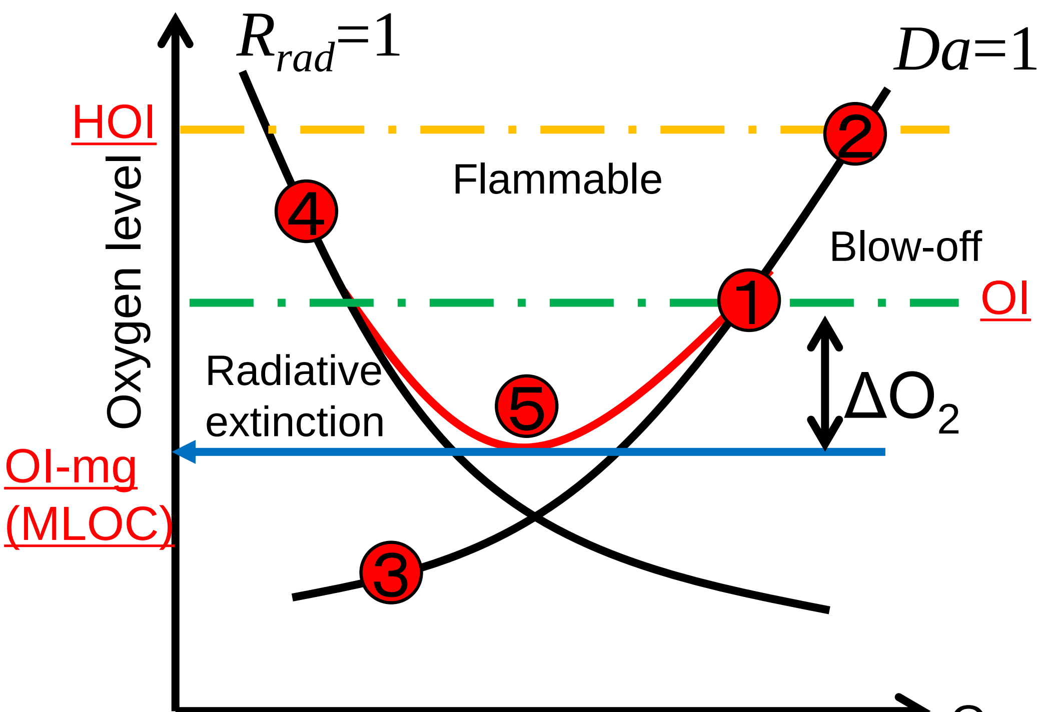
Applying BL model

$$Da \sim \frac{\alpha_g}{V_r^2} \rho_g Y_O A \exp(-E/RT_f) \quad \Rightarrow \quad B_1 \frac{\alpha_g}{V_r} \rho_g Y_O A \exp(-E/RT_f)$$

※ Prediction of Limiting Oxygen Concentration of Thin Materials in Microgravity, S. Takahashi, et al., *Trans. JSASS Aerospace Tech. Japan,* Vol. 16, No. 1, pp. 28-34, 2018.

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) → **ISO/TC 61**
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 $\eta + R_{rad} + 1/Da = 1$.

