This is the Pre-Published Version.
X. Huang, Y. Nakamura, D. Urban (2020) Special Issue on Spacecraft Fire Safety, Fire Technology, 56(1):1-4. https://doi.org/10.1007/s10694-019-00941-6 Editorial

This is a post-peer-review, pre-copyedit version of an article published in Fire Technology. The final authenticated version is available online at: https://doi.org/10.1007/s10694-019-00941-6.

Special Issue on Spacecraft Fire Safety

Xinyan Huang[1], Yuji Nakamura[2,*], David Urban[3]

[1]*Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong*

[2]*Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, Japan*

[3]*NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, USA*

Humankind has progressively increased the duration and extent of missions beyond the surface of the Earth. This journey has not been without risk, and the history of human spaceflight contains a number of catastrophic events [1]. In the history of human spaceflight, of the 10 recorded events that resulted in the loss of crew, two events involved fire. On-orbit, there have been 13 fire or overheat events of which two were grave and represented a clear risk to the crew. Therefore, fire remains a significant risk for spaceflight that merits research for future flights. The fire risk in a spacecraft is more challenging than most terrestrial locations due to the cramped quarters, limited resources for fire response, and limited evacuation strategy. One advantage of spaceflight is that the ability to control the materials that are present in the vehicle is very robust; consequently, the control of material and ignition sources for fire prevention should be carefully followed as the primary defense against the establishment of fires [2].

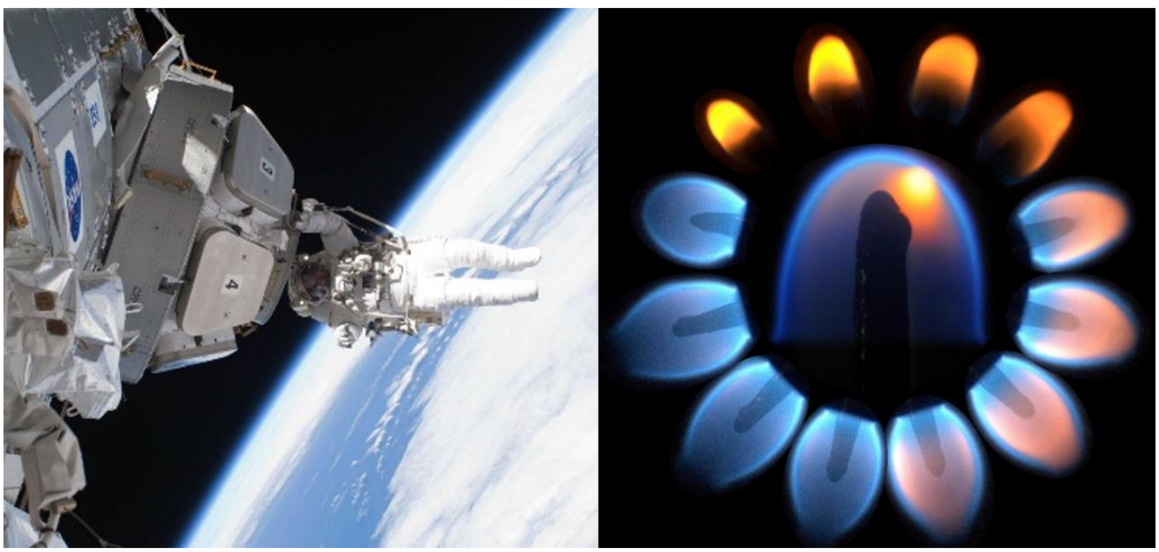

Figure 1. International Space Station and spacewalk, courtesy of NASA (left). The flame spread over the black PMMA rod in microgravity, where the central fire image shows a vapor jet disrupting the blue flame, and surrounding fire images show the opposed flame spread [4] (right).

Spacecraft fire safety has been a research topic in combustion and fire safety engineering, since the beginning of the space program in the 1970s, and has expanded to include future long-term manned missions, and establishment of human habits on the moon, Mars, and beyond. Spacecraft fire research is complex and experimentally costly, constrained by limited access to space experiments and brief ground-based experiments [5]. To help limit the cost to individual agencies and to expand the knowledge base, it has become an active area of international collaborations involving numerous countries and space agencies.

