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A TEST METHOD FOR MEASURING THE MINIMUM OXYGEN CONCENTRATION TO SUPPORT AN INTRALUMINAL FLAME

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ABSTRACT: A test method for measuring the minimum concentration to support an intraluminal flame is described. An oxidizer is flowed through a plastic tube, and an ignition source is applied to the free end of the tube. If the oxygen concentration is sufficient, a flame propagates along the inner surface of the tube, termed an intraluminal flame. The minimum concentration of oxygen, or limiting oxygen index (LOI), that will support such a flame is determined. Results are reported for polyvinyl chloride tubing and compared to those using the standard ASTM D 2863, the candle-type flammability test. In the intraluminal test, the LOI with helium as the diluent gas is lower than that with nitrogen as the diluent, in contrast to results using ASTM D 2863. The effects of buoyancy are reduced in the intraluminal test, and the results may therefore be more applicable to low gravity environments.

KEYWORDS: Flame spread, oxygen index, polyvinyl chloride, combustion, endotracheal tube fires, microgravity

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INTRODUCTION

The minimum oxygen concentration that will support combustion is a useful measure of the relative flammability of solid materials in oxygen enriched atmospheres. The well known candle-type flammability test [1] was originally published in 1970 as the ASTM Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index) D 2863. The minimum oxygen concentration is also referred to as the limiting oxygen index (LOI) [2] or the critical oxygen index (COI) [3]. An alternative experimental methodology to obtain an LOI is presented in this paper.

It is emphasized that a universal LOI does not exist for a given material [3, 4]. Rather, an LOI exists for a material for a given test method. Therefore, application of standardized test results to a particular system must be made with caution. It is left to the discretion of the designer or user of a system to determine whether or not the results from the standard test accurately reflect what can be expected in the system under consideration. Even if quantitative agreement between the standard test and an application is uncertain, it is tempting to speculate that qualitative trends are preserved: if material A is less flammable than material B in the LOI test, then A is less flammable than B in any system. The results reported here suggest that even qualitative agreement can be suspect.

The present work is an outgrowth of research into operating room fire safety problems [5]. The accidental ignition of endotracheal tubes during surgery by surgical lasers, electrosurgical units and electrocautery continues to pose a fire risk in the oxygen-enriched environment of the mouth or airway. In an effort to understand this endotracheal tube fire problem, a simple experiment was developed. Results of this experiment and a discussion of the flame mechanisms are reported in reference [6]. Briefly, an oxidizer is flowed through a plastic tube and an ignition source is applied to the open end of the tube. A flame, termed an intraluminal flame, is observed to propagate along the inside surface of the tube at a measurable speed. It was concluded that this intraluminal flame spread process characterizes endotracheal tube fires.

For a given oxygen concentration, there exist flow limits: if the flow rate of oxidizer is too great or too small, an intraluminal flame cannot be established. As the oxygen concentration is reduced, the rate of flame spread decreases and the flow limits narrow until a limiting oxygen concentration is reached below which an intraluminal flame cannot be established. The results of such tests then represent an alternative measure of the limiting oxygen index. Results from this test are reported and compared to those obtained by the standard ASTM D 2863 method.

EXPERIMENTAL

A brief description of the experimental approach used to determine the limits of intraluminal flame spread in polyvinyl chloride tubing is reported here. Further details can be found in reference [7].

Gaseous flows were obtained from compressed gas cylinders. Flow rates were regulated by mass flow controllers, calibrated with a soap bubble meter. In the present study, various sizes of Clear-flo polyvinyl chloride tubing, obtained from New Age Industries, were used. Data has not yet been obtained for other materials. The ignition source was a pilot flame obtained by flowing natural gas through a small copper tube to yield a diffusion flame approximately 1 cm in height.

To perform the test, a section of tubing, sufficiently long to guarantee fully developed flow, was connected to the oxidizer source. The downstream end was horizontal, open to the atmosphere, and loosely supported by a clamp, allowing the tube to hang cantilevered approximately 15 cm from the clamp. The tube was marked on the outside with a greaseless pen at known intervals, typically 5 cm. A fixed flow rate of oxidizer (oxygen plus diluent) was delivered to the test specimen. The ignition source was applied to the free end after sufficient time was allowed to flush the system. The flame event was successful if an intraluminal flame propagated for at least 5 cm, or survived at least 3 minutes. This criterion is the same as that in ASTM D 2863.