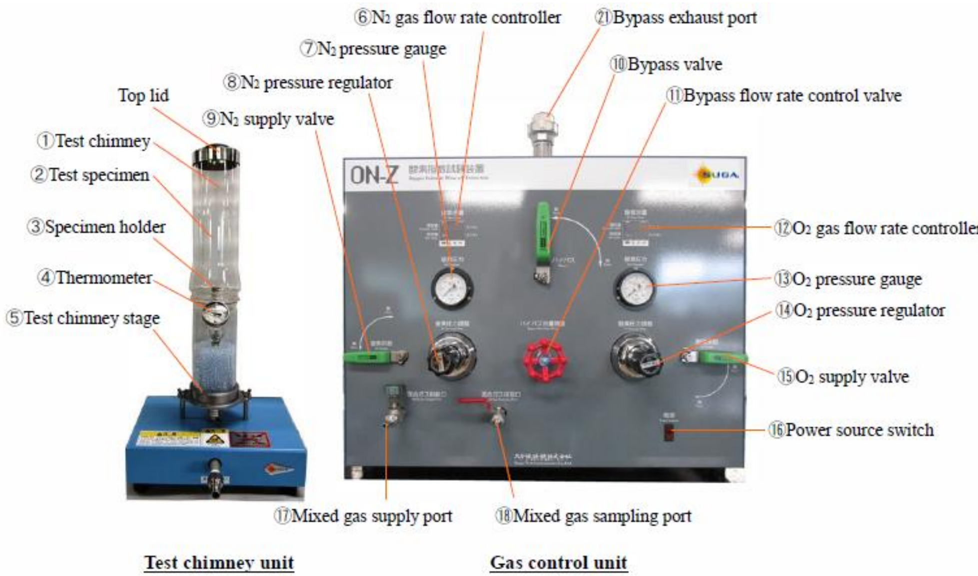


$$Da = B_1 \cdot \frac{\alpha_g}{V_r^2} \rho_g Y_O A \exp(-E/RT_f)$$

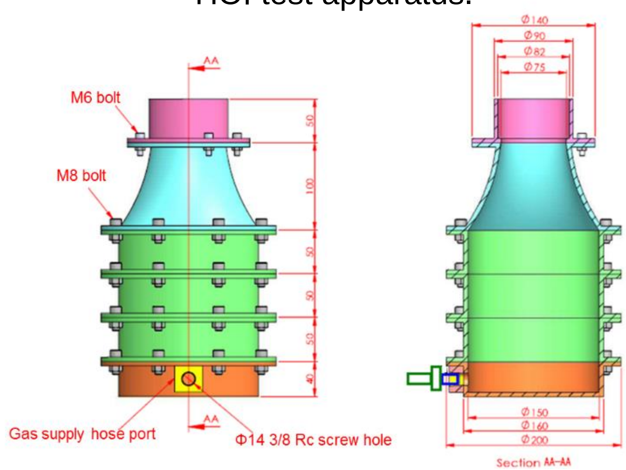
$$R_{rad} = B_2 \cdot \frac{\varepsilon(1-a_{abs})\sigma(T_v^4 - T_\infty^4)}{\rho_g c_g V_r (T_f - T_v)}$$

※ Prediction of Limiting Oxygen Concentration of Thin Materials in Microgravity, S. Takahashi, et al., *Trans. JSASS Aerospace Tech. Japan,* Vol. 16, No. 1, pp. 28-34, 2018.

Test Apparatus to Measure HOI

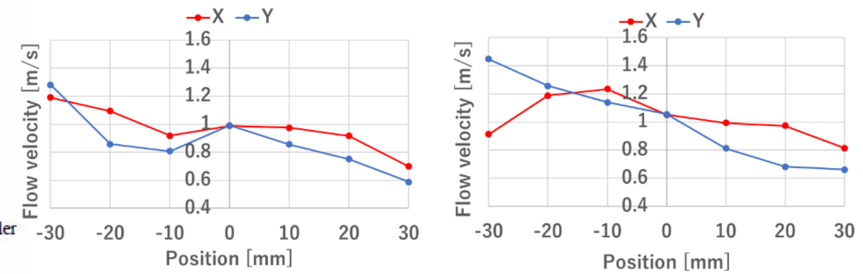


HOI test apparatus.

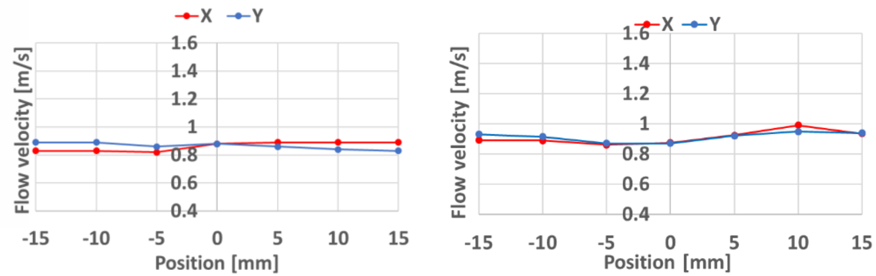


Contracted flow nozzle.

