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ENDOTRACHEAL TUBE FIRES: A FLAME SPREAD PHENOMENON

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ABSTRACT: Three flame types can result when an ignition source is applied to a tube of a combustible material through which an oxidizer flows. If the oxygen concentration inside the tube is greater than the tube material's limiting oxygen index (LOI), an opposed flow flame can spread along the inner surface of the tube (primary intraluminal flame). This flame, which requires a forced flow, consumes the supplied oxygen (fully or in part) and produces combustible, toxic gases which emerge from the free end (and ignition hole where applicable). These gases can then react with the oxygen in the ambient environment and thereby support the second flame type (secondary jet diffusion flame). If the LOI is exceeded outside the tube, an extraluminal flame (the third flame type) can occur, and be supported by natural convection.

KEY WORDS: flame spread, underventilated, endotracheal tube, oxygen index, fire safety

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The problem of operating room fires which arise from ignition (laser or electrocautery) of endotracheal tubes (ETT) continues to be reported [1, 2]. It is clear that the high concentration of oxygen (O2) and/or nitrous oxide (N2O) typically delivered through the airway during surgery is a major factor. Measurements of the limiting oxygen index of flammability (LOI) for different ETT materials [3] and studies of the effects of using different inert gases [4] have increased understanding of the clinical problem. However, there has been little effort to characterize the fundamental nature of the flame phenomena which can occur when the LOI is exceeded and the tube is accidentally ignited.

Much of the current effort to solve the problem is focused on the interaction of the laser source with the tube prior to ignition [2]. However, considerable development work and testing would be required to provide an ETT which is both "laser-proof" and satisfies the strict requirements associated with anesthesia. In addition, other ignition sources could be problematic if a tube was designed to address only the laser ignition problem.

Until an "ultimate" solution exists, there are likely to be procedural and/or simple design modifications which can reduce the risk of operating room fires. Identification of such short term partial solutions should proceed first from a fundamental understanding of the problem. Therefore, the goal of this study is to characterize the flame dynamics which can occur during existing operating room procedures. In this context, the nature of the ignition source (i.e. laser or open pilot flame) plays a small role. Rather, the concentration of the oxidizer supplied and its flow rate are the key variables. The type of inert mixed with the oxidizer can play a secondary role [4].

If an oxidizer (above the LOI) is flowed over a solid fuel and an ignition source is brought into contact with the surface, a flame will propagate against the flow [5, 6]. This phenomenon, termed "flame spread," is characterized by a gas phase diffusion flame front. Heat conducted from the flame gasifies the solid fuel which diffuses back toward the flame. Fuel and oxygen diffuse toward and are separated by the flame front. There are two fundamental measures of a flame spread process: the velocity at which this flame moves relative to the solid fuel (the flame spread velocity), and the rate at which solid fuel is gasified by the flame (the fuel consumption rate, or burning rate).

We hypothesize that endotracheal tube fires can be characterized as cylindrical geometry flame spread phenomena [7]. Three distinct flame types are identified and described in this paper; an external (extraluminal) flame, an internal (intraluminal) flame, and a jet diffusion flame fueled by the intraluminal flame products.

EXPERIMENTAL APPARATUS

A brief description of the experimental apparatus and procedures are reported here. Further details can be found in Stern [8].

Data obtained using polyvinylchloride (PVC) tubing, purchased from New Age Industries, are reported here. Polyvinylchloride and red-rubber endotracheal tubes were also tested and yielded consistent results.

The PVC tubes were slipped over a horizontally positioned 1/4 inch copper tube through which the oxidizer was supplied. The other end of the PVC tube was unsupported, and is referred to as the "free end." The external environment of the tube was ambient air.

Oxygen, nitrogen and helium were obtained from compressed cylinders. Flow rates were controlled by needle valves and measured with either a soap-film flow meter or a mass flow controller.

Ignition of the tube was accomplished for most tests using an open pilot flame. Some tests were performed using a CO2 laser, which yielded identical results. The pilot flame was placed either near the free end of the PVC tube, or at a hole drilled into the side of the tube (used to model laser ignition).

