Topical: Solid Fuel Combustion in Partial and Micro-Gravity

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Introduction

The risk of fire remains an ever-present danger in spaceflight. Most fire safety hazards originate in or eventually involve solid fuels, whether they be cellulosic (e.g., cotton fabric), hydrocarbons (e.g., plastics) or high-energy density electrode materials (e.g., batteries). A key approach to ensuring safety has been to focus on reducing the potential flammability of these materials – achieved by limiting their ignitability, potential for flame spread, and ultimate heat-release potential if ignited [1-3]. This approach has been relatively effective despite several close calls [4]. The limits of our understanding, however, are continually being challenged as future spaceflight missions incorporate partial gravity, enhanced oxygen, new types and classes of materials (e.g., composites), and higher energy-density batteries. This presents both an exciting scientific opportunity to enhance our understanding of solid fuel combustion processes while also posing a dire threat to future long-duration missions to the Moon and Mars.

Physical Processes

Combustion of solid fuels typically initiates when sufficient energy has been transferred to some region of a solid material, such as from an adjacent overheating wire or nearby flame. This infusion of heat pyrolyzes material, consequently releasing hazardous and flammable gases. If the concentration of flammable vapors reaches a critical level, ignition can be achieved with or without a pilot depending on the concentration of flammable vapors and the surrounding thermal conditions [5-9]. If the resulting flame provides sufficient heating, flaming combustion of the solid can then continue. In charring materials, a solid-phase combustion process called smoldering may occur if sufficient heating, often at lower temperatures, is achieved. Regardless of the mode of combustion, if the generated combustion front sufficiently heats adjacent material the flame can spread, which increases the size of the burning region and the eventual fire hazard. While these principles are shared between terrestrial and extraterrestrial fires, changes in the gravitational field, pressure, oxygen concentrations, and the incredibly high-risk environments encountered in spaceflight require further understanding specifically for spaceflight applications.

The reduction or near elimination of gravity limits the buoyancy-induced flows around solids that would support enhanced convective heat transfer; however, it also slows the transport of flammable gases that can cause them to accumulate in some regions [10-12], as well as the heat loss, which would tend to cool the solid. Previous investigations have identified the importance of changes in gravity and burning conditions on extending the flammability boundary of certain materials, allowing them to burn at conditions in partial or micro gravity that cannot be tested or observed under Earth gravity [13]. These effects on material flammability and flame growth have only been partially characterized in terms of heat and mass transfer mechanisms between the fuel, flame, and surroundings. Radiation losses to the environment from the fuel surface and flame become increasingly significant without the buoyant flow induced by gravity, but the microgravity results also showed how mild air flows from ventilation systems can strengthen the flames with fresh oxidizer [14]. Even if the externally forced air flow could be temporarily turned off, the fuel could continue to burn through molecular diffusion effects, convective stirring from fuel vapor jetting, the flame spreading fast enough into fresh quiescent oxidizer, or the system could be hot enough to reignite when the external oxidizer flow is turned back on [15].

Past Investigations

Both ground and space-based experiments have provided a basis for understanding solid fuel combustion processes in spaceflight. Because solid fuels are often thick and their burning process requires long-duration experiments, only a limited number of opportunities have been available in microgravity. Some of these were possible onboard the International Space Station (ISS) (e.g., BASS [16-17], Confined Combustion [18-19]) and on a cargo spacecraft (i.e., SAFFIRE [20]). For instance, BASS experiments [16-17] have generally agreed with ground-based predictions of flammability, except that the limiting regimes for combustion in terms of parameters such as air flow, oxygen concentration, etc. are expanded in actual (i.e., not simulated) microgravity. This becomes a safety issue whereby materials thought to be inflammable via ground-based testing may present spaceflight hazards under a wider range of conditions. SAFFIRE was a significant development as the first and only set of experiments investigating larger fuel samples (41 cm wide and 94 cm long). These experiments clearly identified the influence of fuel geometry, structure, and scale on concurrent and opposed flame spread in microgravity. Furthermore, they showed how a temporary flow suppression can be ineffective depending on the burning conditions. A thin charring sample (cotton) kept smoldering (with possible flamelets) after the flow was turned off for 70 s, and eventually reignited when the flow was turned back on [20]. A similar behavior was observed for thick acrylic materials, where the vapor jetting occurring in the pyrolysis region provided enough mixing to keep the flame alive and growing.