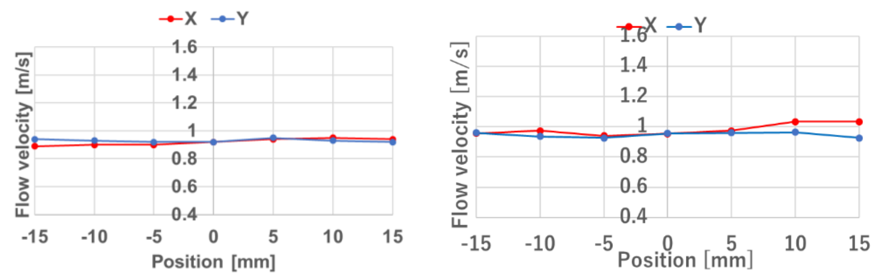
Upper. Lower.



rectification of beads only.



rectification of beads and honeycomb.



rectification of contracted nozzle.

Flow velocity distribution measurement results.

※ Study on rectification and test results of high flow velocity test apparatus in ISO/WD 4589-4, M. Fukuda, et al., Proceedings of JASMAC-30, 31A11, 2018.

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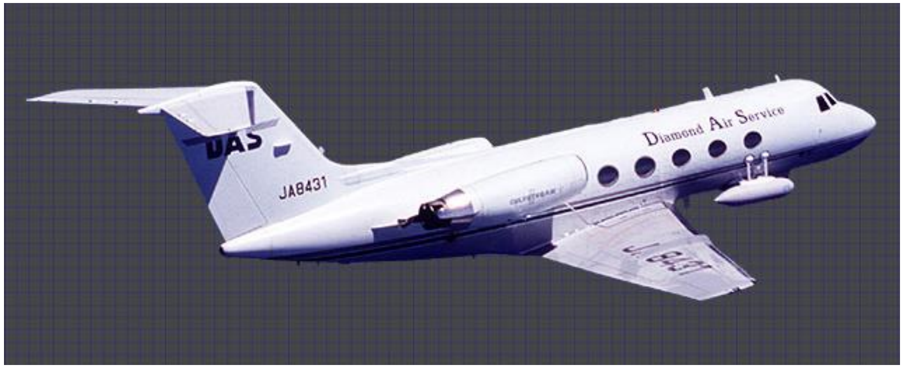
Parabolic Flights in the Project

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

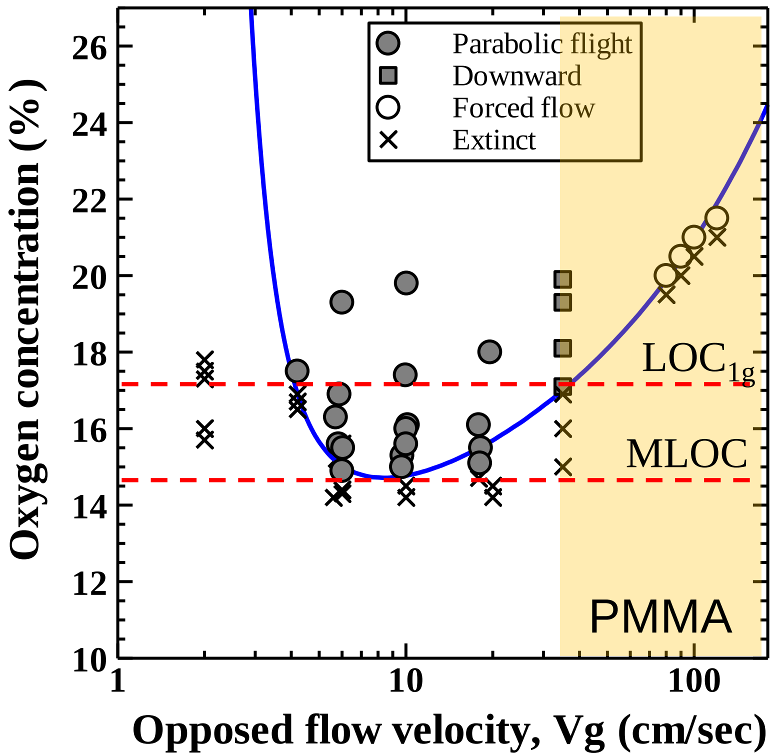
A-310 (http://www.novespace.fr/)