A stopwatch was used to measure the time for the flame to travel a marked distance, from which the velocity of the intraluminal flame spread was calculated. Some experiments were recorded with a video camera, and the velocities obtained were in good agreement with the real-time measurements.

The fuel consumption rate was obtained by weighing the tube sample before and after an experiment, and determining the time the flame existed (the distance traveled divided by the measured flame velocity).

RESULTS AND DISCUSSION

Figure 1 shows photographs of an experiment at three different times (approximately 1 second time interval). The PVC tube material used does not support candle-type combustion in air, but does in pure oxygen. Oxygen flowed through the tube [0.25 inch (0.63 cm) inner diameter (I.D.), 0.5 inch (1.3 cm) outer diameter (O.D)] at a constant flow rate of 0.5 liters per minute from left to right. The tube end, to which a pilot flame ignition source had been applied, was freely suspended in air.

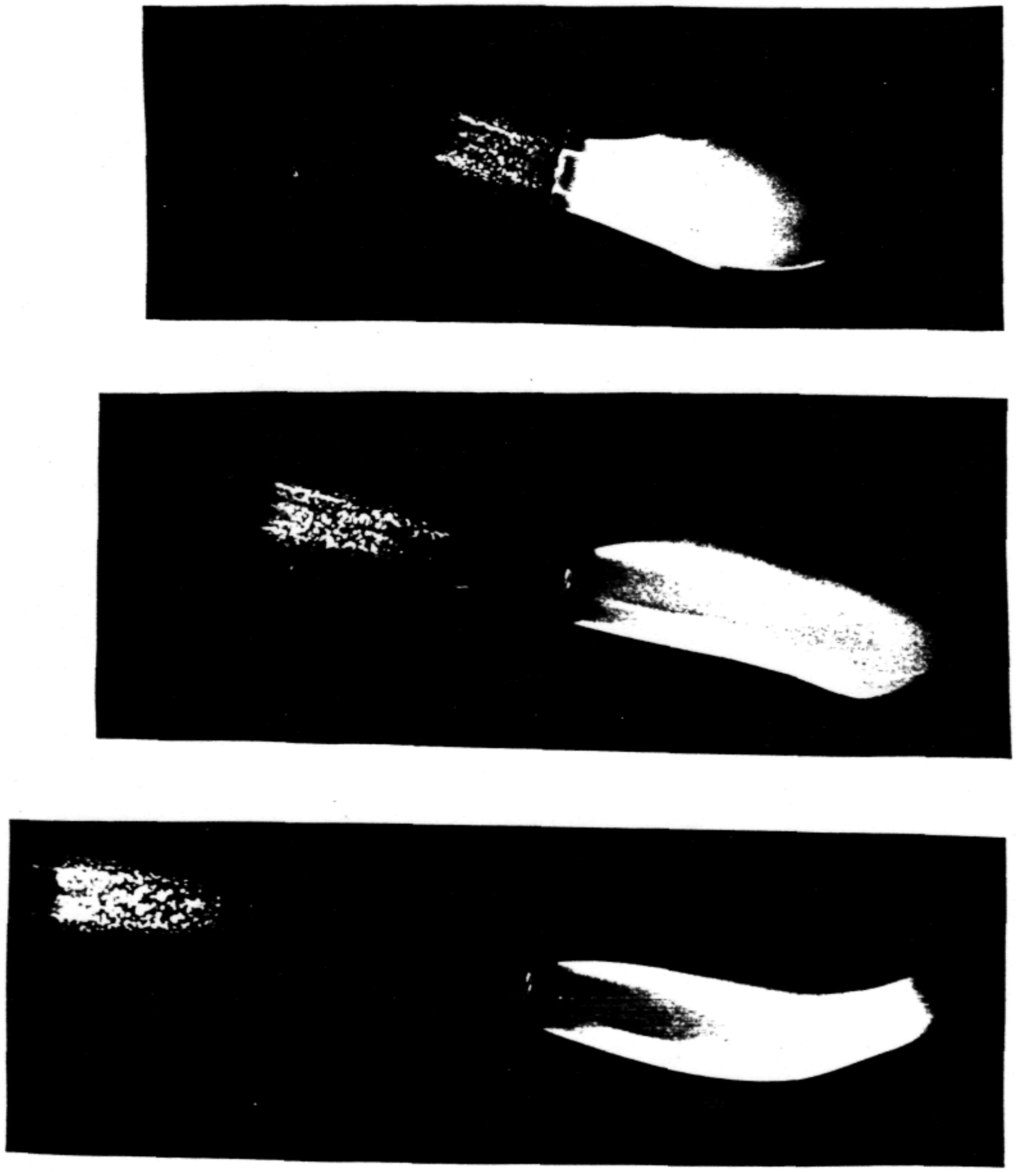

Fig. 1-- Photographs of intraluminal flame spread (left running) and secondary jet diffusion flame (emerging from the free end). The photos are of the same experiment at three times, approximately 1 second apart. The leading edge of the propagating flame is on the inner surface of the tube, and its tail is seen emerging out of the tube in the top photograph. The appearance of the flame behind the leading edge is obscured due to the cylindrical geometry, internal reflections of light, luminosity due to soot particles and the degradation of the inner surface of the tube.

Two distinct flames are observed in each photograph. One flame propagates inside the tube, against the flow, at a steady velocity, and is a flame spread phenomenon. The appearance and velocity of this flame depends primarily on the oxygen concentration and the flow rate of oxidizer supplied. As this intraluminal opposed flow flame moves to the left, the second flame remains attached to the free end. After this experiment, the outer surface of the tube is virtually untouched, although the inside is charred considerably.

Intraluminal Flame Spread Process

Figure 2 is a logarithmic plot of the propagation velocity of the intraluminal flame spread as a function of oxidizer flow velocity. Results using three different tube sizes are reported using pure oxygen [(0.25-, 0.25- and 0.375 inch (0.63-, 0.63- and 0.95-cm, respectively) inner diameters and 0.375-, 0.5- and 0.5-inch (0.95-, 1.3- and 1.3-cm, respectively) outer diameter, respectively). For the 0.25 inch I.D., 0.5 inch O.D. tubes, tests using mixtures of 50 mol% oxygen are reported using two inert gases, nitrogen and helium.