If an event occurred, the oxygen concentration was decreased by either lowering the oxygen flow rate (with fixed diluent flow), or by increasing the diluent flow (with fixed oxygen flow). The test was repeated until a flame did not satisfy the criterion for a successful event.

There was concern that the oxygen concentration in the vicinity of the free end was lowered due to mixing with ambient air. To investigate this effect, tests were performed in which the ignition source was inserted approximately 3 cm into the tube instead of being applied to the free end. The results were not affected by how the ignition source was applied.

A complication of the test was encountered in determining the upper flow limit in some cases. At high oxygen concentrations, it was observed that a flame could be anchored outside of the free end, and slowly consume the entire tube, yielding an apparent flame spread rate. This "free end flame" was considered to be stabilized outside of the flame by a complex recirculation pattern that existed outside the tube. However, the leading edge of this flame never entered into the tube, and is not considered an intraluminal flame. This complication did not occur near the limiting oxygen concentration.

The conventional candle-type ASTM (D 2863) was performed on the same material to allow comparison with the present intraluminal flame test. Following Simpson, et al. [4], the test was adapted to a tube material and other diluents. The flame spread in this test was observed to occur on the outside surface of the tube.

RESULTS

Figure 1 shows the intraluminal flame spread rate as a function of oxidizer velocity for 50% O2 mixtures (by volume) in nitrogen and helium. The techniques used to generate these data are described in reference [6]. In both cases, there is a lower flow limit, and upper flow limit, and a peak in the flame spread rate. It is apparent that helium yields a much higher peak flame spread rate than nitrogen. However, beyond the flame spread rate peak, the

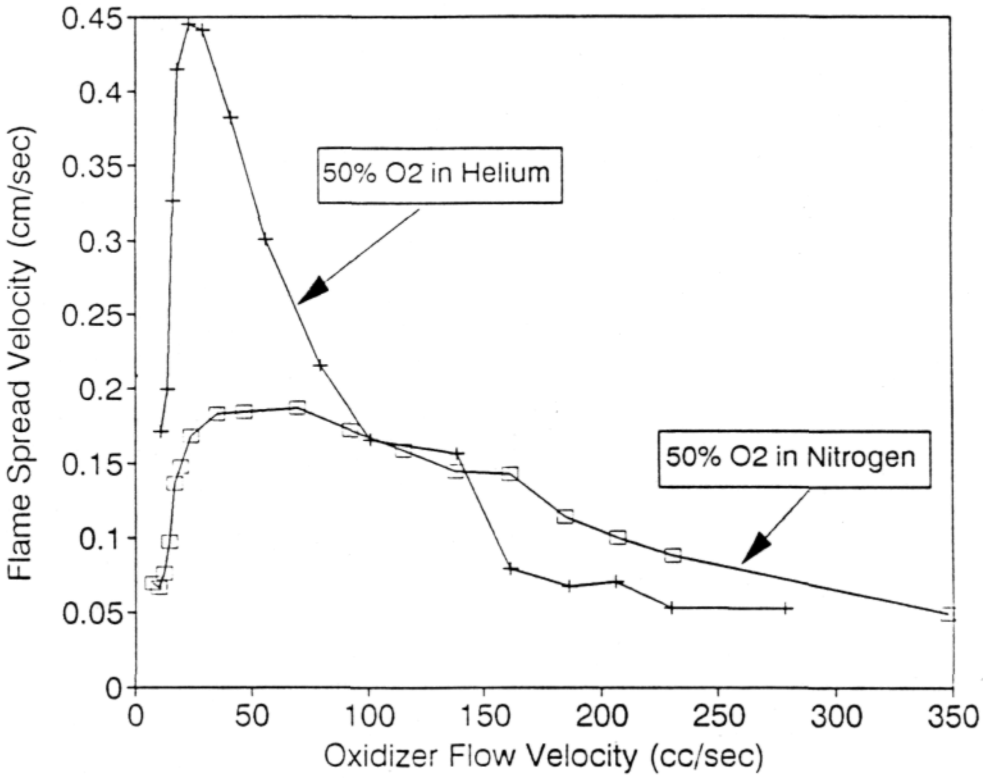

Figure 1 -- Intraluminal flame spread rate versus oxidizer flow velocity for 50 vol% oxygen in two diluent gases. 3.2 mm inner diameter, 6.4 mm outer diameter polyvinyl chloride tubing was used.

rate of decay of flame spread rate with increasing oxidizer flow is also much larger for helium. Therefore, the upper flow limit occurs at a lower total oxidizer flow for helium. For other oxygen concentrations, the shapes of the curves are similar, but the limits are wider for higher oxygen concentrations, and shallower for lower oxygen concentrations. Flammability maps, which indicate flammable and non-flammable regions, can be constructed using data of this type.