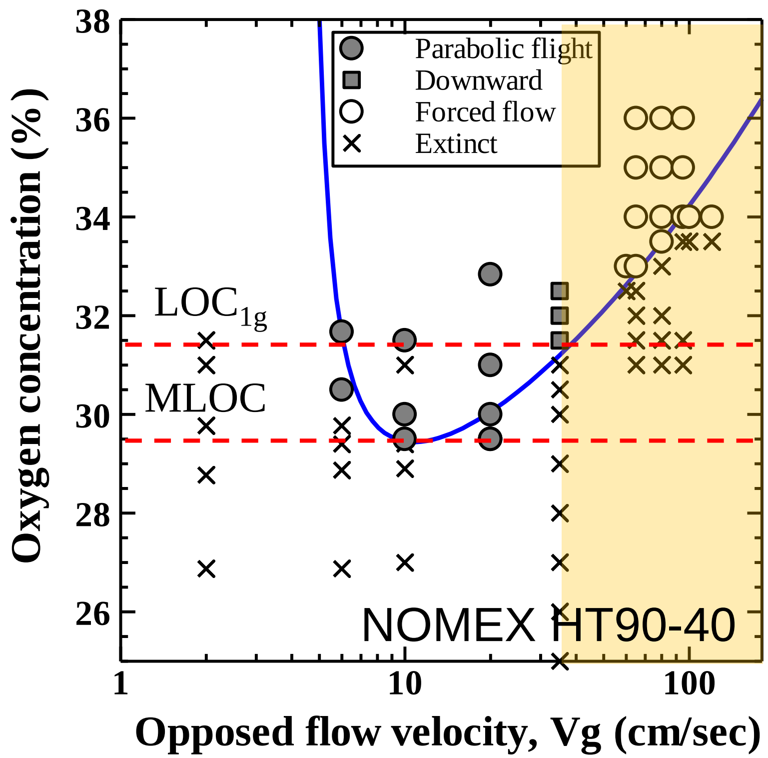
Noble Ability of the New Method

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.**

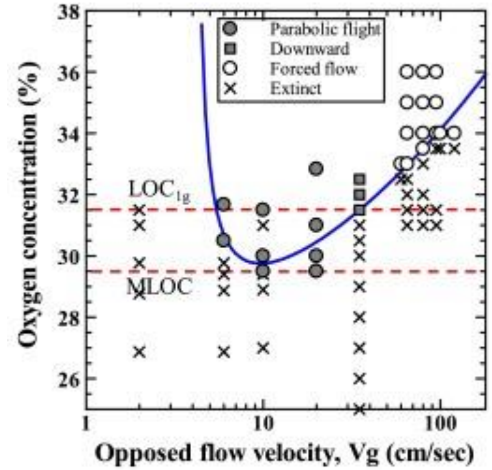
⇨ **We can predict the material is more flammable in microgravity, or not.
Also, increase of the materials selection for space use would be possible with reasonable rationale.**



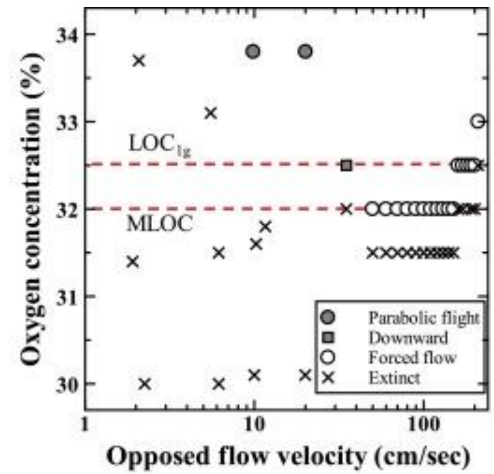


※ Prediction of Limiting Oxygen Concentration of Thin Materials in Microgravity, S. Takahashi, et al., *Trans. JSASS Aerospace Tech. Japan,* Vol. 16, No. 1, pp. 28-34, 2018.

