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Design Considerations for a Ground-Based Flammability Test Method for Screening Spacecraft Materials

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A flammability test method for spacecraft materials screening is proposed based on a confined opposed flow flame spread geometry. The basic approach has been proven by flowing oxidizer through transparent PVC tubing open to the atmosphere and applying an ignition source to the inner surface. For flammable conditions for this geometry, a flame propagates at a measurable speed against an opposed oxidizer flow. Atmospheric pressure results at various inner diameters reveal that buoyancy effects are suppressed at intermediate diameters, which is an important consideration for space applications. Effects of oxygen concentration and inert diluent type show the strong role of flame temperature and thermal diffusivity on the flame spread process. This method can be extended to allow for routine material flammability tests at various pressures and oxidizers, especially those considered for future space exploration atmospheres at elevated oxygen and reduced pressure applications. Materials to be tested are formed into a tube through which the flame will propagate. A thermocouple array will be developed to track the flame spread rate, and its measurement of spread rate will be compared with video imaging of flame spread rate for transparent materials.

Introduction

Material flammability is currently evaluated per NASA-STD-6001, "Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion" [1998]. For nonmetallic solids, the main flammability test is Test 1, Upward Flame Propagation. This test, which has been in use for over 30 years, evaluates whether a material is self-extinguishing under expected worst-case-usage conditions of pressure, temperature, oxygen concentration, and thickness. A material passes if for at least three samples the vertical burn length for all samples is less than 6 in. (15 cm) and the material does not propagate a flame by generating burning debris sufficient to ignite a sheet of paper mounted 8 in. (20 cm) below the sample holder [Lange et al.].

Historically, results of this test have been generally considered conservative for assessing material flammability in microgravity, although the margin of safety is dependent on the forced ventilation flow [Friedman, 1999]. Ohlemiller [1991] evaluated Test 1 critically, noting that materials passing the standard NASA Test 1 screening showed widely varying degrees of flammability enhancement when subjected to external radiation, which is implicit in many normal fire scenarios. As such, materials passing the standard NASA screening test should not be treated as non-flammable.

The Test 1 pass/fail criteria at the worst-case usage conditions does not provide a quantitative measure of the margin of safety for the material, so a recent modification to the Test 1 procedure was suggested that provides a quantitative value of the maximum oxygen concentration (MOC) for non-flammability [Hirsch et al., 2007]. This oxygen concentration can then be compared to the planned usage condition to assess an oxygen margin of safety for the material. A material whose flammability limit MOC is close to the usage condition has a small oxygen margin of safety. Oxygen is used for this assessment rather than pressure, because the flammability limit MOC has a weaker dependence on pressure over the pressure range of interest (approximately 3.0 – 17.3 psia) [Hirsch et al., 2008]. A lower pressure has only a slightly higher MOC at the flammability limit, so it would be conservative to fix the worst case operating pressure (generally regarded as the highest ambient pressure) and determine the MOC for the material at that fixed pressure.

Microgravity tests of three materials were conducted to compare with normal-gravity flammability results.In these tests the maximum oxygen concentration for non-flammability were found to be generally *lower* in microgravity with forced flow in the range of spacecraft ventilation systems [Olson et al, 2008]. The worst material burned at 4% oxygen lower than in 1g. So if the 1g oxygen margin of safety evaluated using the modified Test 1 procedure is less than this 4% oxygen, the material will have an actual 0g *negative* margin of safety, and will burn in the spacecraft usage condition. These results highlight the problems associated with NASA's Test 1, and a better and more fundamentally-based test method is needed for materials screening in future exploration atmospheres.

There is a rich and evolving literature aimed at understanding the fundamental flame spread process (Wichman). An important aim of the present study is to develop a test method that will allow for a wide range of available data to assist that effort.

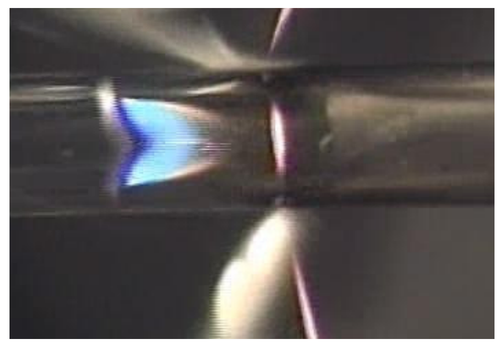

Figure 1: Still from drop tower experiment, shortly after ignition via hot wire (glowing).