Partial gravity presents new challenges as limited testing has been conducted due to the lack of facilities for long-duration experiments. The lack of direct tests in partial gravity is troubling from the viewpoint of fire safety because available results suggest that Lunar and Martian gravity levels could actually enhance the propensity for concurrent-flow flame spread [21]. The limited available testing to date was conducted in aircraft flying parabolic trajectories or in a centrifuge on the 5.2 s drop tower [21-23]. This testing identified a "sweet spot" for expanded flammability regimes with enhanced propensity for flame spread close to Lunar gravity conditions.

Research Needs

Despite improvements in our understanding of solid fuel combustion, our accumulated experiments and modeling have not yet led to an era of predictive fire safety during spaceflight as it has in the built-on-Earth (1g) environment. In 1g a robust understanding of solid-phase kinetics, a rich experimental dataset, and continuous model development have allowed for *performance-based design of fire protection systems*: here, fire initiation, growth, spread, and suppression effectiveness can be predicted and tested. While micro-and partial-g applications will be more challenging, improved understanding offers the possibility of approaching this guideline such that long duration spaceflight missions as well as long term partial gravity habitation can be safely conducted. Specific scientific challenges addressing these issues are outlined below.

Solid phase chemical kinetics are poorly understood both for specific materials and conditions encountered in spaceflight. While the combustion community has approached gas-phase chemical kinetic modeling with great vigor [24], relatively little work has appeared by comparison on systematic solid-phase kinetics. Specific to microgravity, there has been even less work, or application, of advanced solid-phase kinetic studies of materials. This is important as the rate of thermal degradation in the solid phase controls the release of flammable vapors. Although on Earth it is often the case that simple rate equations correlated with temperature are adequate, this may no longer be the case for space applications. In spacecraft, changes in pressure and oxygen concentration, as well as the use of novel materials, play an important role in the solid phase chemical degradation and decomposition process. For fire to become more predictive in space, solid-phase kinetics must be more broadly incorporated to supplement the limited experiments under realistic conditions that are possible. This approach may be helpful in the selection of novel materials for long duration spaceflight because many fire retardants are no longer considered safe:

the evaluation of solid phase kinetics is an important means for assessing the action (and possibly the inaction) of fire retardants. Further description of this degradation will also assist with the prediction of effluents, whether used to assess toxicity or heat-release rates.

The processes that control solid phase degradation in microgravity have not been studied, hence it is unknown what differences may arise with the 1-g studies. For example, in a degrading cellulosic fuel, part of the fundamental mechanism of vapor released from the degrading solid occurs through a web of tortuous paths in the solid as it degrades to a char. This flow is largely driven by the temperature difference between the flame, in-depth solid, and the associated buoyant flow that is established thereby. Since buoyancy is lacking in microgravity, there may be additional channels for vapor expulsion that form the dominant part in the mass transfer process.

Solid phase physical processes in terms of basic transport, material breakdown, and coupled communication with the surrounding gas phase are poorly understood. Since the flame exists in the gas phase (unless smoldering occurs), volatile gases called pyrolysates must "escape" into the gas phase where they encounter flowing oxidant. The nature of the process by which this communication occurs differs depending on the type of material. For example, it has been shown that thermoplastic materials can form internal bubbles that transport volatile gases to the surface when they burst [25,26]. Not only that, but the bursting bubbles generate local flows that can enhance the survivability of the flame [27]. As another example, it has recently been shown that charring materials can form deep fissures and cracks, which serve to link the in-depth solid material (which is degrading) via tortuous paths to the gas phase above it [28-30]. In microgravity the notion of "above" or "below" is largely irrelevant, and so this mode of transport (as well as bubble transport for thermoplastics) can always be relevant. In the case of partial gravity there will be asymmetry, although the influences of this are entirely unknown for problems involving inside-to-outside transport. New methods of analysis of solid phase processes, such as the transformative theoretical/computational solution method known as "peridynamics," have recently become available and can be deployed to study the thermal breakdown of materials in microgravity [31]. Older, but still sophisticated, methods based on the Boltzmann equation and the evaluation of its moments to generate the conservation equations can also be deployed when more accurate measurements of in-depth bubble distribution functions can be made.