The special issue of Spacecraft Fire Safety includes 18 papers with multidisciplinary contributions from different aspects of fire science and technology. Unique space fire experiments have been conducted in the

International Space Station [6, 7], unmanned spacecraft [8], and a satellite [9] to understand the long-term microgravity combustion and fire phenomena. The fire dynamics for small and thin fuels are also explored through ground-based microgravity experiments using drop towers [10] and parabolic flights [11–15]. In addition, combustion and fire experiments under reduced pressures [16–18] and a narrow channel [19] are applied to lower the influence of buoyancy and simulate low-gravity environments on Earth. Numerical simulations also provide essential information on the flame structure, quantify the experimental data, and verify microgravity combustion theory [7, 20].

This special issue covers various aspects of fire dynamics in the spacecraft environment. The changes in *material flammability* resulting from the microgravity environment is a primary fire-safety concern for manned spacecraft. Proper material selection for spaceflight requires a thorough knowledge of fire and flammability behavior in varied gravity. Thus, the critical conditions for flame ignition and extinction in microgravity are extensively explored under different ignition protocols [13], oxygen concentrations [12–14], airflow rates [14] and radiant heat fluxes [12], and for flame retardant materials [14].

Once ignited, the *growth and spread of flames* in microgravity also behave differently from those on Earth, because of the absence of buoyancy flow. Thus, microgravity also provides an ideal environment for fundamental combustion research [5]. Unique phenomena for flame spread in microgravity over thin paper [10], thick plastic plates [8, 11, 19], cylindrical rods [9, 18], spherical fuels [6] and electrical wires of different thicknesses [12, 13, 15, 21] are observed, and the influence of airflow speed, direction, and oxygen concentration on flame stability are investigated. The ample literature on wire fires in microgravity and beyond are also reviewed [21].

The role of *radiation heat transfer* becomes more important for the near-limit flame phenomena in microgravity, where flame radiation and surface reradiation dominate the heat loss from the fuel. Important progress has been made in the quantification of the radiation profile and its effects on flame spread via experimental measurements [7, 15] and computational simulations [7, 20]. For the design of firefighting strategies in spacecraft, special *fire-suppression technologies* are required. In addition to the conventional extinguisher, novel technologies such as vacuuming extinguishing systems [22] and inert-gas balloon [23] are proposed.

Today, we still have a relatively limited understanding of the fire dynamics in low-gravity or microgravity, despite fundamental research input over the last a few decades, mainly because of the high cost of long-term space experiments and the limitation of short-term ground experiments. Particularly, real fire behaviors on large and complex fuels in spacecraft are mostly unexplored, and many details remain unknown. For example, what is the flashover behavior under varying gravity levels? What is the standard for a fire-safe material that should be used for space travel? Is there an optimal spacecraft atmospheric condition that balances the fire safety and crew health? How does one design a more reliable fire protection system for the space station and human habitat on Moon and Mars? It is essential that fire scientists fill the knowledge gaps and fire engineers solve the very practical safety concerns for human space exploration activities. This special issue helps shed some light on these critical needs and aims to inspire future work on this important fire research topic.

References:

1. Packham N, Wood B, Pate D (2015) Significant Incidents and Close Calls in Human Spaceflight. NASA JSC S&MA Flight Safety Office, JS-2015-004 NNJ13RA01B
2. Friedman R (1996) Fire Safety in Spacecraft. Fire and Materials 20:235–243 . doi: 10.1002/(SICI)1099-1018(199609)20:5<235::AID-FAM580>3.0.CO;2-Y
3. Friedman R (1999) Fire Safety Spacecraft in the Low-Gravity Environment
4. Link S, Huang X, Fernandez-Pello C, et al (2018) The Effect of Gravity on Flame Spread over