Figure 2 shows a conceptual diagram of a flammability map, in which flammable regions are separated from non-flammable regions. The oxygen concentration is plotted against the total oxidizer flow rate (or flow velocity) in the tube. For a given oxygen concentration, low flow and high flow limits exist. These limits approach each other as the oxygen concentration is reduced until they meet. The oxygen concentration below which intraluminal flames cannot be established is the limiting oxygen index for intraluminal flame propagation.

The flammable region is separated into two parts. Region A represents intraluminal flame propagation, while region B represents the so-called "free end flames" that were stabilized outside the free end of the tube. For all cases investigated here, the onset of these flames occurred at higher oxygen concentrations than the LOI, and therefore did not interfere with the attainment of the LOI.

The non-flammable region is separated into three parts. Regions C and D represents regions with sufficient oxygen concentration, but are below the lower flow limit, or above the upper flow limit respectively. Region E represents regions in which the oxygen concentration is sufficiently low that intraluminal flames cannot be established for any flow rate.

Figure 3 shows a typical flammability map in which the oxygen concentration is plotted against the oxidizer velocity (total flow rate divided by the area). Conditions that yielded intraluminal flames are reported with one symbol, and conditions which did not yield flames are reported as another symbol. The limiting oxygen index is the lowest oxygen concentration for which a flame existed, and occurs at a particular flow velocity. For every tube material, tube geometry and diluent type, a flammability map similar to Figure 3 must be developed to yield the LOI.

Experience dictated that the lower flow limit was easily and reproducibly obtained. To isolate the lower flow limit, it was most convenient to fix the diluent flow rate, and to vary the oxygen flow rate. In this manner, successive tests yielded points along a line roughly perpendicular to the lower flow limit line. In principle,

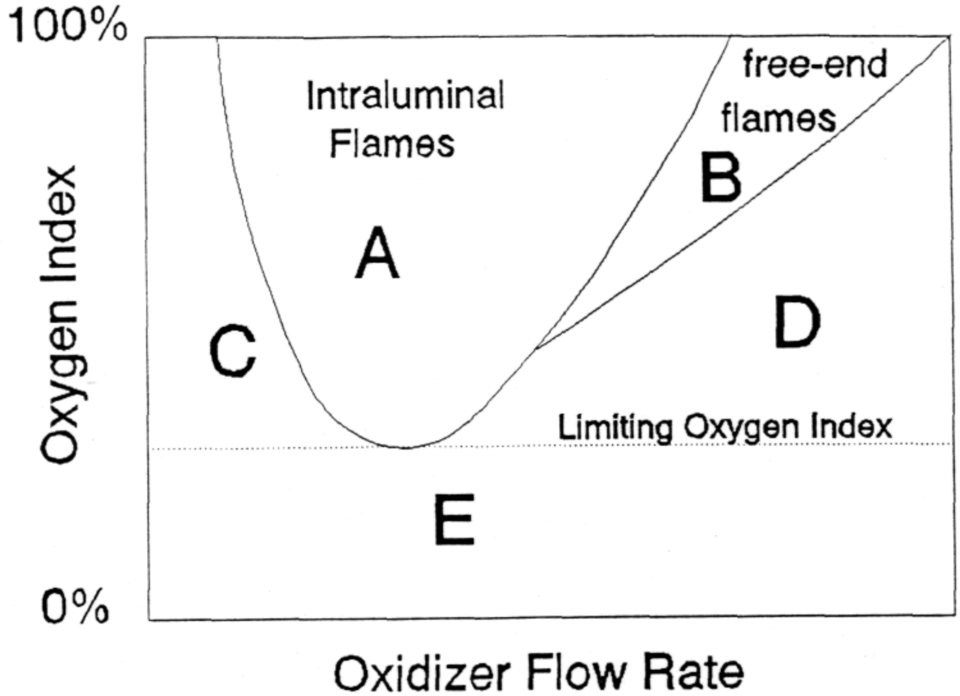

Figure 2 -- Schematic representation of a flammability map.

