OS3-1

FLARE プロジェクトの概要と進展状況

Overview and Current Status of the FLARE Project

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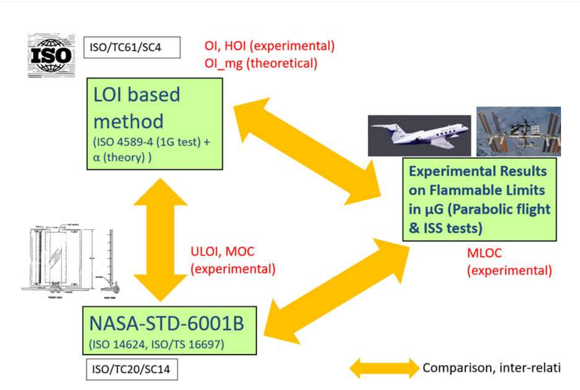
Abstract: The FLARE Project (Fundamental Research on International Standard of Fire Safety in Space -a base for safety of future manned missions-) was selected in fiscal year 2012 as one of the priority research themes for utilization of the "Kibo" module. The project aims to establish a new fire safety standard that takes into account the effects of reduced gravity. The standard will be validated and improved through comparisons with NASA's conventional test methods and experimental data obtained from microgravity experiments, as illustrated in the figure on the right.



Since 2022, long-term microgravity combustion experiments using the Solid Combustion Experiment Module (SCEM) have been ongoing aboard the International Space Station's "Kibo" module. This presentation will provide an overview and current status of the project, as well as recent progress in research related to the combustion of electric wires, which is scheduled to be conducted shortly.

Keywords: Fire safety in space, Solid material flammability, Flame spread, Microgravity, ISS

1. Overview of the FLARE project

Fire safety is one of the most critical requirements in conducting human space activities. One approach to ensuring fire safety is to evaluate whether materials brought into the spacecraft will continue to burn if ignited under the expected atmospheric oxygen concentration inside the spacecraft. A testing method based on this concept is defined in NASA-STD-6001B [1)], but these tests have traditionally been conducted under normal gravity conditions. However, recent studies [2,3)] have revealed that combustion limits may expand under microgravity, meaning that materials deemed safe in ground-based tests may not necessarily be safe in microgravity environments. Given this background, the primary objective of this project is to establish a new material fire safety standard that considers the potential expansion of combustion limits—specifically the Limiting Oxygen Concentration (LOC)—under microgravity conditions. For example, Olson [4)] conducted experiments in which thin paper was burned in microgravity, and the LOC was measured against opposing airflow velocity, as shown in Figure 1. The LOC reached a minimum value (Minimum Limiting Oxygen Concentration, MLOC) at an airflow velocity of around 10 cm/s. Beyond this velocity—whether increasing or decreasing—the LOC increased. This air-flow velocity to give MLOC is significantly lower than the natural convection velocity observed in ground-based combustion, indicating that MLOC is likely to occur in microgravity environments with ventilation flow.

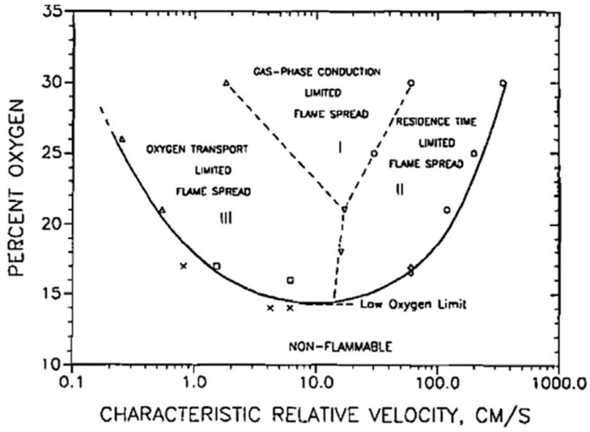


Figure 1. LOC change vs. opposed flow velocity for thin cellulosic paper reported by S.L.Olson [4].