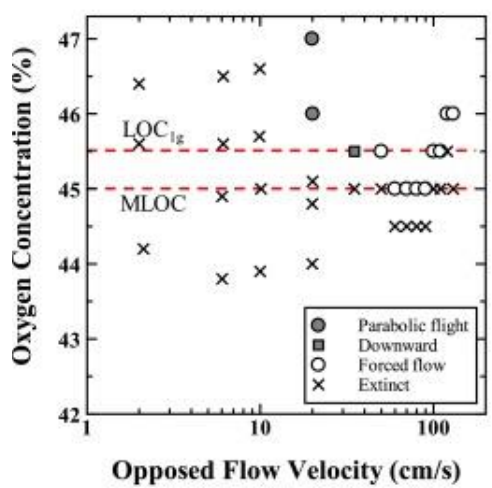
Results of the Parabolic Flight Experiments (Flat Samples)



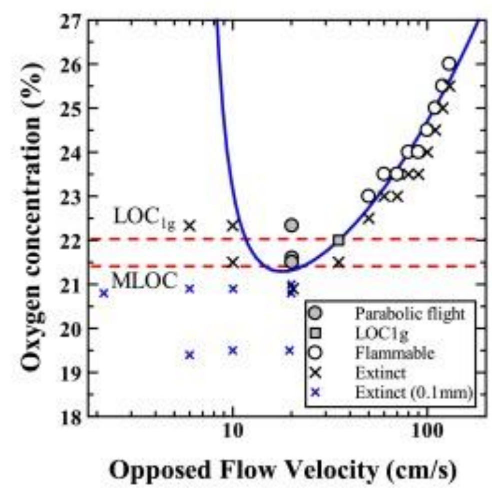
a) NOMEX HT90-40 (meta-aramid fabric: DuPont, t=0.3mm)



b) Kevlar KE5847 (para-aramid fabric: DuPont, t=0.35mm)



c) Kapton 500H (polyimide film: DuPont, t=0.125mm)

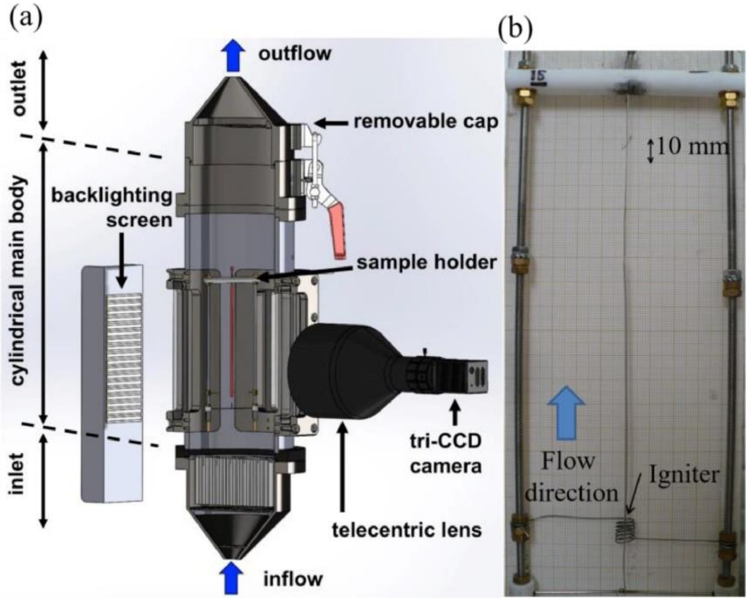


d) CARBOGLASS C110C (polycarbonate: Asahi Glass, t=0.25mm).

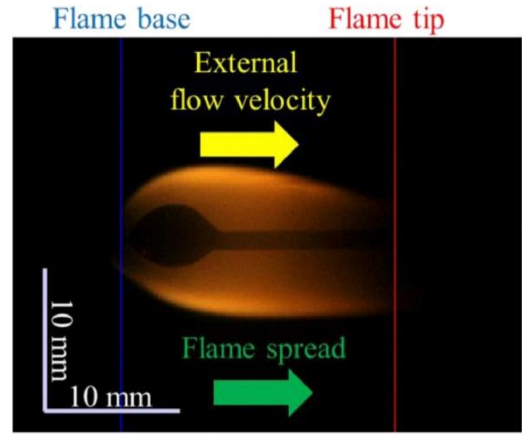
Flammability map of various materials※.