The influence of scale and geometry plays an outsize role in the ignition, growth, and eventual development of fires in micro and partial gravity. On Earth, geometry often affects solid phase combustion via modification of the direction of buoyant forces (e.g., tilted samples) or through different thicknesses of fuels which exhibit steady thermally thin or acceleratory thermally thick behavior [32]. Solid phase materials are particularly affected by their surroundings in micro and partial gravity fires as the role of buoyancy is diminished and re-radiation between surfaces and small changes such as "tripped" flows serve to influence fire growth. Such a change was observed in the SAFFIRE experiments where "peeling" from upstream cotton experiments affected downstream testing on PMMA, substantially altering downstream fire spread and growth [20]. Examining these effects is incredibly challenging in spaceflight as an appropriate scale must be reached, so new approaches for scaling and modeling should be developed alongside further experiments. This may include further pursuit of pressure modeling, where lower pressures on Earth simulate *some* effects of microgravity on fire, however these may not all be realistic with associated changes in mass and heat transfer arising from lower pressures [33,34]. While the connection between these methods and the condition of partial gravity flames and fire spread have not been established, the influence of pressure and gravity on characteristics such as the heat-release rate of fires have been proposed by de Ris [35].

As knowledge accumulates, there is also potential to further enhance and possibly multiply our understanding between different scales by using machine learning (ML) and other tools based on artificial intelligence (AI) methods. These modern techniques may serve to establish heretofore unnoticed or neglected correlations between limited experiments on materials in spaceflight and the comparatively extensive work done in 1-g; however, correlations must remain grounded in chemical and physical properties known to scale [36].

Lithium-ion batteries have become ubiquitous in electronics applications. As a consequence, they are ever present in spaceflight from the craft itself (i.e., the myriad electronic connections and devices) to laptops, cameras, and many other on-board electronics for standard human use. The high energy density that is stored in these components raises significant fire safety hazard considerations as they can be released under pressure from sealed packages. Battery failure often occurs when internal faults or external damage cause thermal runaway within a single battery cell. Spaceflight applications present new challenges – changes in pressure and gravity may considerably change the way in which cooling occurs over batteries and affect the likelihood or process of thermal runaway. Cooling of battery cells may in particular be influenced by the absence or reduction of buoyancy in required cooling processes. The potential release of large amounts of energy and toxic gases into spacecraft present enormous safety concerns. Focused study is urgently needed to classify the energy and species release from batteries used aboard spacecraft, to investigate effects on cooling of cells caused by microgravity and low-pressure conditions, as well as approaches to extinguishing potentially failing, and actively burning, batteries [37].

Partial gravity presents a prime opportunity for fire to grow as the condition of limited buoyancy leads to a buildup of flammable vapors. By contrast, full buoyancy "fans" the flames as they continue to spread and grow. Heat and mass transfer processes under these unique conditions are not well understood. Neither is the response of the fuel to these altered heating conditions. There are opportunities for additional experiments on earth, such as through the proposed upgrade to the Zero Gravity Research Facility at NASA Glenn Research Center to include a controlled fall capsule for partial gravity, a space-based centrifuge platform, or testing time on the lunar surface, which could all supplement experimental knowledge of partial gravity combustion of solid phase fuels. However, a connection between actual microgravity and simulated microgravity, as has been established in the Narrow Channel Apparatus in prior BASS and BASS-II research [38] or pressure modeling [33,34], is completely absent for the condition of partial gravity. An open, and very challenging question is therefore: "How does one simulate, on Earth, the partial gravity conditions encountered in destinations such as the Moon, or Mars?."