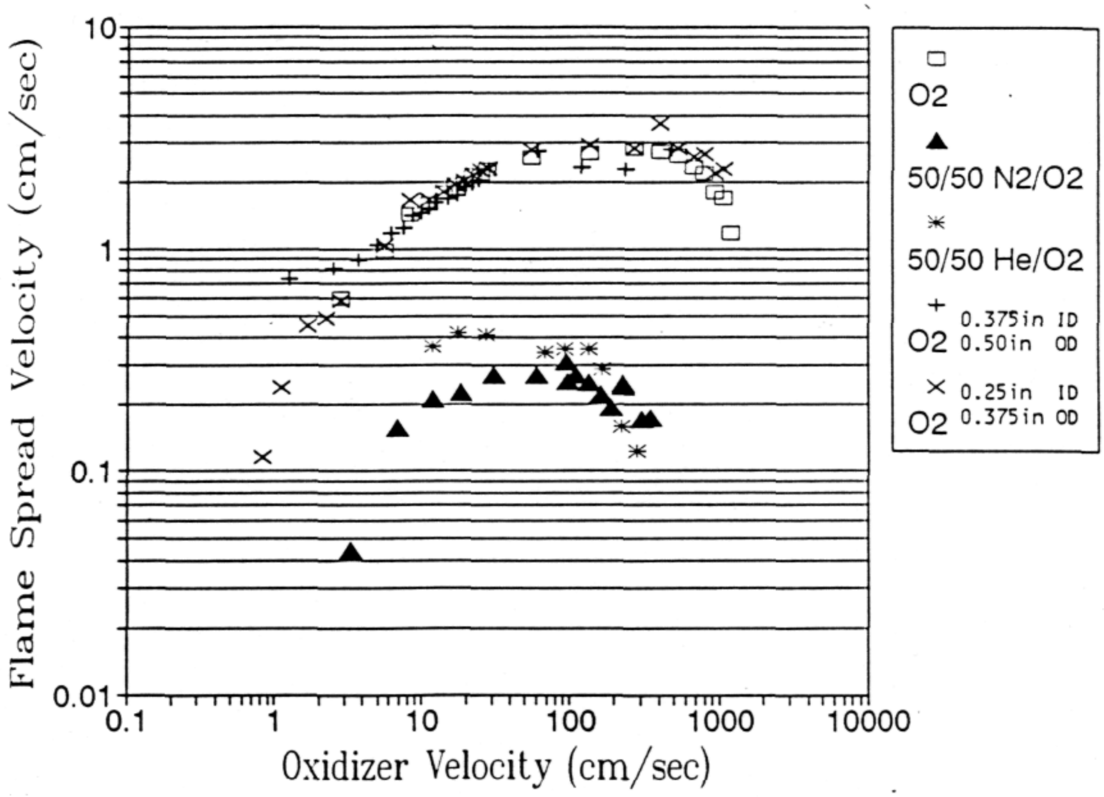

Fig. 2-- Intraluminal opposed flow flame spread velocity versus oxidizer velocity. Data for pure oxygen are shown for three tube geometries, and for 50 mol% oxygen in nitrogen and helium, respectively. Tube size is 0.25-inch (0.63-cm) I.D., 0.5 inch (1.3-cm) O.D. except where indicated.

Flames could not be established when the flow velocity was below approximately 1 cm/sec. This result indicates that the intraluminal flame spread requires a forced flow to exist. For the largest inner diameter tube, the shape of the curves is the same as that observed for flame spread in an opposed flow over flat plates [6]; as the flow velocity is decreased, the flame spread velocity approaches a constant value. This behavior has been attributed to natural convective effects; the naturally-induced flow component is greater than the forced flow component [6]. In contrast, for the smaller inner diameter tubes, the flame velocity decreases sharply as the oxidizer velocity is decreased. The influence of buoyancy is reduced in the smaller tubes, since the hot gases cannot rise and thereby induce a flow into the advancing flame.

For each case, there is an upper limit flow rate above which the flames could not propagate into the tube, called the "blow-out" limit. This phenomenon is essentially the same as that which occurs when a match is "blown out." This upper limit occurs at a much lower flow rate for 50% oxygen compared with the pure oxygen cases.

The blow-out limit is slightly lower when helium is used as the inert instead of nitrogen. However, the flame velocity is significantly greater with helium dilution for most flow velocities. This trend can be attributed to two main effects. First, the gaseous diffusion flame temperature is higher with helium because of its lower heat capacity. Second, helium has a higher thermal conductivity than nitrogen. Both of these factors would tend to increase the heat feedback to the solid fuel, which is a controlling process in flame spread [6]. Nevertheless, it is concluded that the type of inert used is a secondary factor compared with the oxidizer concentration.

The observed upper- and lower- limit behavior suggests that as the oxygen concentration is reduced, the flow range which supports intraluminal flame spread will decrease. Ultimately, the range would collapse to a point which represents a limiting oxygen index for intraluminal flame spread. Efforts are underway to measure this oxygen index and the corresponding flow velocity, and compare it to the LOI obtained in the candle-type flame test [9].

Distinct from the flame velocity, the fuel consumption rate is a measure of the net rate of solid fuel disappearance, and is shown as a function of oxidizer flow rate in Figure 3. The fuel consumption rate correlates with the oxidizer flow rate (not velocity) and is relatively insensitive to tube inner diameter, thickness, oxidizer concentration, and inert type [8]. The fuel consumption rate is somewhat higher for pure oxygen at the higher flow rates as the 50 percent oxygen cases approach the blow-out limit.

