

Microgravity Flame Spread in Exploration Atmospheres: Pressure, Oxygen, and Velocity Effects on Opposed and Concurrent Flame Spread

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ABSTRACT

Microgravity tests of flammability and flame spread were performed in a low-speed flow tunnel to simulate spacecraft ventilation flows. Three thin fuels were tested for flammability (Ultem 1000®, 10 mil film, Nomex HT90-40, and Mylar G®) and one fuel for flame spread testing (Kimwipes®). The 1g Upward Limiting Oxygen Index (ULOI) and 1g Maximum Oxygen Concentration (MOC) are found to be greater than those in 0g, by up to 4% oxygen mole fraction, meaning that the fuels burned in 0g at lower oxygen concentrations than they did using the NASA Standard 6001 Test 1 protocol.

Flame spread tests with Kimwipes® were used to develop correlations that capture the effects of flow velocity, oxygen concentration, and pressure on flame spread rate. These correlations were used to determine that over virtually the entire range of spacecraft atmospheres and flow conditions, the opposed spread is faster, especially for normoxic atmospheres. The correlations were also compared with 1g MOC for various materials as a function of pressure and oxygen. The lines of constant opposed flow agreed best with the 1g MOC trends, which indicates that Test 1 limits are essentially dictated by the critical heat flux for ignition. Further evaluation of these and other materials is continuing to better understand the 0g flammability of materials and its effect on the oxygen margin of safety.

INTRODUCTION

For future space missions, NASA is planning to increase the oxygen concentration and reduce the total pressure of the atmosphere in the Orion crew exploration vehicle, the Altair lander, and future lunar habitats [1]. This atmosphere has the advantages of requiring a lower mass of inert gas (N₂), lowering vehicle internal pressures, and shortening or eliminating the pre-breathing time required to purge nitrogen

from the bloodstream before Extra Vehicular Activity (EVA). However, an enriched oxygen atmosphere also has a significant disadvantage – increased flammability of materials.

One of the major lessons learned from the Apollo 1 fire is that it is impossible to eliminate all ignition sources [2], so fire prevention is achieved in spacecraft through material control and the use of fire resistant materials. Since Skylab, the Space Shuttle and the International Space Station (ISS) have operated at normal sea-level conditions (air, 21% oxygen/79% nitrogen by volume at 14.7 psia total pressure) except for brief pre-EVA activities when oxygen levels are increased for a short period of time to 30% oxygen while the total pressure is lowered to 10.2 psia. Many of the materials now used in the Shuttle or on ISS are therefore only tested and rated to 30% oxygen at 10.2 psia.

The Crew Exploration Vehicle (CEV), Orion, and the lunar lander, Altair, are designed to operate from 8.0 psia to 14.9 psia and at a maximum of 30% and 34% oxygen concentration respectively. The transition from higher pressure, lower oxygen concentrations to lower pressure, higher oxygen concentrations will occur as exploration needs change from ISS crew exchange to Lunar missions. As the oxygen concentration increases, the cabin pressure decreases to follow the normoxic curve which keeps the partial pressure of oxygen constant at the normal atmospheric air equivalent of 0.21 atmospheres, or 3.09 psia. The partial pressure of oxygen in the spacecraft will be controlled to 2.6-3.1 psia, which creates a band of operating conditions on the hypoxic side of the normoxic curve.

NASA tests materials for flammability using NASA STD-6001 Test 1 [3], which is an upward burning test at the worst-case atmospheric conditions in which the material will be used. Materials that do not self-extinguish after six inches of burning must undergo other special considerations and/or tests if they are to be used on spacecraft. During the early stages of the Constellation Program (CXP), NASA Materials and

Processes (M&P) personnel realized that changes to the baseline oxygen concentration during vehicle development or from vehicle to vehicle during the implementation of the CxP would require repeated testing of many materials to document their flammability at the new baseline.

Anticipating these changes in the baseline oxygen concentration, NASA set out to determine the maximum oxygen concentration (MOC) for a set of spacecraft materials identified by NASA M&P personnel. (The MOC was defined as the maximum oxygen concentration at which a material passed the standard 1-g flammability test, NASA-STD-6001 Test 1. The measurement of the MOC using the standard Test 1 protocol 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, but has not been formally approved as a standard test.

In this approach [5], the oxygen concentration in Test 1 is successively reduced to identify the Upward Limiting Oxygen Index (1g ULOI) and the Maximum Oxygen Concentration (1g MOC) that consistently results in self-extinguishment of

the material. The 1g ULOI is defined as the oxygen concentration at which a material passes the NASA STD 6001 Test 1 burn length criterion approximately half the time. The 1g MOC is defined as the oxygen concentration where at least five samples passed the burning criterion [3] and where at least one sample failed in the environment that contained 1 percent more oxygen by volume.