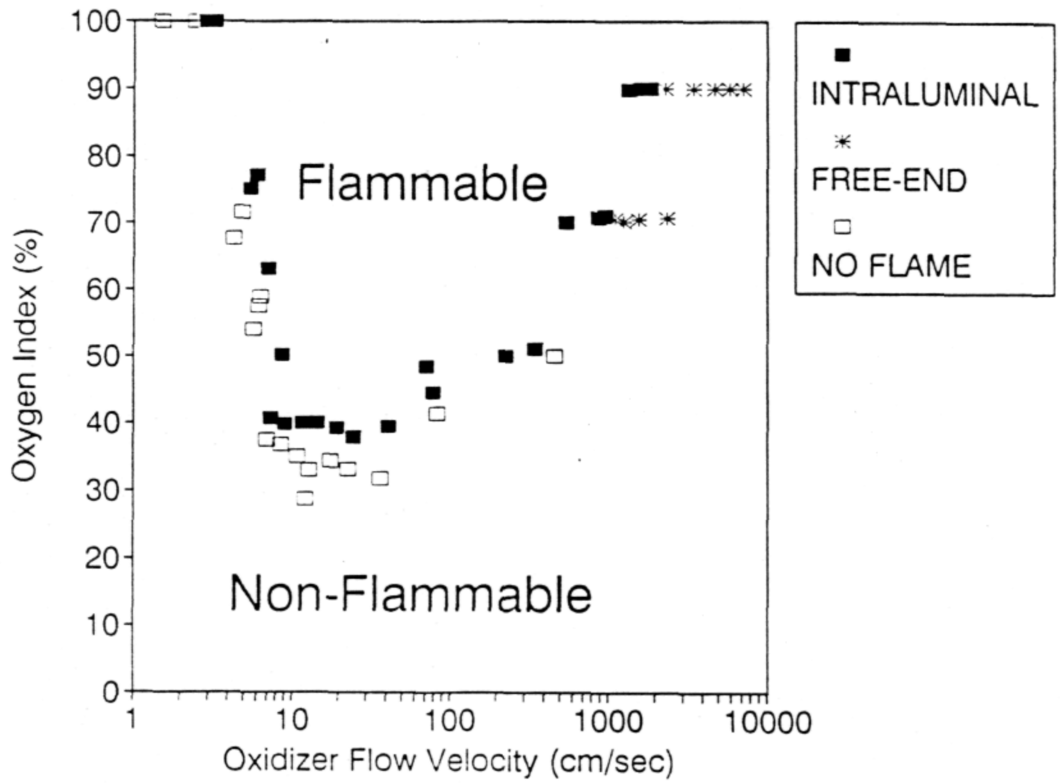

Figure 3 -- Typical flammability map. 3.2 mm inner diameter, 6.4 outer diameter tubing. Nitrogen is the diluent gas. Data points indicate the type of flame observed for conditions tested.

the upper flow limit could similarly be most conveniently obtained by fixing the oxidizer flow and varying the diluent flow. However, since the magnitude of the slope of the lower flow limit was much steeper than that of the upper flow limit, it was found that this approach was not necessary to find the LOI.

Figure 4 shows the effect of the inner diameter on the LOI for four different diluents. It is apparent that the LOI decreases with increasing tube inner diameter for the intraluminal flame test. The LOI obtained with helium is consistently lower than that obtained with nitrogen. This result suggests that nitrogen is a more effective flame suppressant than helium. Carbon dioxide (CO2) yielded the highest LOI, and argon yielded the lowest LOI.

The conventional candle-type flammability test (ASTM D 2863) was performed on the same material using nitrogen and helium as diluents. The LOI was found to be weakly dependent on size for the candle type test. The average LOI was 24.2 for nitrogen mixtures, and 30.2 for helium mixtures. This trend of greater values of LOI when helium is used as compared to nitrogen is consistent with that reported by Werley [4] and Simpson et al. [5], and suggests that helium is a more effective diluent at suppressing flame spread, in contrast to the conclusion using the intraluminal test. The results with carbon dioxide and argon using the candle-type test [4] are consistent with those found in the present study.