Basic Test Method and Results

In the course of investigating the problem of accidental ignition of polyvinylchloride (PVC) breathing tubes during surgery, Sidebotham and co-workers (1991, 1993) developed a simple method for the fundamental study of opposed flow flames and proposed a test method for finding the lowest oxygen concentration that will support a flame of this type. The basic experiment (Figure 1 and Figure 2) consists of flowing an oxidizer through a cylindrical passage of a material to be tested (tube form), and applying an ignition source to the inner surface (pilot flame to the

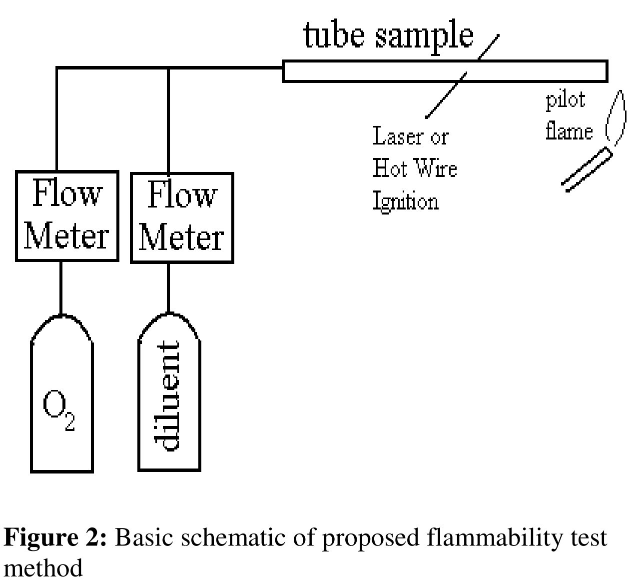

Figure 2: Basic schematic of proposed flammability test method

end open to the atmosphere, or application of a heat source away from the free end). Test results are reported in Figures 3 and 4 in the form of flame spread rate plotted against opposed flow velocity (averaged across the cross-sectional area of the tube).

Figure 3 shows the effect of inner diameter. Except for the smallest tube diameter tested (0.159 cm), the curves coalesce in the thermal regime where the flame spread rate increases with opposed flow velocity (~5 – 100 cm/s). The scatter at higher flows is attributed to difficulty in conducting the experiment at high opposed flows (bright flames, more erratic behaviors, etc.). The smallest id tubes demonstrate a lower flame spread rate in this flow range attributed to wall quenching effects. The largest tube studied shows an inflection point attributed to buoyancy. The lack of an inflection point for 0.635 cm and smaller tubes suggested that buoyancy effects are suppressed in this confined geometry. This effect was confirmed for the 0.635 tube by comparing normal and microgravity spread rates (Sidebotham 2008). Buoyancy did not affect flame-spread rates for flow velocities exceeding approximately 6 cm/s. The role of buoyancy in these confined flames must be more carefully scrutinized in future work.

