

MATERIAL FLAMMABILITY AT LUNAR AND MARTIAN GRAVITY. Paul Ferkul,¹ Nathan Kralik², and Ya-Ting Liao²

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Introduction: NASA relies on NASA-STD-6001B Test 1 for screening material flammability for flight [1]. The test is conducted in normal Earth gravity, with the assumption that if a material passes the 1-g test, then it is considered safe for spaceflight. This approach has provided a practical means to assess the great number of materials that are used currently, and which have been used in the past. But the approach has important uncertainties. Microgravity research over the last few decades has shown that normal gravity may not necessarily represent the most flammable condition for a material. Theoretical and experimental results have demonstrated that some materials that will not burn in 1-g will burn in 0-g (with a low-speed flow) or in partial gravity (such as Lunar-g).

This can be understood by examining the role of buoyant flow on flame spread. On Earth, buoyancy causes hot product gases to accelerate upwards and out of the flame, at the same time drawing fresh oxidizer into the flame base. This introduction of fresh oxygen sustains the flame. The speed of the air entering the flame can be so high, however, that the chemical reactions are unable to keep pace. Furthermore, the rate of heat release and/or transport may be too low to provide the energy to heat the incoming cold flow. These effects can lead to flame de-stabilization, commonly known as blowoff. The governing non-dimensional parameter is the Damkohler Number, which is the ratio of the characteristic flow time to the chemical reaction time.

Consider a material that is marginally non-flammable on Earth. The same material may be flammable at a lower gravity level (for example, on the Moon) since the crucial mechanism of buoyant oxygen entrainment at the flame base is still present, but at a slower rate, allowing the chemical reaction rates to “keep up” and the flame to adequately heat the incoming cool air. Alternatively, a material that is not flammable on Earth can be burned in microgravity, but with the introduction of a low speed forced flow of air. Applying a flow below the buoyant blowoff limit speed permits a material to burn in microgravity, albeit with a smaller flame size, even though it may not burn at all in 1-g.

Current Knowledge: Using drop towers, aircraft, sounding rockets, and modeling, it is observed that certain partial-g environments are expected to increase

the flammability limits for some materials. Early numerical and experimental evidence suggested that Lunar gravity could be more hazardous, since flame spread rate as a function of gravity peaks there [2]. Related work suggests that oxygen concentration for flammability reaches a minimum value in the vicinity of $g = g_{\text{Lunar}}$.

Furthermore, in order to facilitate the convenient donning of space suits, future explorers of the Moon and Mars are likely to live in atmospheres at sub-atmospheric pressure but higher oxygen concentration compared to standard air. Consequently, partial-g fire in an extraterrestrial habitat is a real hazard that is expected to be substantially worse than in 0-g and potentially worse than even 1-g.

Discussion: This work contributes directly to filling knowledge and capability gaps in spacecraft fire safety that have been the focus of many projects at the NASA John H. Glenn Research Center. NASA has undertaken extensive tests examining solid fuel flame spread with a particular application to material flammability in microgravity culminating in a number of flight experiments (e.g., [3-7]). Partial gravity tests can be performed in drop towers [8] and aboard aircraft [2], but the available times are too short to provide significant flame development (5 s for drop tower and ~25 s for aircraft). For an orbital platform such as the International Space Station (ISS), partial gravity tests can be performed using centrifuges, but those currently available have small radii of rotation producing appreciable Coriolis effects for the length scales necessary, adding complexity to the interpretation of results. A sounding rocket utilizing vehicle rotation to simulate Lunar gravity provided test times on the order of 150 s, burning two different materials, but again the Coriolis force introduces uncertainty.

Combustion on the Moon: The first-ever combustion experiments on another world will be performed, with a planned launch date of late 2026. Flammability of Materials on the Moon (FM²) will burn a total of four solid fuel samples in quiescent habitable atmospheres in actual long duration Lunar gravity (Fig. 1). Cameras will be used to record flame characteristics, including spread rate. Radiometers and an oxygen sensor will be included. The tests will provide benchmark data and are part of the larger

effort to understand how Lunar gravity will affect material flammability.

Direct Lunar access offers the best way to assess flammability of materials on the Moon. An extensive materials qualification test series there would be ideal, but such tests will need to be put off until an extended human presence on the Moon is established. Prior to this, a limited series of tests would enable a comparison between fires on the Moon and Earth and would validate models and theories developed using 0-g and 1-g testing.