The core concept of the FLARE project is to theoretically predict this velocity dependent behavior of LOC and to develop a fire safety evaluation method that accounts for the differences in combustion limits between microgravity and normal gravity. To apply combustion limit prediction formulas to fire safety evaluations, it is essential to verify their accuracy across various materials. However, obtaining such verification data on the ground is difficult, which is why experiments aboard the International Space Station (ISS) are being conducted as part of the FLARE project. Especially for materials with low flammability or long combustion durations, reliable data cannot be obtained through other means. Table 1 summarizes the samples to be used in the planned ISS experiments. In addition to commonly used materials in combustion research such as filter paper and PMMA sheet, the list includes practical materials like cotton fabric and NOMEX, as well as samples simulating electrical wires. Alongside the ISS experiments, the project also plans to compare results with existing data obtained using NASA's standard testing methods [1] to verify the reliability of the new approach. This concept of cross-comparison is illustrated in the graphic abstract. To make this research possible, the project is an international collaboration involving JAXA, NASA, ESA, CNES, DLR, and university researchers from Japan (Hokkaido University, Hiroaki University, The University of Tokyo, Shinshu University, Toyohashi University of Technology, Gifu University, and abroad (UC Berkeley, Sorbonne University, University of Bremen).

Table 1. Test samples and lead investigators for the ISS/KIBO experiments in the FLARE project.

Exp. No.	Insert type	Lead investigator	Test samples	Sample size (mm)	Number of samples (Max. exp. runs)	Remarks
1-1	2	S. Takahashi (Gifu Univ.)	PMMA sheet & plate (○)	130 x 20 x 0.125 130 x 20 x 1	35 (62)	Incl. experiments at low ambient pressure.
1-2	2	H. Torikai (Hirosaki Univ.)	Filter paper sheet (◎)	130 x 20 x 0.12 130 x 40 x 0.12	26 (76)	
1-3	2	S. L. Olson (TBD) (NASA GRC)	Cotton fabric sheet	140 x 40 x 0.12	40 (80)	Incl. experiments at low ambient pressure.
1-4	2	S.Takahashi (Gifu Univ.)	NOMEX® sheet (◎)	130 x 20 x 0.12	13 (26)	Incl. experiments at low ambient pressure.
1-5	2	F.Meyer (U. Bremen)	PMMA plate (○)	130 x 40 x 2	8 (16)	Incl. experiments at low ambient pressure.
2-1	2	C. Fernandez-Pello /Fujita/Hashimoto/Konno(UC Berkeley/ Hokkaido U)	LDPE cylinder with core (○)	130 x Ø (4.0/2.5) 130 x Ø (4.0/0.5) 130 x Ø (3.0/1.88)	12 (12)	
2-2	1	Fujita//Hashimoto/Konno/G. Legros (Hokkaido U. /Sorbonne U.)	LDPE & ETFE insulated wire (Cu & NiCr)	Ø 0.8/0.5 Ø 1.1/0.5	2 (171)	Incl. experiments at low ambient pressure.
3-1	1	Fujita/Hashimoto/Konno (Hokkaido U.)	LDPE insulated wire (NiCr)	Ø 0.8/0.5 Ø 1.1/0.5	1 (57)	Self-ignition of wires by excess electric current.

2. Current Status

Regarding the ISS-based experiments, the experimental hardware—Solid Combustion Experimental Module (SCEM)—was launched in 2020. After adjustments, the first experiment was successfully conducted in May 2022. The initial experiment involved filter paper samples (1-2 in Table 1), and a stable and visually striking flame characteristic of microgravity was observed as shown in Fig.2 [5)]. The results of the filter paper combustion experiments have already been published in Refs.[5,6)]. These studies confirmed the reliability of the prediction methods. As of September 2025, experiments with samples 1-2 (Filter paper) and 1-4 (NOMEX) in Table 1 are nearly complete. Additionally, partial experiments have been conducted for samples 1-1 (PMMA sheet), 1-5 (thick PMMA plate) and 2-1 (thick LDPE rod with copper core) under planned conditions.

