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Zero-Gravity Centrifuge Used for the Evaluation of Material Flammability in Lunar Gravity

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Experiments were conducted to examine the maximum oxygen concentration at which three different materials ignited in lunar gravity would self-extinguish. All three materials burned to lower oxygen concentrations in lunar gravity than in normal gravity, although the low-gravity extinction-limit criteria are not the same as 1 *g*, due to time constraints in drop testing. The margin of safety of the 1 *g* test method relative to actual low-gravity material performance is presented. In broader application, a modified NASA test protocol is suggested to provide the option of selecting better materials based on the best margin of safety relative to the use environment, as opposed to what would be considered just "passing" from a flammability point of view.

I. Introduction

ONE of the major lessons learned from the Apollo 1 fire is that it is impossible to eliminate all ignition sources [1], so fire prevention is achieved in spacecraft through material controls near potential ignition sources and the use of fire-resistant materials. Currently, NASA-STD-6001 [2] test 1 is the major method used to evaluate flammability of materials intended for use in habitable environments of U.S. spacecraft. The method is a pass/fail upward flame propagation test conducted in the most severe flaming combustion environment (oxygen concentration, pressure) expected in the spacecraft. Materials that do not self-extinguish after 6 in. of burning must undergo other special considerations and/or tests if they are to be used on spacecraft.

After Skylab, the space shuttle and the International Space Station (ISS) have operated at normal sea-level conditions (air, 21% oxygen, and 79% nitrogen by volume at 101 kPa pressure), except for brief pre-extravehicular-activity (EVA) activities when oxygen levels are increased for a short period of time to 30% oxygen while the total pressure is lowered to 70.3 kPa. Many of the materials now used in the shuttle or on ISS are therefore only tested and rated to 30% oxygen at 70.3 kPa.

For future space missions, it is desirable to increase the oxygen concentration and reduce the total pressure of the cabin or habitat [3]. This atmosphere has the advantages of requiring a lower mass of inert gas (nitrogen), lowering vehicle internal pressures, and shortening or eliminating the prebreathing time required to purge nitrogen from the bloodstream before EVA. However, an enriched oxygen atmosphere also has a significant disadvantage: increased flammability of materials.

Recently, a modified test 1 has been evaluated [4–7] to provide additional information about the flammability limits of the material and not just a pass/fail statement regarding its use in the worst-case atmosphere. This approach allows a better understanding of the margin of safety for the material in the real-use atmosphere.

In the modified procedure [4], the oxygen concentration in test 1 is successively reduced to identify the upward-limiting oxygen index (ULOI; 1 *g*) and the maximum oxygen concentration (MOC; 1 *g*) that consistently results in self-extinguishment of the material. The 1 *g* ULOI is defined as the oxygen concentration at which a material passes the NASA-STD-6001 [2] test 1 burn-length criterion approximately half the time. The 1 *g* MOC is defined as the oxygen concentration where at least five samples passed the burning criterion (according to the NASA-STD-6001 [2] test 1 definition) and where at least one sample failed in the environment that contained 1% more oxygen by volume. This is shown schematically for an arbitrary material in Fig. 1.

II. Experiment Description

To better understand a material's flammability limits at reduced gravity, we evaluate three materials in lunar gravity. These tests are combined with previous 1 *g* tests performed at NASA's White Sands Test Facility (WSTF) and microgravity tests with forced convection at NASA's John H. Glenn Research Center at Lewis Field (GRC). Understanding the flammability of these three materials in the very different flow environments is important to assess not only the performance of the individual material, but also the effectiveness of the screening test (NASA test 1).

To create a lunar-gravity environment, an artificial-gravity (or partial-gravity) centrifuge was used in a drop-tower environment. The rotating apparatus produces an effective centrifugal force that can be varied, depending on the rotation rate. The apparatus is subject to the usual constraints on size and volume for the Zero Gravity Research Facility at the NASA GRC [8]. The centrifuge consists of a flat circular base (turntable) and the chamber dome. The chamber was designed to maximize the rotation radius possible on the drop bus. The strength of the chamber was built to permit tests up to 2 atm absolute pressure. A photograph and schematic of the chamber are shown in Fig. 2. Overall capabilities are summarized in Table 1.