※ Flammability limit of thin flame retardant materials in microgravity environments, S. Takahashi, et al., *Proceedings of the Combustion Institute*, In Press, 2018. (https://doi.org/10.1016/j.proci.2018.06.102)

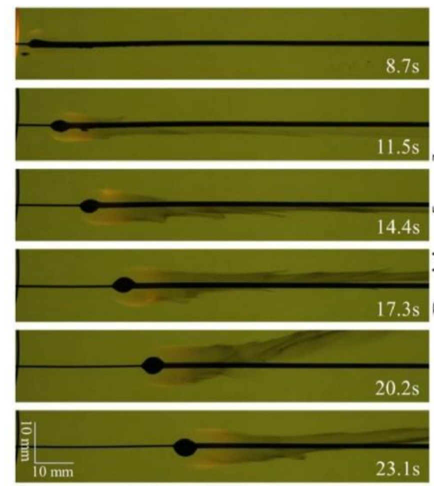
Results of the Parabolic Flight Experiments (LDPE Insulated Wire Samples)



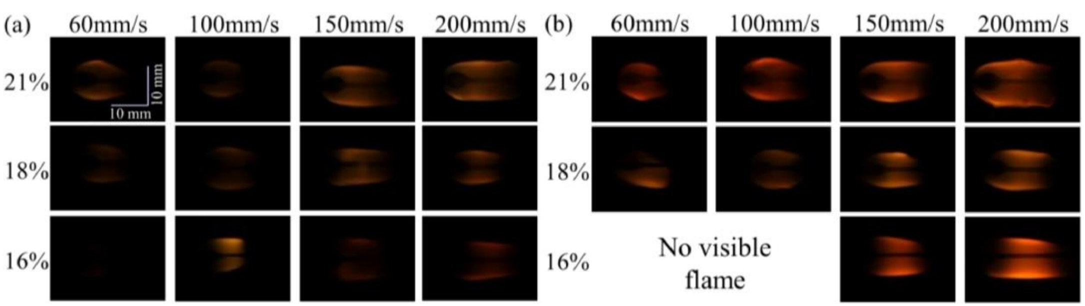
Experimental set-up for the parabolic flight experiments by A310 in France.



Typical frame showing the shape of the flame spreading in a concurrent flow (velocity: 150 mm/s; O_2 concentration: 18%).



Frames with backlighting on (NiCr core wire; concurrent flow velocity: 150 mm/s; O_2 concentration: 18%);



NiCr core wire

Cu core wire

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

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

※ Can a spreading flame over electric wire insulation in concurrent flow achieve steady propagation in microgravity ?, M. Nagachi, et al., *Proceedings of the Combustion Institute*, In Press, 2018. (https://doi.org/10.1016/j.proci.2018.05.007)