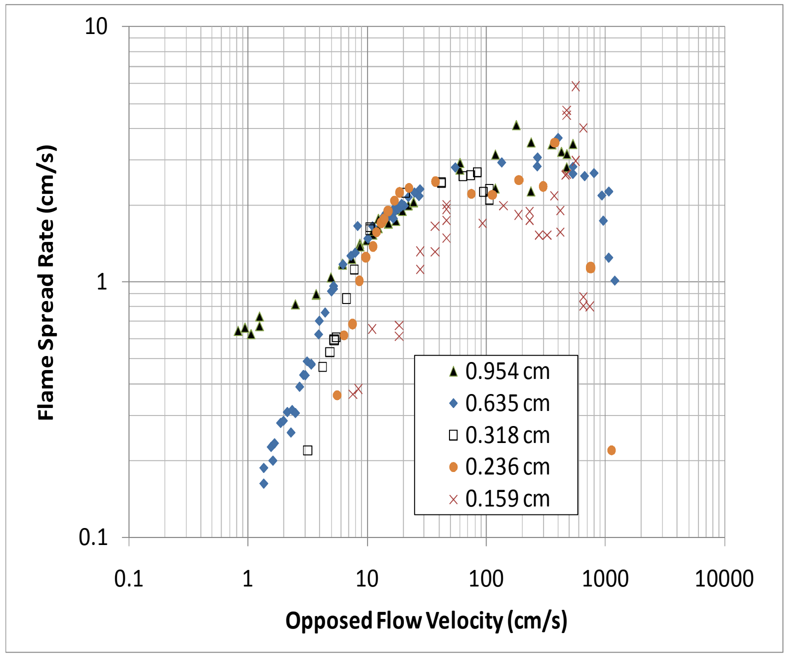

Figure 3: Effect of Tube Diameter on Flame Spread Rate. Flow of 100% O_2 at atmospheric pressure through PVC tubing

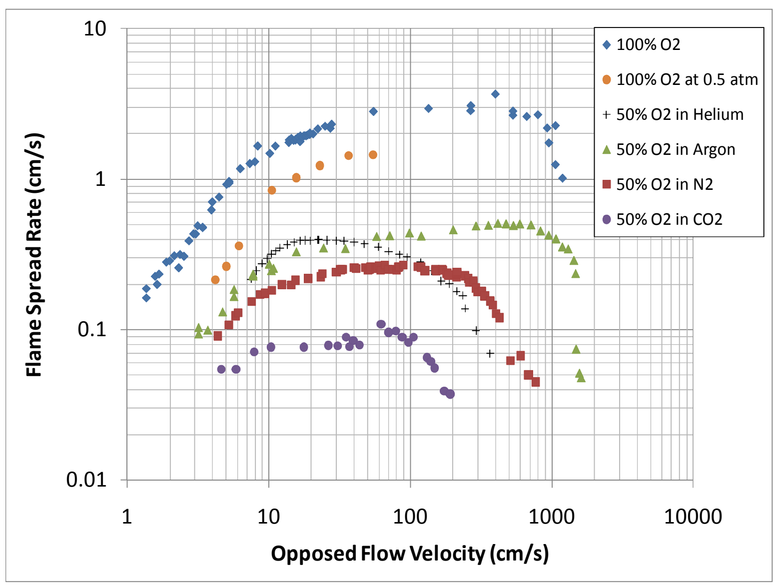

Figure 4: : Effect of Pressure and Dilution on Flame Spread Rate. 0.635 cm inner diameter PVC tubing

Figure 4 shows the effect of oxygen concentration, pressure, and diluent type on flame spread rate for 0.635 cm inner diameter tubing. Reducing the oxygen concentration from 100% to 50% (molar) reduces the flame spread rate by an order of magnitude and reduces the flammable flow range. The use of different inert gases allows for investigation of the effects of flame temperature (inerts with different specific heats but similar molecular weights, i.e., Ar, N_2, CO_2) and diffusive effects (same specific heat, different molecular weights, i.e., Ar and He). Reducing the pressure from 1 to 0.5 atm for 100% O2 has a much less dramatic effect than changing the oxygen concentration from 100% to 50% (molar), and appears to shift the curve to higher opposed flow velocities. No further attempts at data analysis are made here. The primary objective is to demonstrate the range and type of repeatable data available in a low cost basic experiment.

Functional Requirements of Proposed Test Method

The apparatus for the proposed test method must satisfy the following functional requirements:

1. Controlled oxidizer (O2 and diluents) flow through a test sample prepared in a tube form (nominal inner diameters from 0.2 to 0.7 cm) with fully developed laminar flow in test region
2. Controlled pressure less than or equal to 17.3 psia (for contingency procedures such as decompression sickness treatment)
3. Controlled oxidizer composition external to tube sample
4. Easy removal of spent sample and insertion of fresh sample
5. Nonflammable materials and gases, except for tube sample
6. Optical access to test
7. Sensor-based measurement of flame spread rate
8. Ability to incorporate instrumentation such as gas sampling, laser diagnostics, etc.