Electrical feedthrough is performed via slip rings to permit continuous uninterrupted rotation. There is some volume available on the chamber (both internally and externally) to permit specialized hardware to be mounted. Centrifugal accelerations from about 0 to 1.5 *g* can be established. Only constant accelerations are considered, but the hardware permits variable rotational acceleration tests (ramp rates on the order of 1 rad/s^2 are possible). All the internal volume is available for an experiment; however, some of this is taken up by auxiliary electronics boxes, etc. The experiment is mounted to the turntable, which has a regular pattern of bolt holes to allow for flexibility in positioning. Care was taken to balance the mass distribution in the rotating structure to minimize vibration.

The fuels used include Ultem® 1000, Nomex® HT90-40, and Mylar® G or Melinex® 515. These three materials were evaluated for microgravity and lunar flammability limits to compare with the 1 *g* ULOI and 1 *g* MOC.

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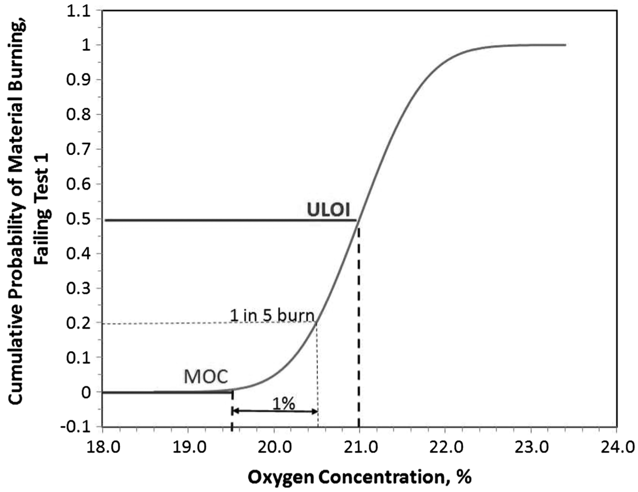

Fig. 1 Near-limit probability that an arbitrary material will burn or not, with the ULOI and MOC indicated.

Ultem 1000 (polyetherimide) in 0.25-mm-thick film is inherently fire-retardant, with charring characteristics, a very low smoke signature, very low smoke toxicity, and a low heat-release rate.

Nomex HT90-40 is a 0.30-mm-thick fire-retardant aromatic nylon fabric that does not melt or drip as it burns. When exposed to a heat source, the Nomex fibers swell and seal the spaces between the fibers, stopping air movement through the fabric and thus inhibiting heat transfer through the fabric.

Mylar G is a 0.13-mm-thick plastic film made from polyethylene terephthalate. It is not fire-retardant, melts as it burns, and was selected primarily for its noncharring character. The WSTF comparison tests used Melinex 515, a very similar Dupont Teijin film.

The solid fuel sample was mounted within the chamber, as shown schematically in Fig. 3. The fuel sheet is mounted parallel to the turntable and near the outer periphery. It is sandwiched between two 0.13-mm-thick mica rectangular frames (5×15 cm opening), which are in turn sandwiched between 0.25-mm-thick stainless steel rectangular frames. The fuel is ignited with a hot wire at the furthest point from the center so that a concurrent-flow flame-spread geometry is established.

The chamber is filled to the desired atmosphere. Before the drop, the chamber is rotated for at least 5 min to allow the interior gases to come up to speed (solid-body rotation). To achieve lunar-gravity levels, the rotation rate required is 20.4 rpm. Lunar-gravity level is achieved at the radial distance of the igniter.

To maximize available drop time, the goal was to get the samples ignited right at the drop. For the Ultem and Nomex samples, the igniter current was initiated 2.1 s before drop and was on for a total of 3.5 s. For the Mylar samples, ignition was easier to achieve. The igniter current was initiated 1 s before the drop and was on for a total of 2 s. The Mylar sample ignitions were assisted using a small strip of thin tissue paper (Kimwipes, 0.5 cm width), which helped provide a uniform energy deposition to this melting fuel. For all cases, the average igniter power was 58 W.

The goal was to provide just enough energy to provide ignition in a reasonable time. While the flame response depends to some degree on the ignition energy, it was beyond the scope of this project to examine this effect in detail. Furthermore, due to the expense of the drop tests, an extensive repeatability and uncertainty study was not feasible. Instead, we took care to keep the ignition consistent for each material.