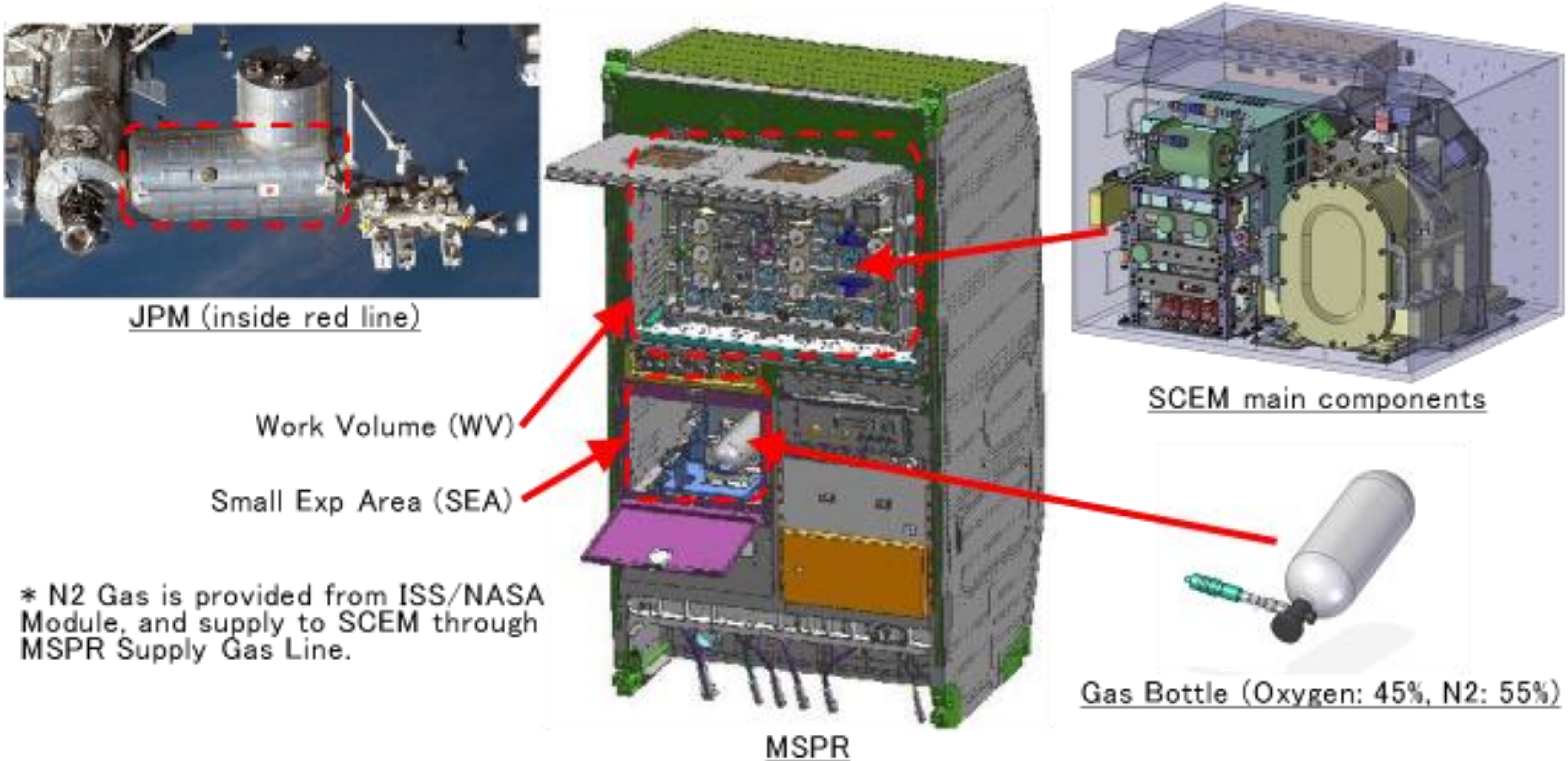
Contents

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.*

Exp. No.	Lead Investigator	Test Samples	Experiment Outline
1-1	S. Takahashi (Gifu Univ.)	PMMA sheet & plate	Flame spread experiment to find the extinction limit (inc. sample thickness effect)
1-2	H. Torikai (Hirosaki Univ.)	Filter paper sheet	Flame spread experiment to find the extinction limit (inc. sample width effect)
1-3	S. L. Olson (NASA GRC)	Cotton fabric sheet	Flame spread experiment to find the extinction limit
1-4	S. Takahashi (Gifu Univ.)	NOMEX® sheet	Flame spread experiment to find the extinction limit
2-1	C. Fernandez-Pello (UC Berkeley)	Polyethylene insulated wire & rod	Flame spread experiment to find the extinction limit
2-2	O. Fujita/ G. Legros (Hokkaido Univ./UPMC)	Polyethylene & ETFE insulated wire	Flame spread experiment to find the extinction limit (inc. the effects of diameter, core wire material, and pressure)
3-1	O. Fujita (Hokkaido Univ.)	Polyethylene insulated wire	Self-ignition experiment of wire to find the ignition limit by excess electric current