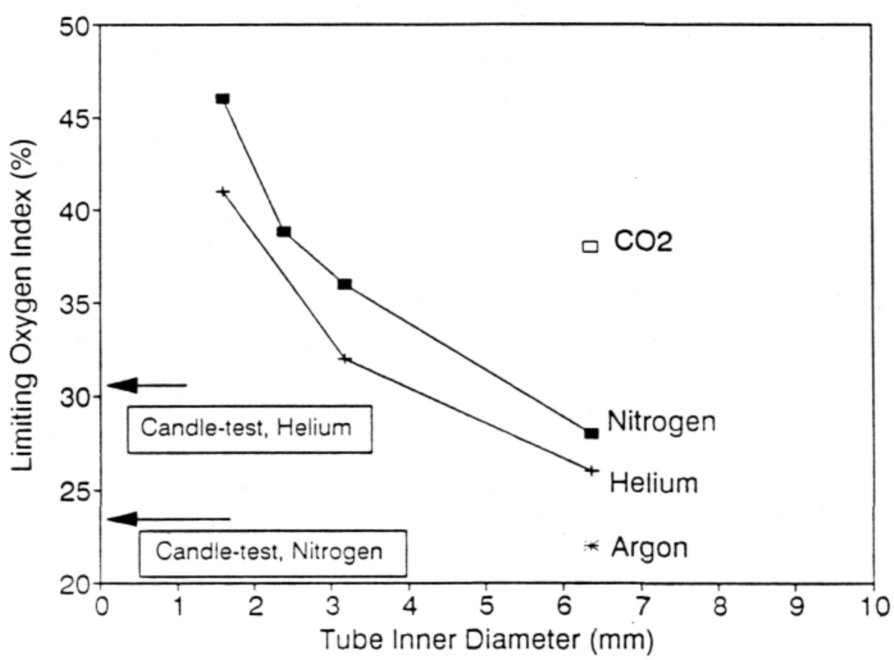

Figure 4 -- Limiting oxygen index as a function of tube inner diameter. Four different inerts were tested. Results from ASTM D 2863 are indicated for nitrogen and helium.

DISCUSSION

In order to understand the trends observed in the intraluminal LOI test, it is helpful to reconsider the mechanisms of flame spread, discussed by Glassman [2], as applied to intraluminal flame spread [6]. A schematic of the intraluminal flame spreading process is shown in Figure 5. The bulk of the flame is a gas phase diffusion flame in which the gaseous fuel is obtained by gasification of the solid fuel. The energy for gasification comes from heat conducted through the gaseous fuel vapor to the solid fuel. There is a quenching layer between the flame and the solid fuel because the solid fuel vaporizes at a much lower temperature than that at the diffusion flame surface. Inside the quenching layer and near the leading edge of the flame, fuel and oxidizer mix. Therefore, the leading edge is a pre-mixed flame which propagates toward the opposed flow at a distance from the solid fuel, termed the quenching distance.

At low flows, the flame spread rate increases with increasing oxidizer flow because of the increase in fuel gasification rate associated with the improved heat transfer rate from the hot flame gases to the solid fuel. However, as the oxidizer flow rate is increased, the spreading flame must propagate against a stronger opposed flow. Eventually,

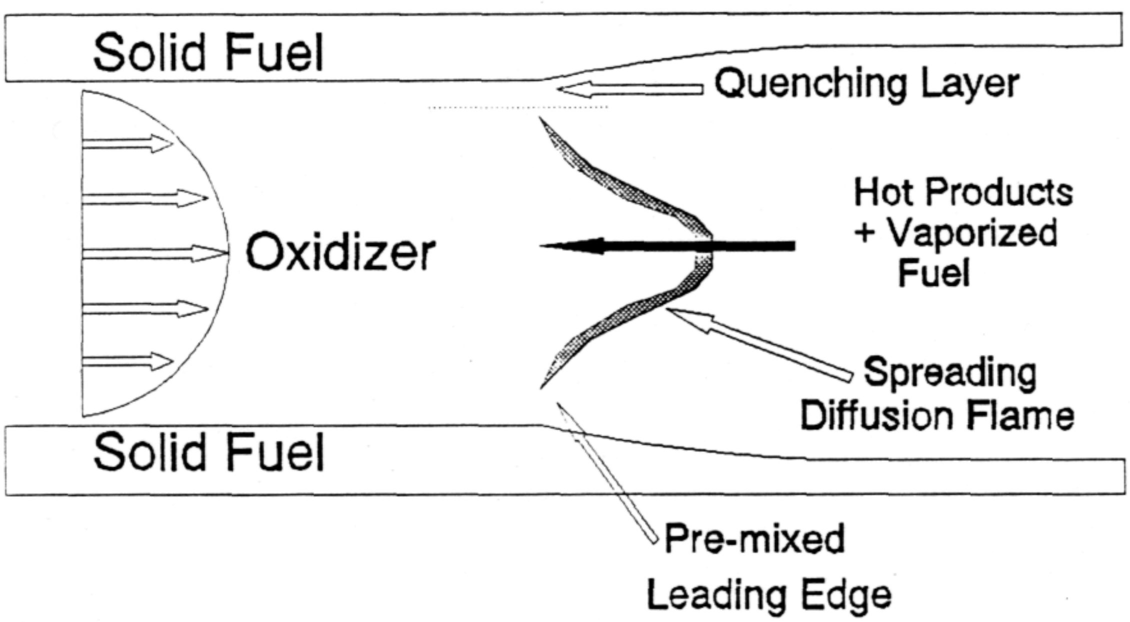

Figure 5 -- Schematic of an intraluminal flame. The flame is spreading from right to left as indicated by the solid arrow. The fuel is thinner downstream of the flame because of fuel vaporization.