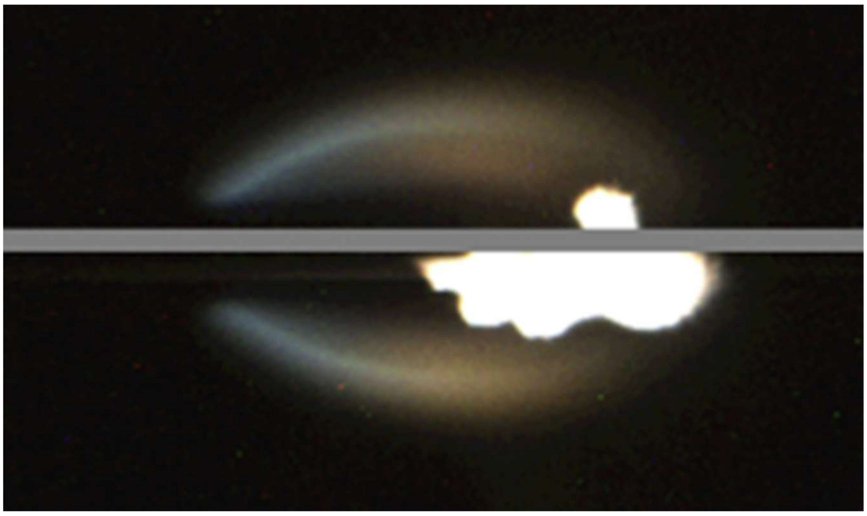


Figure 2. Typical flame spreading over filter paper in opposed flow (from left to right, 20cm/s) at an oxygen concentration of 15.9%, captured in SCEM aboard the ISS/KIBO [5)].

On the other hand, regarding the development of new fire safety standards and the underlying theoretical research, results related to the prediction methods have been published in references [ex.7,8)]. Furthermore, a method for determining the velocity dependence of LOC under high airflow conditions—which is key to predicting MLOC—has been formalized as ISO-4589-4 [9,10)], issued through this project. Research on wire samples, which are scheduled for future experiments abord ISS, is also steadily progressing. Wire samples contain internal conductors and have cylindrical outer shapes, making LOC prediction more complex. A prediction method that accounts for these effects under opposing airflow conditions has been successfully developed [11,12,13)]. Even for wire samples, LOC exhibits a velocity-dependent minimum value under specific airflow conditions, allowing identification of the MLOC, where flammability is highest. These results are also scheduled to be verified in upcoming ISS orbital experiments.

3. Following Projects

The FLARE project has focused primarily on samples commonly used in combustion research, and the test conditions have been selected to verify or refine theoretical models. Therefore, the project has concentrated on relatively standard conditions. However, considering future human space missions such as the Artemis program, it becomes necessary to test a wider range of practical materials and realistic spacecraft atmospheric conditions, such as the so-called Exploration Atmosphere. The FLARE-2 project (PI: Shuhei Takahashi from Gifu University) is designed with this broader perspective. Looking further ahead, as missions expand to the Moon and Mars, it will be essential to develop methods for evaluating material flammability under partial gravity conditions. To address this necessity, the FLARE-3 project (PI: Nozomu Hashimoto from Hokkaido University) is currently being prepared.