Preliminary Design Concepts

Figures 5 and 6 show a basic schematic of the test stand and burner envisioned. The requirement of controlled pressure dictates the creation of a test chamber that can be filled with chamber gases and vented as needed. The test chamber will need to be easily opened to change samples and allow for optical access (for transparent samples). It is possible that optical access will be gained by placing cameras inside the chamber. The test gases will be a mixture of O_2 and a diluent. The chamber gas can be fed as a mixture of air and an inert. The total fuel loading will be contained in the tube sample and the pilot flame, and therefore the severity of worst case accidental fire is well characterized.

The burner is envisioned to consist of a test gas flowing into a vertical test sample with an outer shield gas, which could be the point of entry of the chamber gases. A retractable natural gas pilot flame ignition of the inner surface is envisioned for symmetric application. Alternatively, a hot wire could be imbedded in the sample as needed. Thermocouples (a minimum of 2) imbedded in the walls will be used to measure flame spread rates. Thermocouples can be placed in the gas stream as well, but will contribute loading errors which will be especially important near extinction limits.

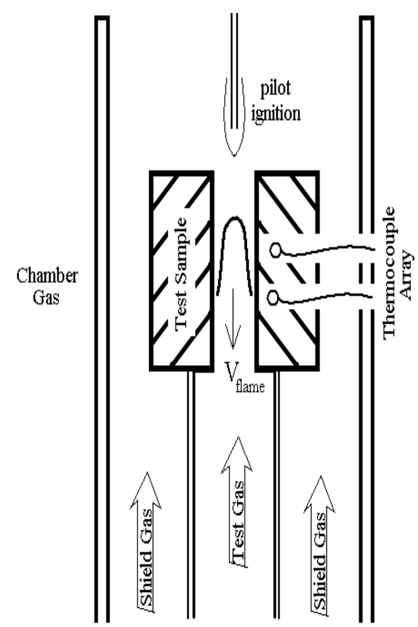

Figure 5: Conceptual schematic of burner

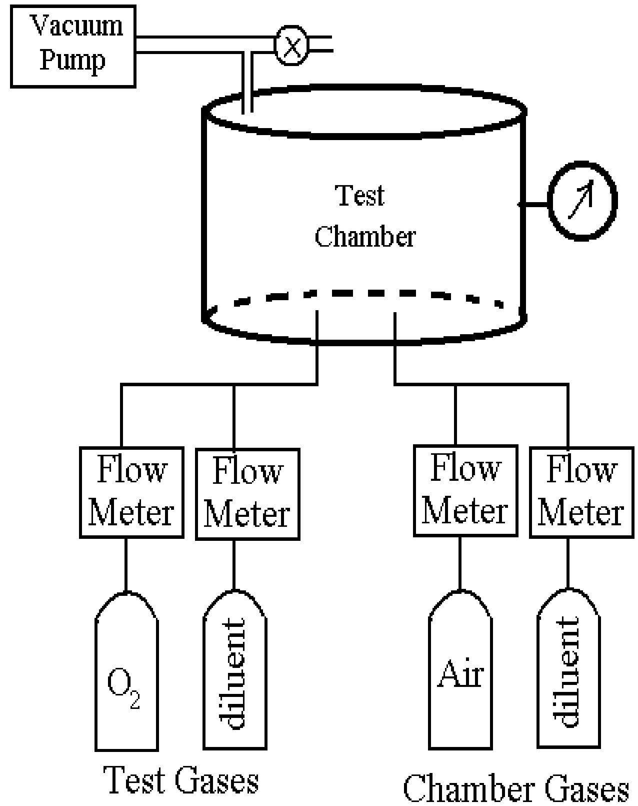

Figure 6: Schematic of proposed test stand

Conclusions

A flammability test method for spacecraft materials screening is proposed based on a confined opposed-flow flame-spread geometry where the inner surface of a fuel tube is burned with the support of a fully-developed oxidizer flow through the tube. Flame spread rates are presented over the range of flammable flow conditions from blowoff to quenching extinction for various oxygen concentrations, ambient pressures, diluent types, and tube diameters. These results show that buoyant effects are suppressed at intermediate diameters, which is an important consideration for space applications. Effects of oxygen concentration and inert diluent type show the strong role of flame temperature and thermal diffusivity on the flame spread process. This method can be extended to allow for routine material flammability tests at various pressures and oxidizers, especially those considered for future space exploration atmospheres at elevated oxygen and reduced pressure applications.

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