Most Probable Fire Scenarios in Spacecraft and Extraterrestrial Habitats - Why NASA's Current Test 1 Might Not Always Be Conservative

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NASA's current method of material screening determines fire resistance under conditions representing a worst-case for normal gravity flammability - the Upward Flame Propagation Test (Test 1[1]). Its simple pass-fail criteria eliminates materials that burn for more than 12 inches from a standardized ignition source. In addition, if a material drips burning pieces that ignite a flammable fabric below, it fails.

The applicability of Test 1 to fires in microgravity and extraterrestrial environments, however, is uncertain because the relationship between this buoyancy-dominated test and actual extraterrestrial fire hazards is not understood. There is compelling evidence that the Test 1 may not be the worst case for spacecraft fires, and we don't have enough information to assess if it is adequate at Lunar or Martian gravity levels.

Microgravity Flames do Strange Things

Flames in microgravity are known to preferentially spread upwind (ie opposed flow) [2], not downwind (i.e. concurrent flow) as in the normal gravity upward flammability screening Test 1. Over most of the range of air ventilation rates (5-20 cm/s) comparable to spacecraft ventilation, upstream flame spread was the only viable flame. Only when the flow becomes strong enough (estimated to be $\geq$ 10 cm/s), will at least a partial downstream flame become viable. Numerical and experimental results [7] predict an upstream flame only at 5.0 cm/s, an upstream flame and two localized edge flames propagating downstream at 10.0 cm/s, and both an upstream and downstream flame at 20.0 cm/s.

This propensity to spread upwind does not only occur for thin materials, but also occurs for thicker materials and other shapes. For example, experiments were conducted aboard the Mir space station using plastic cylinders. The intent was to burn them with a concurrent flame spread similar to that of Test 1. However, rather than spread along the rod, the flame stabilized at the front tip of the rod and burned like a candle flame at the end of a fat wick [3,4],

Under the right flow conditions in space, things will burn that won't burn on Earth. This is most clearly demonstrated by a flammability map [5,6]. In the opposed flow flame spread flammability map for a cellulose fuel, the LOI, or limiting oxygen index on Earth in opposed flow is 16.5% O_2. However, if the flow is on the order of spacecraft ventilation (5-20 cm/s), flames can be sustained even at 14 % O_2. Thus a normal gravity measure of flammability does not guarantee that the material won't burn in space.

Some preliminary work on independent opposed and concurrent flame spread was conducted in a glovebox experiment [8]. The flame spread results in the cabin air (~21% O2) show that the quenching region spans from +0.5 to -2 cm/s, so even correcting for the small spread rate, the concurrent flame has a higher flow flammability boundary than the opposed flow flame.

On the Moon or Mars (0.17g and 0.38 g, respectively), where buoyant flows will be greater than 20 cm/s, the concurrent flame spread will be viable simultaneously with any opposed flow flame. Experiments conducted aboard the KC-135 [9] demonstrate the faster burning of concurrent flames in partial gravity environments. These higher flow test conditions are on the blowoff side of the flammability boundary.

If a fire is initiated, and the crew takes steps to extinguish it, the first line of defense is to turn off the flow. As demonstrated by the data above, the flame cannot survive indefinitely without a supply of fresh oxygen. Once the fire is out, the crew would reactivate the flow to clean up any residual smoke.

However, experiments have shown that even a very slight air flow of a fraction of a cm/s [4] is sufficient to allow the flame to survive. These flames can become almost undetectable (small, non-luminous) and yet persist for many minutes [10, 11] for a fingering flame spread observed under very weak ventilation. The tiny flamelet (~6 mm x 2mm) spread steadily, albeit slowly, for 80 seconds. When the flow was turned up 100-fold to 50 cm/s, the flame did not blow out as one would expect, but flared up into a much larger spreading flame. The fingering behavior is unique to low gravity. The formation of these different flame structures is due to changes in lateral diffusive flux of oxygen from the outer flow to the flame, convective flow patterns and oxygen shadow caused by oxygen consumption at the upstream flamelet. These types of behaviors must be known and understood so that the crew can watch for them.

References

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