Experimental Facility and Computational Needs

On Earth, standard apparatus have been designed to evaluate material flammability from the microscale all the way to full room tests [39]. While some tests are similar to NASA's upward flame spread STD-6001 Test 1 in offering a pass/fail criteria for material flammability [40], earth-based tests such as the microscale calorimeter [41], cone calorimeter [42], lateral ignition and spread test [43,44], and others can provide quantitative measures of ignition, flame spread, and sometimes material properties alongside pass/fail criteria, enabling future performance-based design of whole compartments [45]. Despite some efforts [46], none of these apparatus are specially adapted to restricted gravity conditions. Some apparatus, such as the Narrow Channel Apparatus (NCA) may serve as a model to follow. Here, a geometric alteration of the flame spread process (restriction to a very narrow channel to suppress buoyancy) produced flame spread measurements that were in good agreement with actual microgravity measurements to date [47]. More measurements in microgravity and actual or simulated partial gravity are still sought.

In general, it is true that much of flame spread and flammability research involves diagnostic measurements that lack sophistication. Part of this is a necessary condition, because sophisticated diagnostics require simple physical configurations; however, clear opportunities exist to improve both physical understanding and the validation data sets needed for numerical modeling. These include laser diagnostics for low-speed flow and spatial chemical species measurements, multispectral imaging for thermal measurements on solids, and gas sensing for integrated toxic product and heat-release measurements. Extension of 1g diagnostics to microgravity conditions has also been performed primarily over axisymmetric configurations [48, 49] such as electric wires, providing detail mappings and new insights regarding radiative heat transfer, radiative quenching, and smoke emission [50-52], but without application to more complex, realistic configurations. Flame and fire spread are highly dependent on the transfer of heat from a flame to the surface immediately ahead of the flame; therefore, even increased densities of simple thermocouples and heat-flux gauges may improve our physical understanding. Alongside scaling, analytical methods, and directed simulation, dissection of the flame structure may be accomplished to improve our understanding of fire in micro and partial gravity.

Numerical modeling for coupled solid and gas phase combustion (i.e., fire) is important for spacecraft fire safety and the broader fire science community [53]. Current numerical models for microgravity fires [54-56] solve fully elliptic Navier-Stokes equations of mass, momentum, species, and energy for the gas phase. These models may include flame radiation, finite-rate kinetics, soot formation, conduction, and solid fuel thermal decomposition. Such models have replicated features of fires in small (~ cm) [57,58] and moderate (~1 m) scale [59,60] microgravity experiments for *idealized* solid materials.

It is anticipated that more materials will be used when humans build a permanent habitat on the Lunar surface requiring additional phenomena to be incorporated in the solid model. For example, most previous models did not consider pyrolysate mass transport in-depth for solid materials. Charring, smoldering, swelling, shrinkage, and in-depth solid radiation were not modeled either. In addition, determination of solid kinetic models (both decomposition steps and kinetic parameters) remains challenging. The model parameters depend on the geometry and scale of the test to which they are deduced. Gravity can also play a role for thick samples (when inhomogeneity presents). To simulate realistic solid materials, considerable efforts need to be made in multi-dimensional multi-physics solid phase modeling.

For the gas-phase, most microgravity models rely on Direct Numerical Simulation (DNS) to capture the gas-solid coupling, a key factor for robust fire modeling. However, DNS is computationally expensive and might not be a practical strategy in partial gravity as the fire is expected to scale up with buoyant flows. In normal gravity, most computational fire models are based on Large-Eddy Simulation (LES). Assumptions are needed for sub-grid phenomena and the near-wall (solid-fire interface) phenomena. However, these assumptions have been based solely on Earth observations. Over the next decade, a novel numerical strategy will be needed to precisely capture the solid-gas interaction and effectively handle the thermal, chemical, and transport processes in the gas phase.