this latter effect dominates the former, and the flame spread rate in the laboratory reference frame is observed to peak, then decrease with increasing oxidizer flow. Ultimately, the opposed flow rate at the quenching distance is greater than the leading edge pre-mixed flame speed, and the flame cannot enter into the tube. This effect then yields the upper flow limit, or "blow-out" limit.

Helium vs. Nitrogen

Helium has a much higher thermal diffusivity, hence higher quenching distance, than nitrogen*. Therefore, since the velocity profile is parabolic, the velocity at the quenching distance is larger for helium than for nitrogen for the same oxidizer flow velocity. An intraluminal flame with helium as the inert is more sensitive to an increase in flow velocity.

Helium has a lower specific heat than nitrogen, hence higher flame temperatures, than nitrogen. Therefore, since the leading edge pre-mixed speed increases strongly with temperature, the flame spread rate for helium is greater than that for nitrogen for low opposed flow rates (where the effects of the opposing flow are not dominant).

Buoyancy Effects

The effects of natural convection, or buoyancy, on flame spread help explain the difference between the standard candle-type test and the intraluminal flame test. For opposed flow flame spread with an oxidizer of infinite extent, the flame can induce a flow into the flame [2]. The hot gases produced by the flame have a low density, and therefore experience a buoyant upward acceleration. To conserve mass, these rising gases are replaced by fresh gas. As a result, the spreading flame experiences an induced opposed flow even in a quiescent atmosphere. When the forced flow is much less than that generated by natural convection, the flame spread rate is independent of the forced flow. This result is experimentally verified for flame spread over flat plates [2]. Further, for these experiments, a low flow limit of flame spread has never been reported.

In contrast, for intraluminal flames, the flame does not propagate into an oxidizer of infinite extent. Hot

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* The depth of the quenching layer is related to heat conduction. The magnitude of the quenching distance is proportional to the thermal diffusivity of the gas (the thermal conductivity divided by the density and the specific heat), which varies approximately with the inverse square root of the molecular weight.

gases generated in the flame have no place to rise in the confines of the tube. Therefore, there is no induced flow due to buoyant effects, and the only flow rate the flame experiences is the forced flow supplied through the tube. Indeed, as the oxidizer flow rate decreases, the flame spread rate decreases until the lower flow limit is reached. The only previous reports of low flow limits of flame spread are those in microgravity experiments [8].

The candle-type flammability test yields results for LOI which are insensitive to forced flow within the oxidizer flow range dictated (provided there is no mixing of ambient air [3]). It is thus argued that the flow field in the vicinity of the burning sample is controlled by buoyant effects. A plausible explanation for higher LOIs in helium compared to nitrogen is that with the larger quenching distance, and induced buoyant flow rate, the leading edge of the helium flame experiences a higher opposed velocity.

Application to Other Material Geometries

While the intraluminal flammability test is well suited to tube geometries of transparent materials, it may be possible to extend the test to solid materials which are not in tubular form. For example, holes of a given size can be drilled into a plate of plexiglass to simulate a tube geometry, and an oxidizer flowed through the holes. Alternatively, the flame spread between two sheets of plexiglass through which an oxidizer flows can be attempted. If the test is to be extended to opaque materials, a method of flame detection must be identified.

CONCLUSIONS

1) The minimum oxygen concentration which will support an intraluminal can be measured easily and reproducibly.
2) In comparing the effects of nitrogen versus helium, opposite trends are observed with the intraluminal test as compared to the standard ASTM test. The intraluminal test is considered to be more relevant to the endotracheal tube fire problem.
3) The results of the test depend on the inner diameter of the tube. This dependence must be further understood prior to proposing a standard test method.
4) In principle, adaptations of the intraluminal test can be applied to any solid material which can be tested using the standard candle-type test.
5) The effects of buoyancy are much less important in the intraluminal flammability test than they are in the candle-type test. Therefore, the intraluminal flame test may be useful for low gravity applications.

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