3. Summary

This article summarized the overall scope and current progress of the FLARE project, which focuses on fire safety in space environments. The main points are summarized as follows:(1) FLARE project is developing a new material screening method for fire safety in space. (2) The main challenge is theoretical estimation of MLOC, comparable to O_2 concentration in spacecraft. (3) Theoretically estimated flame spread rate and MLOC will be compared with data taken in ISS/KIBO tests and in conventional NASA standard method. (4) The established method will contribute to improving fire safety in future space exploration. (5) Following the FLARE project, FLARE-2 is underway, focusing on more practical materials and realistic conditions, while FLARE-3 aims to develop methods for evaluating flammability under partial gravity conditions.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1) NASA STD 6001B, *Flammability, Offgassing, and Compatibility Requirements and Test Procedures* (2011).
2) S.L. Olson and P.V. Ferkul, Evaluating Material Flammability in Microgravity and Martian Gravity Compared to the NASA Standard Normal Gravity Test, *42nd International Conference on Environmental Systems*, AIAA 2012-3492 (2912), DOI: 10.2514/6.2012-3492
3) K. Mizutani, K. Miyamoto, N, Hashimoto, Y. Konno, O. Fujita, Limiting Oxygen Concentration Trend of ETFE-Insulated Wires under Microgravity, *Int. J. Microgravity Sci. Appl*. 35: 350104 (2018). https://doi.org/10.15011/jasma.35.1.350104
4) S. L. Olson, Mechanisms of Microgravity Flame Spread Over a Thin Solid Fuel: Oxygen and Opposed Flow Effects, *Combust. Sci. Technol.* 76:233–249 (1991). 10.1080/00102209108951711
5) S. Takahashi, H. Torikai, Y. Kobayashi, M. Kikuchi, O. Fujita, Quantitative prediction of the flammability limits of filter paper in microgravity conditions, *Proceedings of the Combustion Institute*, Volume 40, Issues 1–4, 2024, 105200 https://doi.org/10.1016/j.proci.2024.105200
6) S. Takahashi, H. Torikai, Y. Kobayashi, M. Kikuchi, O. Fujita. Flame Spread Behavior Over a Filter Paper Near Extinction Limit Under Microgravity on the ISS/Kibo. *Fire Technol* **60**, 313–334 (2024). https://doi.org/10.1007/s10694-023-01507-3
7) S. Takahashi, M. A. F. bin Borhan, K. Terashima, A. Hosogai, Y. Kobayashi, Flammability limit of thin flame retardant materials in microgravity environments, *Proc. Combust. Inst*. 37: 4257-4265 (2019). DOI: 10.1016/j.proci.2018.06.102.
8) S. Takahashi, K. Terashima, M. A. F. bin Borhan, Y. Kobayashi, Relationship Between Blow-Off Behavior and Limiting Oxygen Concentration in Microgravity Environments of Flame Retardant Materials. *Fire Technol* **56**, 169–183 (2020). https://doi.org/10.1007/s10694-019-00880-2.
9) ISO 4589-4:2021, Plastics -Determination of burning behaviour by oxygen index - Part 4: High gas velocity test (2021).
10) Y. Konno, M. Z. Bin Zainal, N. Hashimoto, O. Fujita, Application of ISO 4589-4 to determine limiting oxygen concentrations for opposed-flow flame spread over thin electric wires and their comparison with microgravity data *Fire Safety. J*. 141: 103989 (2023). https://doi.org/10.1016/j.firesaf.2023.103989
11) Y. Konno, N. Hashimoto, O. Fujita, Role of wire core in extinction of opposed flame spread over thin electric wires *Combust. Flame* 220:7-15 (2020), https://doi.org/10.1016/j.combustflame.2020.06.026
12) Y. Konno, N. Hashimoto, O. Fujita, On the radiation extinction of opposed flame spread over curved solid surface in low flow velocity conditions, *Combust. Flame* 254: 112836 (2023). https://doi.org/10.1016/j.combustflame.2023.112836
13) Y. Konno, N. Hashimoto, O. Fujita, Modelling of opposed flame spread over thin electric wires: estimation of flame spread rates and limiting oxygen concentrations, *Combust. Theory Model.* 28: 459-490 (2024). https://doi.org/10.1080/13647830.2024.2355906