References

1. Huang, X, Yuji N, and Urban, D. "Introduction to special issue on spacecraft fire safety." (2020): 1-4. Fire Technology. https://doi.org/10.1007/s10694-019-00941-6
2. Friedman R (1996) Fire safety in spacecraft. Fire Mater 20:235–243. https://doi.org/10.1002/(SICI)1099-1018(199609)20:5%3C235::AID-FAM580%3E3.0.CO;2-Y
3. Ross HD (2001) Microgravity combustion: fire in free fall. Academic Press, New York (ISBN: 0080549977, 9780080549972)
4. 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
5. Fernandez-Pello, A. C. (1979). Flame spread in a forward forced flow. Combustion and Flame, 36, 63-78. https://doi.org/10.1016/0010-2180(79)90046-4
6. G. H. Markstein and J. de Ris, "Upward fire spread over textiles," Proceedings of the Combustion Institute, vol. 14, no. 1, pp. 1085-1097, 1973. https://doi.org/10.1016/S0082-0784(73)80098-0
7. H. T. Loh and A. C. Fernandez-Pello, "Flow assisted flame spread over thermally thin fuels," Fire Safety Science, vol. 1, pp. 65-74, 1986. doi:10.3801/IAFSS.FSS.1-65
8. K. Saito, J. G. Quintiere and F. A. Williams, "Upward turbulent flame spread," Fire Safety Science, vol. 1, pp. 75-86, 1986. doi:10.3801/IAFSS.FSS.1-75
9. L. K. Honda and P. D. Ronney, "Mechanisms of concurrent-flow flame spread over solid fuel beds," Proceeding of Combustion Institute, vol. 28, pp. 2793-2801, 2000. https://doi.org/10.1016/S0082-0784(00)80701-8
10. M. C. Johnston, J. S. T'ien, D. E. Muff, X. Zhao, S. L. Olson and P. V. Ferkul, "Self induced buoyant blow off in upward flame spread on thin solid," Fire Safety Journal, vol. 71, pp. 279-286, 2015. https://doi.org/10.1016/j.firesaf.2014.11.007
11. S. L. Olson, P. V. Ferkul and J. S. T'ien, "Near-limit flame spread over a thin solid fuel in microgravity," Symposium (International) on Combustion, vol. 22, no. 1, pp. 1213-1222, 1988. https://doi.org/10.1016/S0082-0784(89)80132-8
12. S. L. Olson and F. J. Miller, "Experimental comparison of opposed and concurrent flame spread in a forced convective microgravity environment," Proceedings of the Combustion Institute, vol. 32, no. 2, pp. 2445-2452, 2009. https://doi.org/10.1016/j.proci.2008.05.081
13. Feier, I. I., Shih, H. Y., Sacksteder, K. R., & Tien, J. S. (2002). Upward flame spread over thin solids in partial gravity. Proceedings of the Combustion Institute, 29(2), 2569-2577. https://doi.org/10.1016/S1540-7489(02)80313-3
14. Olson, S. L., Ferkul, P. V., Microgravity flammability boundary for PMMA rods in axial stagnation flow: Experimental results and energy balance analyses, Combustion and Flame 180 (2017), pp. 217-229. https://doi.org/10.1016/j.combustflame.2017.03.001
15. Urban, D. L., Ferkul, P., Olson, S., Ruff, G. A., Easton, J., James, S., Liao, Y. T., Li, C., Fernandez-Pello, C., Toreo, J. L., Legros, G., Eigenbrod, C., Smirnov, N., Fujita, O., Rouvreau, S., Toth, B., and Jomaas, G. (2019). Flame spread: effects of microgravity and scale. Combustion and Flame, 199, 168-182. https://doi.org/10.1016/j.combustflame.2018.10.012
16. Olson, S., Ferkul, P., Fernandez-Pello, C., Miller, F., Wichman, I., & T'Ien, J. (2019, July). Flammability limits from BASS-II testing in microgravity compared to normal

gravity limits. 49th International Conference on Environmental Systems. https://hdl.handle.net/2346/84505