Experiments were conducted to examine the maximum oxygen concentration at which the three different materials burning in lunar gravity would self-extinguish. (Experiment materials and test conditions were chosen to match earlier tests performed at WSTF, described below.) The MOC for these tests was defined as the maximum oxygen concentration at which the flame was observed to self-extinguish during the drop time. The ULOI criterion was the minimum oxygen concentration at which the flame survived the full drop time. Images of the ULOI conditions for each are shown in Fig. 4. Since it is possible that the very weak flames might have extinguished given the longer time in lunar gravity, the limits found are conservative.[‡]

The NASA WSTF tests were conducted using the STD-6001 [2] test 1 protocol, except a hot-wire igniter was used to ignite the samples instead of a chemical igniter, to better compare with the low-gravity results. This is because the chemical igniter provides heat for 25 s, and the longest low-gravity time is 5 s. In addition, the atmosphere of the test was modified to find the ULOI and MOC, as described earlier. In Fig. 5, flame images shortly after ignition at the ULOI conditions are shown [9]. In these tests, the flame consumed the full 15 cm of material and thus failed the test. At the MOC, the material burned less than the required 15 cm, although usually at least 5–10 cm.

The microgravity tests were performed in a low-speed flow tunnel, shown schematically in Fig. 6. The flow tunnel provides 0–30 cm/s forced flow of gas (0 to 100% O_2 in diluent) through a 20-cm-i.d. duct at 0 to 101 kPa pressure [10]. The flow system includes a second gas reservoir such that oxygen concentrations can be changed during a test. A backpressure control valve maintains chamber pressure with flow at up to 101 kPa.

For the material-flammability tests, the switching of the flow between source bottles was timed so that the sample was ignited in an enriched oxygen concentration greater than the1 g ULOI, and the test oxygen level reached the sample shortly after release into zero gravity. The established flame then had $\sim$5 s in which to respond to the new atmosphere by either extinguishing (0 g MOC) or shrinking to a reduced burning state at the lower oxygen concentration. The lowest oxygen concentration where the flame survived to the end of the drop is considered the 0 g ULOI. Whereas some of these flames may extinguish given a longer time, the limited-duration Zero Gravity Research Facility test time forces us to define these low-gravity limits in this way. These limits are clearly a conservative measure of the limits in 0 g. Note these limits are not identical to the 1 g limits, due to the intrinsic limitations of the drop time, but they are a reasonable comparison.

The flow was started before the drop to establish a steady speed and pressure in the tunnel. Ignition was initiated in 1 g, because the time for ignition was about as long as the available drop time. Once ignited, the experiment was released and the gas was switched to the

Table 1 Capabilities of the zero-gravity centrifuge

Dimensions	Cylindrical chamber 30.48 cm high, capped by hemispherical top with 81.28 inside diameter
Maximum internal radius	40.64 cm
Gross volume	299 liters
Pressure	Up to 200 kPa absolute
Maximum rotation rate	1.1 RPS
Minimum rotation rate	0.01 RPS
Maximum centrifugal acceleration	14.3 m/s^2 (1.5 g) at a 30 cm radius
Minimum centrifugal acceleration	0.001 m/s^2 (10^{-4} g) at a 30 cm radius
Video views	Two independent video views are available
Data	Thermocouple or pressure transducer channels are available
Accelerometers	Three-axis accelerometers are recorded
Power	28 V available to centrifuge via electrical feedthrough

[‡]The flames in these lunar-gravity centrifuge tests were relatively small compared with the sample size and spread only a short distance along the available fuel in the 5.18-s-duration drop-tower tests. Since the local centrifugal acceleration level is proportional to radius from the center of rotation, this means that the flame stays in a region of approximately constant gravity level (lunar gravity). On the other hand, if the flame were to spread a significant way along the fuel, the local acceleration level experienced by the flame would change appreciably as it spread.

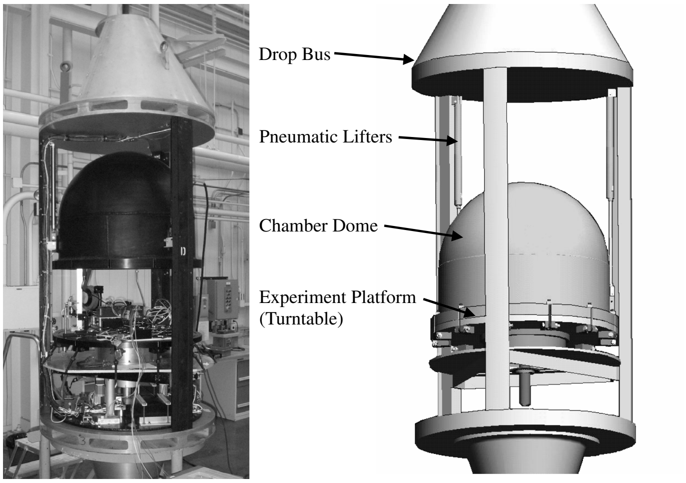

Fig. 2 Schematic and photograph of zero-gravity centrifuge.