The objective of this work is to begin to assess the relative flammability limits between Test 1 and concurrent flammability limits in microgravity, to better understand how the 1g margins of fire safety in spacecraft environments are modified in actual microgravity. Based on microgravity tests conducted at various oxygen levels with three fuels tested previously by WSTF [8], we define an oxygen margin of safety parameter that can be used to assess material safety in the intended use atmosphere. In addition, the effects of oxygen concentration, pressure, and forced flow velocity are studied to understand how changing the atmosphere along the normoxic curve affects the robustness of the flame as measured by flame spread rate.

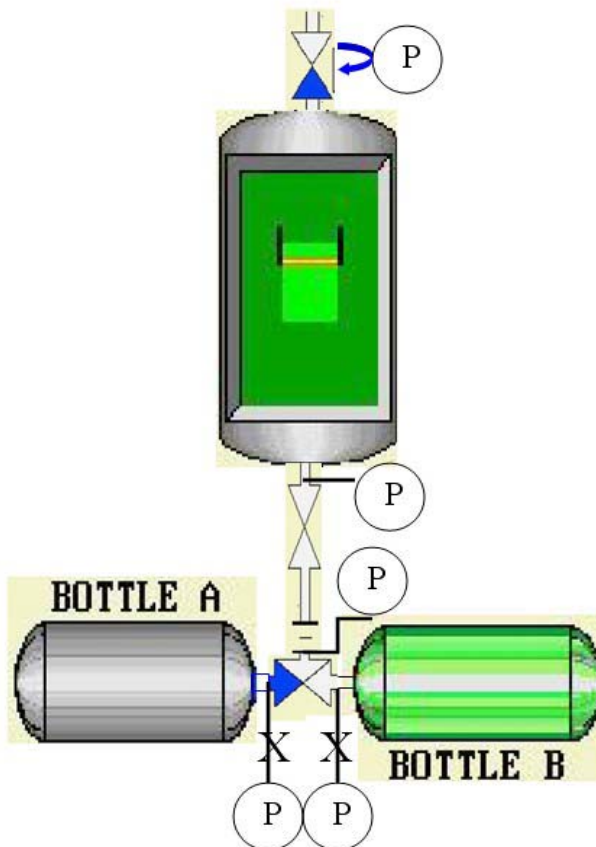


Figure 1: Schematic of the flow system on the Drop Bus. Two separate bottles can contain two gas mixtures so that conditions (oxygen concentration, diluent, pressure) can be switched during the experiment if needed. A critical flow orifice controls the flow through the test chamber, while a back pressure valve controls the pressure in the chamber. The sample and orange igniter are shown within the chamber.

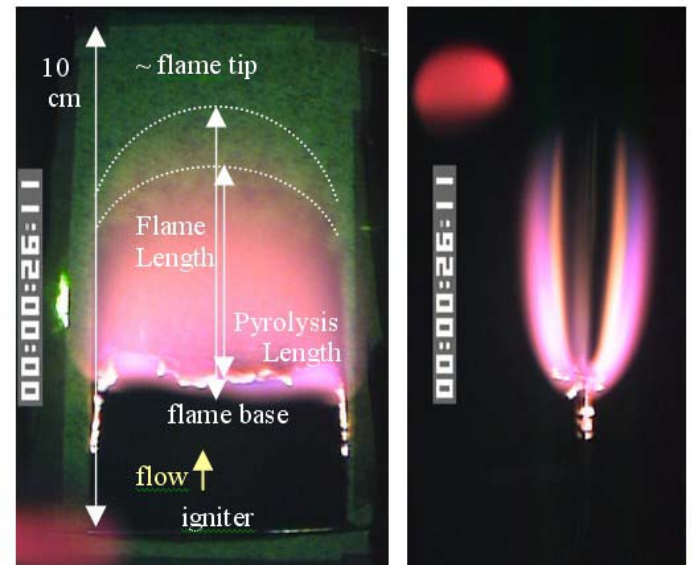


Figure 2: a) Front view of a Kimwipes® fuel sample in the 0.5 mm thick stainless steel holder, showing a concurrent flame test at 24% oxygen, 30 cm/s, 6.4 psia (not near limit). The cutout in the holder is 5 cm x 10 cm for the sample, but the holder itself is 20 cm wide and over 35 cm long, extending 12.7 cm upstream of the sample. The Kimwipes® sample appears green due to the LED illumination. The igniter can be positioned at either end of the sample, so both opposed or concurrent (shown) tests can be done in the same holder. b) Side view of same flame. The constant intensity red LEDs in both views was used to judge the actual flame brightness, since the camera was on auto-gain.