17. 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, no. 2, pp. 2971-2978, 2017. https://doi.org/10.1016/j.proci.2016.06.028
18. Y. Li, Y.-T. Liao, P. V. Ferkul, M. C. Johnston, and C. Bunnell: Confined Combustion of Polymeric Solid Materials in Microgravity, Combustion and Flame, Vol. 234, 111637, 2021. https://doi.org/10.1016/j.combustflame.2021.111637
19. Y. Li, Y.-T. T. Liao, P. V. Ferkul, M. C. Johnston, and C. Bunnell: Experimental Study of Concurrent-Flow Flame Spread over Thin Solids in Confined Space in Microgravity, Combustion and Flame, Vol. 227, pp. 39-51, 2021. https://doi.org/10.1016/j.combustflame.2020.12.042
20. Urban, D.L., Ruff, G.A., Ferkul, P., Easton, J., Owens, J., Olson, S., Meyer, M., Fortenberry, C., Brooker, J., Graf, J., Casteel, M., Toth, B., Meyer, F., Eigenbrod, C., T'ien, J.S., Liao, Y-T. T., Fernandez-Pello, A.C., Legros, G., Guibaud, A., Smirnov, N., Fujita, O., Jomaas, G., Fire safety implications of preliminary results from Saffire IV and V experiments on large scale spacecraft fires, 50th Int. Conf. Environmental Systems, 12-15 July 2021. https://hdl.handle.net/2346/87224
21. 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. https://doi.org/10.1016/S0082-0784(06)80816-7
22. I. I. Feier, H.-Y. Shih, K. R. Sacksteder and J. S. T'ien, "Upward flame spread over thin solids in partial gravity," Symposium (International) on Combustion, vol. 29, no. 2, pp. 2569-2577, 2002. https://doi.org/10.1016/S1540-7489(02)80313-3
23. Kleinhenz, J., Feier, I. I., Hsu, S. Y., James, S., Ferkul, P. V., and Sacksteder, K. R. (2008). Pressure modeling of upward flame spread and burning rates over solids in partial gravity. Combustion and flame, 154(4), 637-643. https://doi.org/10.1016/j.combustflame.2008.05.023
24. Miller, James A., Robert J. Kee, and Charles K. Westbrook. "Chemical kinetics and combustion modeling." Annual Review of Physical Chemistry 41.1 (1990): 345-387. https://doi.org/10.1146/annurev.pc.41.100190.002021
25. Kashiwagi, T. and Ohlenmiller, T., "A Study of Oxygen Effects on Nonflaming Transient Gasification of PMMA and PE During Thermal Irradiation," 19th Symposium on Combustion, pp. 815-823 (1982). https://doi.org/10.1016/S0082-0784(82)80257-9
26. Butler, K. M., "A Numerical Model for Combustion of Bubbling Thermoplastic Materials in Microgravity," NISTIR 6894, U. S. Department of Commerce, August (2002).
27. Olson, S. L., & Hegde, U. (1994). Imposed radiation effects on flame spread over black pmma in low gravity. Eastern States Section Fall Technical Meeting of the Combustion Inst., January 1994. https://ntrs.nasa.gov/citations/19970003275
28. Nguyen, Y. T., Pence, T. J. and Wichman, I. S., "Crack Formation During Solid Pyrolysis: Evolution, Pattern Formation and Statistical Behaviour," Proceedings of the Royal Society A, Vol. 475, 20190211. http://dx.doi.org/10.1098/rspa.2019.0211.