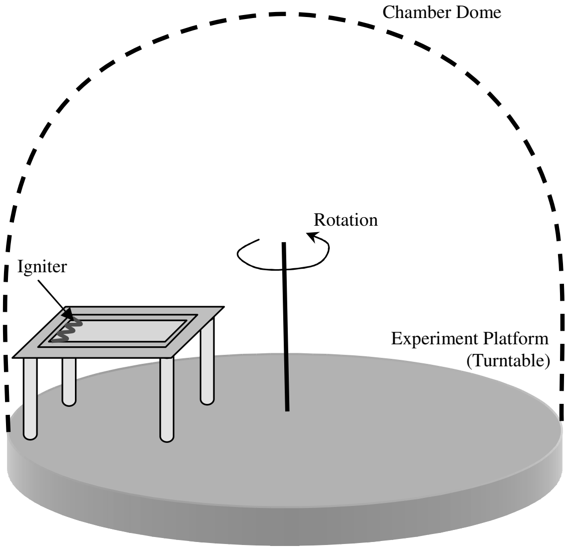

Fig. 3 Schematic of zero-gravity centrifuge showing fuel location; buoyant flow is toward the center of the turntable.

test atmosphere. The microgravity period lasted 5.18 s. When the drop rig reached the bottom of the evacuated drop shaft and stopped in the deceleration cart, the test section was vented to vacuum to extinguish any remaining flame.

Ignition and flame spread were recorded by two orthogonal color video cameras with automatic gain control. In Fig. 7, sample images are shown [11]. Flame shape, size, and spread rate were measured using Spotlight software [12]. Relative luminosity was compared between video frames using a constant-brightness red LED in the corner of the flame images, which also flashes at release.

III. Results

Materials flammability tests were conducted for three materials at lunar gravity and 1 g ULOI and 1 g MOC were compared with 0 g values obtained at a concurrent flow of 30 cm/s, which is a reasonable maximum local spacecraft ventilation velocity [13].

The limiting oxygen values (ULOI and MOC) for each fuel are found in Table 2. The near-limit flames are generally small and localized to the upstream edge of the material. We noticed that any distortion of the burned edge of the material, such as curling, swelling, or contracting, weakens the flame apparently by influencing the flow around the burned edge. Since oxygen transport is critical to low-gravity flames, anything that reduces the free flow of oxygen past the sample will reduce the material's flammability.

From the limit data, we can evaluate the oxygen margin of safety of the material in low gravity relative to the 1 g test 1 data. The oxygen margin of safety, or $\Delta O_2\%$, is defined here as the mean 0 g limit or the lunar limit minus the mean 1 g limit as follows:

$$\Delta O_2\% = \left(\frac{(\text{ULOI} + \text{MOC})}{2}\right) - \left(\frac{(\text{ULOI}_{1\,g} + \text{MOC}_{1\,g})}{2}\right) \tag{1}$$

In Eq. (1), the lowest $\%O_2$ at which the material burned in the drop test for the full test time was taken as the 0 g or lunar ULOI; the maximum $\%O_2$ where the material extinguished during the drop test was taken as the 0 g or lunar MOC. It should be noted that the low-gravity extinction-limit criteria are not the same as 1 g, due to time constraints in drop testing. A positive $\Delta O_2\%$ means that the flame will burn in 1 g at lower oxygen concentrations than in low gravity (lunar gravity or 0 g). Conversely, a negative $\Delta O_2\%$ means that the flame will propagate in lunar gravity or 0 g at a lower oxygen