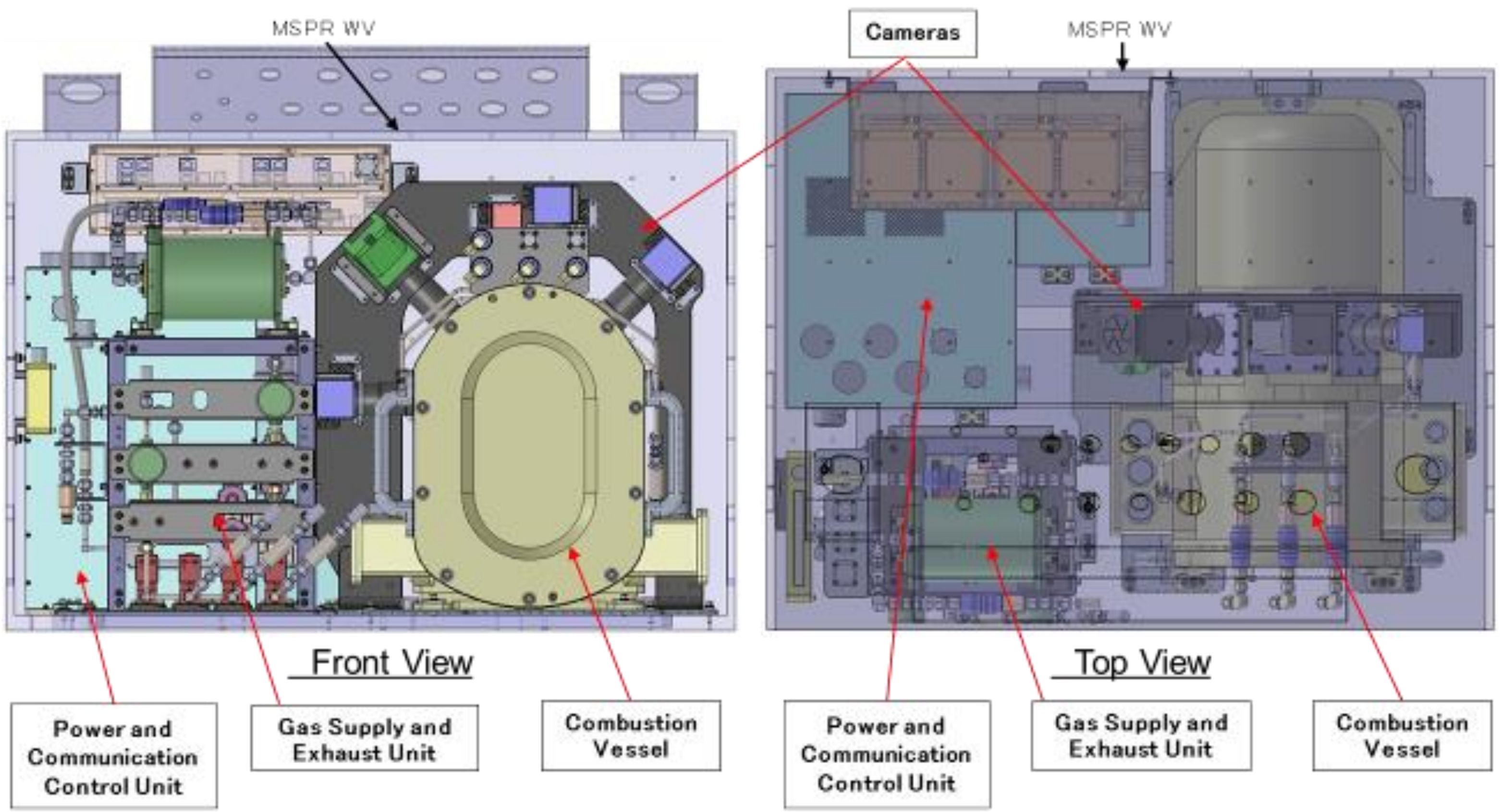
Experimental Apparatus



Schematics of the experimental apparatus for the experiments onboard the ISS/Kibo※.

※ Development status of Solid Combustion Experiment Module (SCEM) for experiment in “Kibo”, Y. Kan, et al., Proceedings of JASMAC-30, 31A12, 2018.

Overview of SCEM



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

※ Development status of Solid Combustion Experiment Module (SCEM) for experiment in “Kibo”, Y. Kan, et al., Proceedings of JASMAC-30, 31A12, 2018.

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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.