29. Nguyen, Y. T., Wichman, I. S. and Pence, T. J., "Cracking During Flame Spread over Pyrolyzing Solids," Progress in Scale Modeling, Vol. 1 (2020). https://doi.org/10.13023/psmij.2020.09
30. Wichman, I. S., Nguyen, Y. and Pence, T. J., "A Model for Crack Formation During Active Solid Pyrolysis of a Char-Forming Solid: Crack Patterns; Surface Area Generation; Volatile Mass Efflux, Combustion Theory and Modelling, 2020. https://doi.org/10.1080/13647830.2020.1772510.
31. Javili, A., Morasata, R., Oterkus, E., & Oterkus, S. (2019). Peridynamics review. Mathematics and Mechanics of Solids, 24(11), 3714-3739. https://doi.org/10.1177/1081286518803411
32. Gollner, M. J., Miller, C. H., Tang, W., & Singh, A. V. (2017). The effect of flow and geometry on concurrent flame spread. Fire Safety Journal, 91, 68-78. https://doi.org/10.1016/j.firesaf.2017.05.007
33. Thomsen, M., Fernandez-Pello, C., Urban, D. L., Ruff, G. A., and Olson, S. L. (2019). On simulating concurrent flame spread in reduced gravity by reducing ambient pressure. Proceedings of the Combustion Institute, 37(3), 3793-3800. 10.1016/j.proci.2018.05.004
34. Kleinhenz, J., Feier, I. I., Hsu, S. Y., James, S., Ferkul, P. V., and Sacksteder, K. R. (2008). Pressure modeling of upward flame spread and burning rates over solids in partial gravity. Combustion and flame, 154(4), 637-643. 10.1016/j.combustflame.2008.05.023
35. J.L. de Ris, "Mechanism of buoyant turbulent diffusion flames", Procedia Engineering 62, pp. 13-27, 2013. https://doi.org/10.1016/j.proeng.2013.08.040
36. Gagnon, L., Carey, V. P., & Fernandez-Pello, C. (2021). Using an Artificial Neural Network to Predict Flame Spread Across Electrical Wires. Journal of Energy Resources Technology, 143(9), 092305. https://doi.org/10.1115/1.4050816
37. Padilla Rosa E., Dietrich, Daniel L, Pitz, William, Ruff, Gary, Urban, David. "Battery Fire Risk Assessment" International Conference on Environmental Systems, 2021. https://ttu-ir.tdl.org/handle/2346/87240?locale-attribute=es
38. Olson, S., Ferkul, P., Fernandez-Pello, C., Miller, F., Wichman, I., & T'Ien, J. (2019, July). Flammability limits from BASS-II testing in microgravity compared to normal gravity limits. 49th International Conference on Environmental Systems.
39. Janssens, M. L. (2005). Material flammability. In Handbook of Environmental Degradation of Materials (pp. 207-225). William Andrew Publishing. https://www.elsevier.com/books/handbook-of-environmental-degradation-of-materials/kutz/978-0-323-52472-8
40. NASA STD-6001, Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion,, Test 1, Upward Flame Propagation, (formerly NHB 8060.1C), (February 9, 1998).
41. Lyon, R. E., & Walters, R. (2002). A microscale combustion calorimeter. Federal Aviation Administration, Washington DC Office of Aviation Research. https://apps.dtic.mil/sti/citations/ADA401490
42. Babrauskas, V. (2016). The cone calorimeter. In SFPE handbook of fire protection engineering (pp. 952-980). Springer, New York, NY.
43. Quintiere, J. (1981). A simplified theory for generalizing results from a radiant panel rate of flame spread apparatus. Fire and Materials, 5(2), 52-60. https://doi.org/10.1002/fam.810050204