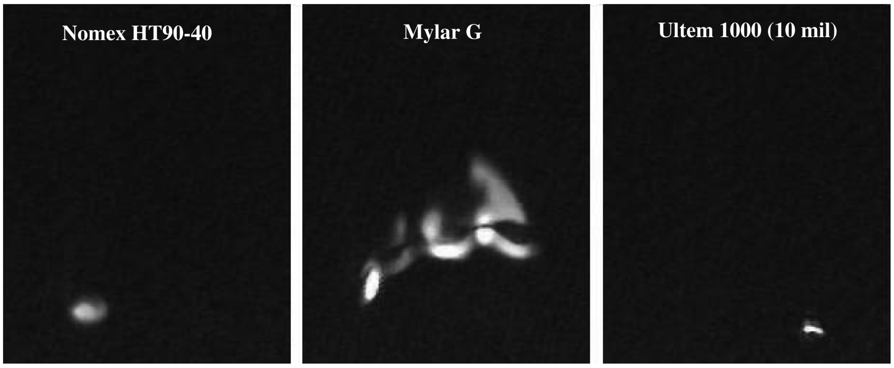

Fig. 4 Front-view pictures of lunar-gravity concurrent flames for three different fuels samples at the ULOI.

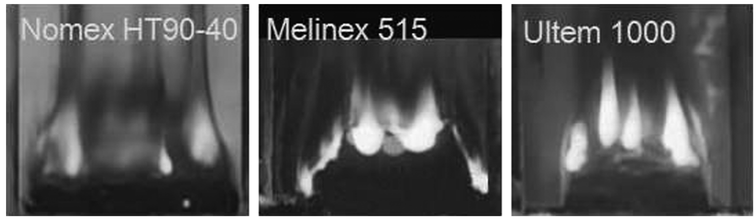

Fig. 5 Front-view pictures of 1 g upward flame spread at the ULOI (WSTF modified test 1 with hot-wire ignition). Samples are 5 cm wide in each image.

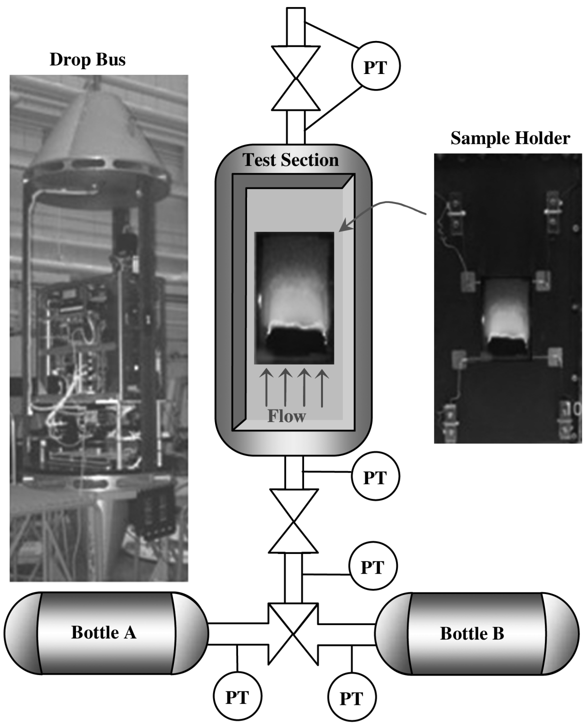

Fig. 6 Microgravity wind-tunnel rig shown schematically with two supply bottles and the test section. The sample holder is shown on the right and is installed in the test section before the drop. The experiment drop bus is shown on the left.

concentration than in 1 g and as reflected by the negative margin of safety. Values of $\Delta O_2\%$ for both 0 g and lunar gravity are included in Table 2.

As shown in Fig. 8 and Table 2, the 1 g flammability limits are generally not conservative for these materials, as evidenced by the negative $\Delta O_2\%$, by up to -5.75% oxygen. For low-gravity concurrent (upward) flow conditions, the absence of or reduction of buoyancy reduces convective heat loss from the flame zone. As such, the flame does not have to release as much heat as in 1 g to provide the same amount of heat flux to the unburned fuel. Thus, it is not surprising that the low-gravity flammability limits are lower than the 1 g flammability limits, which is the general trend noted in Table 2 and Fig. 8. The evaluation of the magnitude of this $\Delta O_2\%$ for other materials is continuing for concurrent flammability limits, to be followed by evaluation of the limits for opposed flow. If proven for more materials, this may indicate the need to include a factor of safety on 1 g flammability limits.

Nomex and Ultem are charring fuels. Char-layer formation is a known fire-retardant mechanism, since it reduces the heat-release rate of the material. For these charring materials, the oxygen margin of safety in 0 g is very close to zero, indicating that any reduced charring for 0 g may be offset by less heat release in the reduced convective environment. In lunar gravity, the oxygen margin of safety for these charring fuels is $\sim$2.5% lower than 1 g. It may be that with adequate but not excessive convection, materials burn better, as predicted by flammability maps [14].