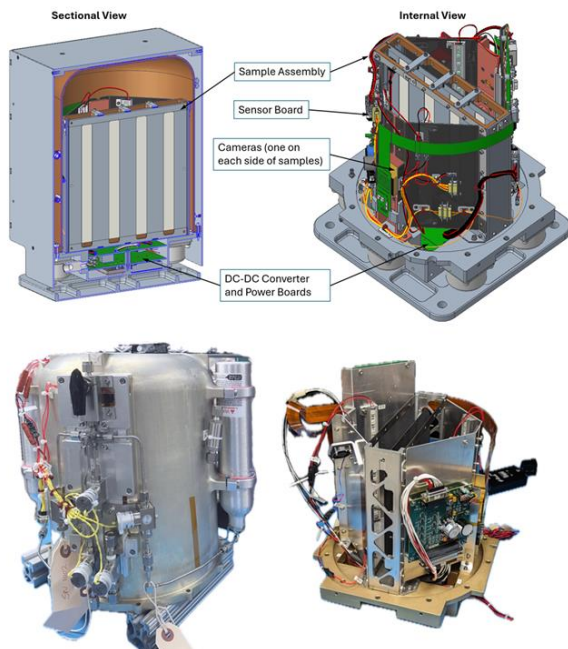


Figure 1. Top: FM² experiment design showing solid model and cross section of the combustion chamber. Four flat samples are burned in separate tests. Small, pressurized gas bottles provide air for each test. Cameras record flame images while sensors include thermocouples, radiometers, and O₂ concentration. Bottom: FM² Hardware. Left: Chamber exterior; Right: Internal components.

The outcome of this work would include the first-ever, long-duration observation and measurement of flame spread in a partial-g environment. It is expected that the fuels tested will provide verification of the hypothesis that some materials burning in partial-g environments may be more flammable compared to 1-g. The results will provide a bridge between the current 1-g material screening method and actual behavior in reduced gravity. This will refine understanding of the conditions when the test may not be conservative enough, and likely will lead to an amended test procedure which is safer and more accurate.

References: [1] Mulville, D., "NASA-STD-6001B: Flammability, off-gassing, and compatibility requirements and test procedures," NASA, 2016. [2] K. R. Sacksteder and J. S. T'ien, "Buoyant downward diffusion flame spread and extinction in partial-gravity accelerations," *Symposium (International) on Combustion*, vol. 25, no. 1, pp. 1685-1692, 1994. [3] D. L. Urban, P. Ferkul, S. Olson, G. Ruff, J. Easton, J. S. T'ien, Y.-T. T. Liao, C. Li, C. Fernandez-Pello, J. Torero, G. Legros, C. Eigenbrod, N. Smirnov, O. Fujita, S. Rouvreau, B. Toth and G. Jomaas, "Flame spread: effects of microgravity and scale," *Combustion and Flame*, vol. 199, pp. 168-182, 2019. [4] X. Zhao, Y.-T. T. Liao, M. C. Johnston, J. S. T'ien, P. V. Ferkul and S. L. Olson, "Concurrent flame growth, spread, and quenching over composite fabric samples in low speed purely forced flow in microgravity," *Proceedings of the Combustion Institute*, vol. 36, pp. 2971- 2978, 2017. [5] Bhattacharjee, S., and Altenkirch, R.A., "A comparison of theory and experiment in flame spread over thin condensed fuel in quiescent microgravity environment," *Proc. of the Combustion Institute*, pp. 1669-1676, 1992. [6] Bhattacharjee, S., Altenkirch, R.A., and Sacksteder, K., "Implications of spread rate and temperature measurement in quiescent, microgravity, space-based environment," *Combustion Science and Technology*, Vol. 91, pp. 225-231, 1993. [7] S. L. Olson and P. V. Ferkul, "Microgravity flammability boundary for PMMA rods in axial stagnation flow: experimental results and energy balance analyses," *Comb. Flame* 180, 2017. [8] P. V. Ferkul and S. L. Olson, "Zero-gravity centrifuge used for the evaluation of material flammability in Lunar gravity," *Journal of Thermophysics and Heat Transfer*, vol. 25, no. 3, pp. 457-461, 2011.