PMMA Cylinders. Scientific Reports 8:120 . doi: 10.1038/s41598-017-18398-4
5. Ross HD (2001) Microgravity combustion : fire in free fall. Academic Press
6. Endo M, T'ien JS, Ferkul P V., et al (2020) Flame Growth Around a Spherical Solid Fuel in Low Speed Forced Flow in Microgravity. Fire Technology. doi: 10.1007/s10694-019-00848-2
7. Carmignani L, Dong K, Bhattacharjee S (2020) Radiation from Flames in a Microgravity Environment: Experimental and Numerical Investigations. Fire Technology. doi: 10.1007/s10694-019-00884-y
8. Olson SL, Urban DL, Ruff GA, et al (2020) Concurrent Flame Spread Over Two-Sided Thick PMMA Slabs in Microgravity. Fire Technology. doi: 10.1007/s10694-019-00863-3
9. Wu C, Huang X, Wang S, et al (2020) Opposed-flow flame spread over cylindrical fuel under oxygen-enriched microgravity environment. Fire Technology. doi: 10.1007/s10694-019-00896-8
10. Vetturini A, Cui W, Liao YT, et al (2020) Flame Spread Over Ultra-thin Solids: Effect of Area Density and Concurrent-Opposed Spread Reversal Phenomenon. Fire Technology. doi: 10.1007/s10694-019-00878-w
11. Kobayashi Y, Terashima K, bin Borhan MAF, Takahashi S (2020) Opposed Flame Spread over Polyethylene Under Variable Flow Velocity and Oxygen Concentration in Microgravity. Fire Technology. doi: 10.1007/s10694-019-00862-4
12. Konno Y, Kobayashi Y, Fernandez-Pello C, et al (2020) Opposed-flow flame spread and extinction of electric wire: The effect of gravity, external radiant heat flux, and wire characteristics on wire flammability. Fire Technology. doi: 10.1007/s10694-019-00935-4
13. Nagachi M, Mitsui F, Citerne JM, et al (2020) Effect of Ignition Condition on the Extinction Limit for Opposed Flame Spread Over Electrical Wires in Microgravity. Fire Technology. doi: 10.1007/s10694-019-00860-6
14. Takahashi S, Terashima K, bin Borhan MAF, Kobayashi Y (2020) Relationship Between Blow-Off Behavior and Limiting Oxygen Concentration in Microgravity Environments of Flame Retardant Materials. Fire Technology. doi: 10.1007/s10694-019-00880-2
15. Guibaud A, Citerne JM, Consalvi JL, et al (2020) Experimental Evaluation of Flame Radiative Feedback: Methodology and Application to Opposed Flame Spread Over Coated Wires in Microgravity. Fire Technology. doi: 10.1007/s10694-019-00853-5
16. Yamazaki T, Matsuoka T, Li Y, Nakamura Y (2020) Applicability of a Low-Pressure Environment to Investigate Smoldering Behavior Under Microgravity. Fire Technology. doi: 10.1007/s10694-019-00911-y
17. Migita T, Yamahata T, Strempfl P, et al (2020) Methodology to Achieve Pseudo 1-D Combustion System of Polymeric Materials Using Low-Pressured Technique. Fire Technology. doi: 10.1007/s10694-019-00877-x
18. Thomsen M, Fernandez-Pello C, Huang X, et al (2020) Buoyancy Effect on Downward Flame Spread Over PMMA Cylinders. Fire Technology. doi: 10.1007/s10694-019-00866-0
19. Matsuoka T, Yoshimasa A, Masuda M, Nakamura Y (2020) Study on Fingering Pattern of Spreading Flame Over Non-charring Solid in a Narrow Space. Fire Technology. doi: 10.1007/s10694-019-00865-1
20. Guibaud A, Jean I, Rond L, et al (2020) Soot Production and Radiative Heat Transfer in Opposed Flame Spread over a Polyethylene Insulated Wire in Microgravity. Fire Technology. doi: 10.1007/s10694-019-00850-8
21. Huang X, Nakamura Y (2020) A Review of Fundamental Combustion Phenomena in Wire Fires. Fire Technology 1–32 . doi: 10.1007/s10694-019-00918-5
22. Nakamura Y, Usuki T, Wakatsuki K (2020) Novel Fire Extinguisher Method Using Vacuuming Force Applicable to Space Habitats. Fire Technology. doi: 10.1007/s10694-019-00854-4
23. Torikai H (2020) Extinguishing Characteristics of a Pool Fire with a Rubber Balloon Filled with Inert Gases. Fire Technology. doi: 10.1007/s10694-019-00929-2