Mylar is a noncharring material. Just as for metals combustion [15] the absence of gravitational-induced dripping keeps heated molten fuel in the flame zone, rather than removing it, and the result is a significantly negative oxygen margin of safety ($\sim$4–5%) in both lunar gravity and 0 g.

IV. Conclusions

A series of drop-tower tests were completed to determine the upward flame-spread oxygen-concentration extinction limits of three materials at microgravity (with forced convection) and lunar buoyant-flow gravity levels for comparison with upward normal-gravity limits. The limiting oxygen levels at lunar gravity were significantly lower than normal gravity (up to 5.75% O_2 lower), and microgravity was also lower than normal gravity (up to 4.1% O_2 lower). It should be noted that the low-gravity extinction-limit criteria were different compared with those in 1 g, due to time constraints in drop testing. This consistent trend of negative margins of safety on normal-gravity flammability screening tests suggests that normal-gravity material-flammability screening tests may not be conservative, and some materials tested to be safe for use in space may actually be flammable. If proven for more materials, this may

Fig. 7 Front-view pictures of microgravity concurrent flames with three different fuel samples at the ULOI. The concurrent forced-flow velocity was 30 cm/s. An LED in the lower left corner is the same true brightness, giving an indication of the relative brightness between the flames. Background illumination was not used for the Mylar, as it caused too much specular reflection.

Table 2 Limiting oxygen molar concentrations and oxygen margin of safety for different gravity levels

Fuel	Mylar G 70.3 kPa	Ultem 1000 70.3 kPa	Nomex HT90-40 101 kPa
1 *g* ULOI[a]	21.2	23.5	23.5
1 *g* MOC[a]	20.0	23.0	22.1
Lunar ULOI	15.6	21.0	21.0
Lunar MOC	14.1	19.9	19.9
0 *g* ULOI[b]	17.0	24.0	23.0
0 *g* MOC[b]	16.0	23.0	22.0
Lunar ΔO_2%	−5.75	−2.8	−2.35
0 *g* ΔO_2%	−4.1	0.25	−0.3

[a]Hot-wire ignition, upward flammability test.
[b]30 cm/s concurrent forced convective flow.

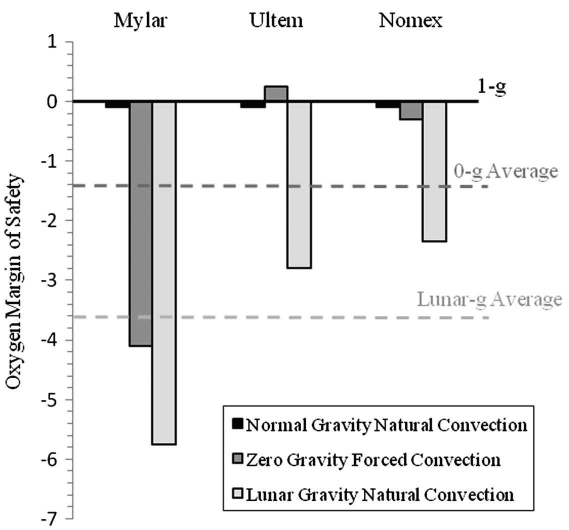

Fig. 8 Oxygen margin of safety for three different gravity levels. The normal-gravity data have zero oxygen margin of safety (by definition), since it is the test standard upon which materials are ranked. Both lunar- and microgravity oxygen margins of safety are generally negative by as much as −5.75%. The average 0 *g* oxygen margin of safety for these three materials is −1.4%, and the average lunar-gravity oxygen margin of safety is −3.6% (indicated by dashed lines).

indicate the need to include a factor of safety on 1 *g* flammability limits.

A modified NASA STD-6001 [2] test 1 protocol was suggested. This protocol measures the actual upward flammability limit (akin to the limiting oxygen index) for the material so that a more accurate assessment of the margin of safety of the material in the real-use space environment can be made, rather than merely qualifying materials as pass/fail in the worst-expected environments.

The centrifuge apparatus is a useful tool to achieve gravitational acceleration levels in a range that is not easily attainable in simple drop-tower or aircraft experiments, especially as NASA embarks on future missions that may be conducted in non-Earth gravity. Additional research projects could make use of the chamber for their own specific objectives.

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