44. Quintiere, J., Harkleroad, M., & Walton, D. (1983). Measurement of material flame spread properties. Combustion Science and Technology, 32(1-4), 67-89 https://doi.org/10.1080/00102208308923653
45. Quintiere, J. G. (1993). A simulation model for fire growth on materials subject to a room-corner test. Fire Safety Journal, 20(4), 313-339. https://doi.org/10.1016/0379-7112(93)90053-S
46. Fujita, O. (2015). Solid combustion research in microgravity as a basis of fire safety in space. Proceedings of the Combustion Institute, 35(3), 2487-2502. 10.1016/j.proci.2014.08.010
47. Wichman, I. S., Olson, S. L., Miller, F. J. and Tanaya, S. A., "On the Uses of the Narrow Channel Apparatus in Evaluations of Flame and Flamelet Spread over Cellulosic Materials," Fire and Materials. Online: 3 JUL 2012. https://dx.doi.org/10.1002/fam.2143. Print: Vol. 37/7, pp. 503-519 (2013).
48. Guibaud, A., Citerne, J.M., Orlac'h, J.M., Fujita, O., Consalvi, J.L., Torero, J.L. and Legros, G., 2019. Broadband modulated absorption/emission technique to probe sooting flames: Implementation, validation, and limitations. Proceedings of the Combustion Institute, 37(3), pp.3959-3966. https://doi.org/10.1016/j.proci.2018.06.199
49. Comparions with 2-color pyrometry for future space-bound diagnostics: Guibaud, A., Citerne, J.M., Consalvi, J.L., Torero, J.L., Fujita, O., Kikuchi, M., Ferkul, P.V., Smirnov, N., Jomaas, G., Toth, B. and Rouvreau, S., 2021. Accessing the soot-related radiative heat feedback in a flame spreading in microgravity: optical designs and associated limitations. Proceedings of the Combustion Institute, 38(3), pp.4805-4814. https://doi.org/10.1016/j.proci.2020.06.036
50. Guibaud, A., Citerne, J.M., Consalvi, J.L., Fujita, O., Torero, J. and Legros, G., 2020. Experimental evaluation of flame radiative feedback: methodology and application to opposed flame spread over coated wires in microgravity. Fire Technology, 56(1), pp.185-207. https://doi.org/10.1007/s10694-019-00853-5
51. Guibaud, A., Citerne, J.M., Consalvi, J.L. and Legros, G., 2020. On the effects of opposed flow conditions on non-buoyant flames spreading over polyethylene-coated wires–Part I: Spread rate and soot production. Combustion and Flame, 221, pp.530-543. https://doi.org/10.1016/j.combustflame.2020.07.044
52. Guibaud, A., Citerne, J.M., Consalvi, J.L. and Legros, G., 2020. On the effects of opposed flow conditions on non-buoyant flames spreading over polyethylene-coated wires–Part II: Soot oxidation quenching and smoke release. Combustion and Flame, 221, pp.544-551. https://doi.org/10.1016/j.combustflame.2020.08.038
53. Brown, A., Bruns, M., Gollner, M., Hewson, J., Maragkos, G., Marshall, A., McDermott, R., Merci, B., Rogaume, T., Stoliarov, S. and Torero, J., 2018. Proceedings of the first workshop organized by the IAFSS Working Group on Measurement and Computation of Fire Phenomena (MaCFP). *Fire safety journal*, *101*, pp.1-17.1-17.https://doi.org/10.1016/j.firesaf.2018.08.009
54. C. Li, Y.-T. T. Liao, J. S. T'ien, D. L. Urban, P. Ferkul, S. Olson, G. A. Ruff, and J. Easton: Transient Flame Growth and Spread Processes over a Large Solid Fabric in Concurrent Low-Speed Flows in Microgravity – Model versus Experiment, Proceedings of the Combustion Institute, Vol. 37, Issue 3, pp. 4163-4171, 2019 https://doi.org/10.1016/j.proci.2018.05.168

55. J.-L. Consalvi, A. Guibaud, A. Coimbra, J.-M. Citerne, and G. Legros, "Effects of oxygen depletion on soot production, emission and radiative heat transfer in opposed-flow flame spreading over insulated wire in microgravity", Combustion and Flame, vol. 230, 111447, 2021. https://doi.org/10.1016/j.combustflame.2021.111447
56. A. Guibaud, J.-L. Consalvi, J.-M. Citerne, and G. Legros, "Pressure Effects on the Soot Production and Radiative Heat Transfer of Non-Buoyant Laminar Diffusion Flames Spreading in Opposed Flow over Insulated Wires", Combustion and Flame, vol. 222, pp. 383-391, 2020. https://doi.org/10.1016/j.combustflame.2020.09.003
57. 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. 10.1016/j.proci.2016.06.028
58. Y. Li, Y.-T. Liao: Numerical Study of Flame Spread in a Narrow Flow Duct in Microgravity – Effects of Flow Confinement and Radiation Reflection, Combustion and Flame, in press. https://doi.org/10.1016/j.combustflame.2021.111714
59. C. Li and Y.-T. T. Liao: Effects of Ambient Conditions on Concurrent-Flow Flame Spread over a Wide Thin Solid in Microgravity, Proceedings of the Combustion Institute, Vol. 38, Issue 3 pp. 4775-4784, 2021. https://dx.doi.org/10.1016/j.proci.2020.05.011
60. C. Li, Y.-T. T. Liao, J. S. T'ien, D. L. Urban, P. Ferkul, S. Olson, G. A. Ruff, and J. Easton: Transient Flame Growth and Spread Processes over a Large Solid Fabric in Concurrent Low-Speed Flows in Microgravity – Model versus Experiment, Proceedings of the Combustion Institute, Vol. 37, Issue 3, pp. 4163-4171, 2019 https://doi.org/10.1016/j.proci.2018.05.168