EXPERIMENTAL APPARATUS

The microgravity tests are performed in a low-speed flow tunnel that provides 0-30 cm/s forced flow of gas (0-100% O₂ in diluent) through a 20 cm ID duct at 0-14.7 psia pressure.

The flow tunnel is mounted on a NASA Zero Gravity Research Facility drop rig bus [9], but with modifications to the flow system and software control. The flow system of the rig is shown schematically in Figure 1. The flow modifications include a second gas reservoir such that oxygen concentrations (or another parameter such as diluent or extinguishing agent) can be changed during a test and a new back pressure control valve for greater flow capacity of up to 30 cm/s at pressures up to 14.7 psia. Higher permeability porous plates and honeycomb were installed to improve the flow distribution and laminarity at these higher flow rates. 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 the 1g ULOI, and the test oxygen level reached the sample shortly after release into zero gravity. The established flame then had ~ 5 seconds in which to respond to the new atmosphere by either extinguishing (0g 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 0g ULOI. While some of these flames may extinguish given longer time, the limits provided by the Zero Gravity Research Facility tests are a conservative measure of the limits in 0g. Note these limits are not identical to the 1g limits due to the intrinsic limitations of the drop time, but they are a reasonable comparison.

Tests were performed using a fuel sample taped to a sheet metal sample holder with an igniter wire on either the upstream or downstream end of the 5 cm wide by 10 cm long sample (Fig. 2). The flow was started before the drop to establish a steady flow speed and pressure in the tunnel prior to the drop rig release. The hot wire igniter was energized either in 1g or at release, depending on the objective of the test (flammability limit tests used 1g ignition; flame spread tests used 0g ignition). The microgravity period lasted 5.18 seconds – the first two seconds of which are typically used for 0g ignition and flame spread away from the igniter. When the drop rig reaches the bottom of the evacuated drop shaft and stops in the deceleration cart, the test section is vented to vacuum to extinguish the flame.

The fuels used in this study include Kimwipes®, Ultem 1000®, Nomex HT90-40, and Mylar G®. Kimwipes® are tested to expand the database for thin cellulose fuel that chars as it burns but is not treated for fire resistance. Front and side view images of a Kimwipes® burn are shown in Figure 2. With this fuel we can obtain flame spread and extinction data in the limited microgravity test time. Ultem 1000® (fire retarded polyetherimide (PEI)) in 10 mil thick film is inherently flame-retarding, with self-charring characteristics, a very low smoke signature, very low smoke toxicity, and a low heat-release rate. Nomex HT90-40 is a 12 mil thick fire retarded aromatic nylon fabric which 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 5 mil thick plastic film made from polyethylene terephthalate. It is not fire-retarded, melts as it burns, and was selected primarily for its non-charring character.

Ignition and flame spread were recorded by two orthogonal color video cameras with automatic gain control; sample images are shown in Figure 2. Flame shape, size, and spread rate were measured using Spotlight software [10]. Relative luminosity is compared between video frames using a constant brightness red LED in the corner of the images which also flashes at release marking the drop in the video.

MATERIAL FLAMMABILITY RESULTS

Materials flammability tests were conducted for three materials and the 1g ULOI and 1g MOC were compared with 0g values obtained at a concurrent flow of 30 cm/s, which is a reasonable maximum local spacecraft ventilation velocity [11]. The limiting oxygen values for each fuel are found in Table 1, and flame images for near limit 0g flames are shown in Figure 3. 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 microgravity flames, anything that reduces the free flow of oxygen past the sample will reduce the material's flammability.



Figure 3: Front view pictures of microgravity flames on three different fuels samples at the ULOI. The concurrent forced flow velocity was 30 cm/s. The red LED in lower left is the same true brightness, giving an indication of the relative brightness between the flames. The green LED was not used for the Mylar as it caused too much specular reflection.

Table 1.
Comparison of 1g and 0g flammability limits for three fuels.

Fuel	1g ULOI	1g MOC	0g ULOI (burns)	0g MOC (extinguishes)
Nomex HT90-40 fabric	25.4% O ₂ (±0.6), 14.7 psia*	22% O ₂ , 14.7 psia*	23% O ₂ , 14.7 psia, 30 cm/s	22% O ₂ , 14.7 psia, 30 cm/s
Ultem 1000, 10 mil	26.5% O ₂ , 10.2 psia*	24% O ₂ , 10.2 psia*	24% O ₂ , 10.2 psia, 30 cm/s	23% O ₂ , 10.2 psia, 30 cm/s
Mylar G	20.8% O ₂ , 10.2 psia*	20% O ₂ , 10.2 psia*	17% O ₂ , 10.2 psia, 30 cm/s	16% O ₂ , 10.2 psia, 30 cm/s

* WSTF data [8]

An example flammability map is shown in Figure 4. Ultem 1000, where the 1g limits are compared to 0g test results over