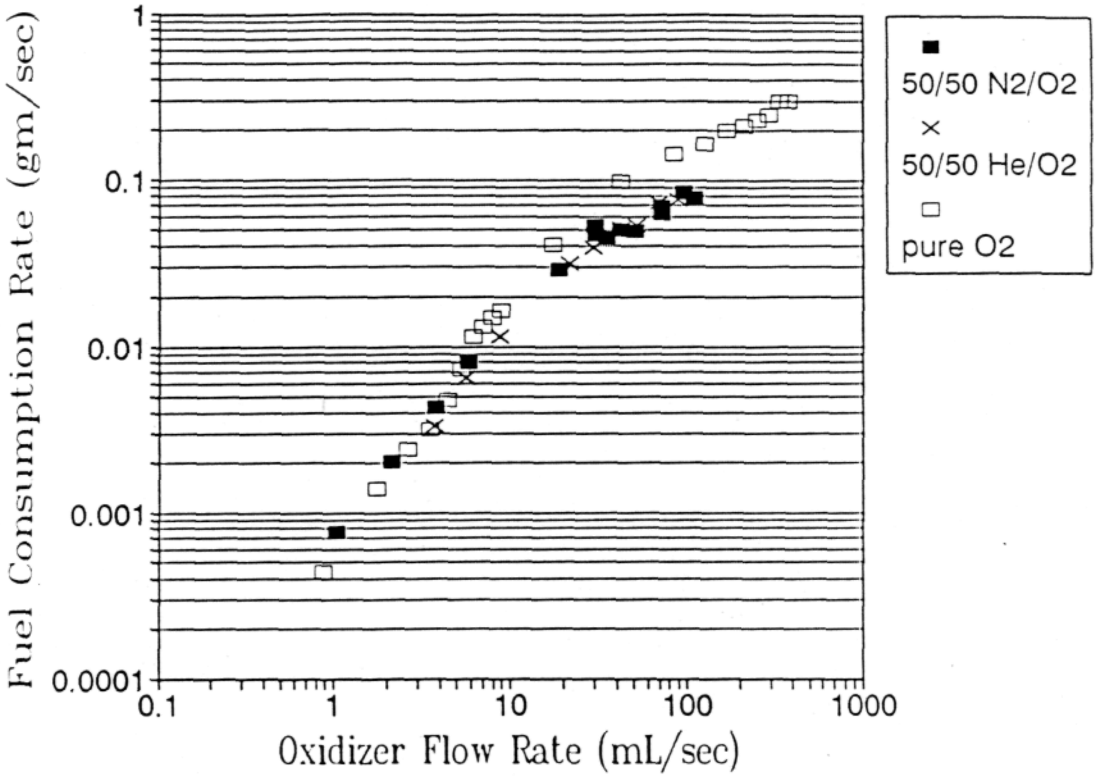

Fig. 3-- Fuel consumption rate versus oxidizer flow rate. Data for 0.25-inch inner diameter, 0.5-inch outer diameter PVC tubes are presented.

As the oxidizer flow rate is increased, the fuel consumption rate increases. This trend is in agreement with the visual observation of the tubes after the experiment; the higher the flow rate, the greater the degree of charring of the tube. In some cases, for tubes with thinner walls, the fuel consumption rate peaks, then decreases with flow. However, the phenomenon is different with thin walls in that the advancing flame completely consumes the tube material, and the flame spread and fuel consumption rates are no longer independent.

Another way to present fuel consumption data is to calculate an overall equivalence ratio of the intraluminal flame spread process, shown in Figure 4 as a function of oxidizer flow rate. The equivalence ratio (ER) is defined as the fuel consumption rate divided by the oxidizer supply rate normalized by the fuel/oxidizer ratio required for complete combustion of PVC to CO_2, H_2O, and HCl. It is assumed that the fuel is pure PVC. The inclusion of a plasticizer would yield a lower fuel/oxygen stoichiometric ratio, hence a higher calculated equivalence ratio. When the measured fuel/oxygen ratio is greater than this value (ER > 1), more fuel is liberated than can be completely consumed by oxygen. It is seen that this "underventilated" condition is satisfied for most flow rates.

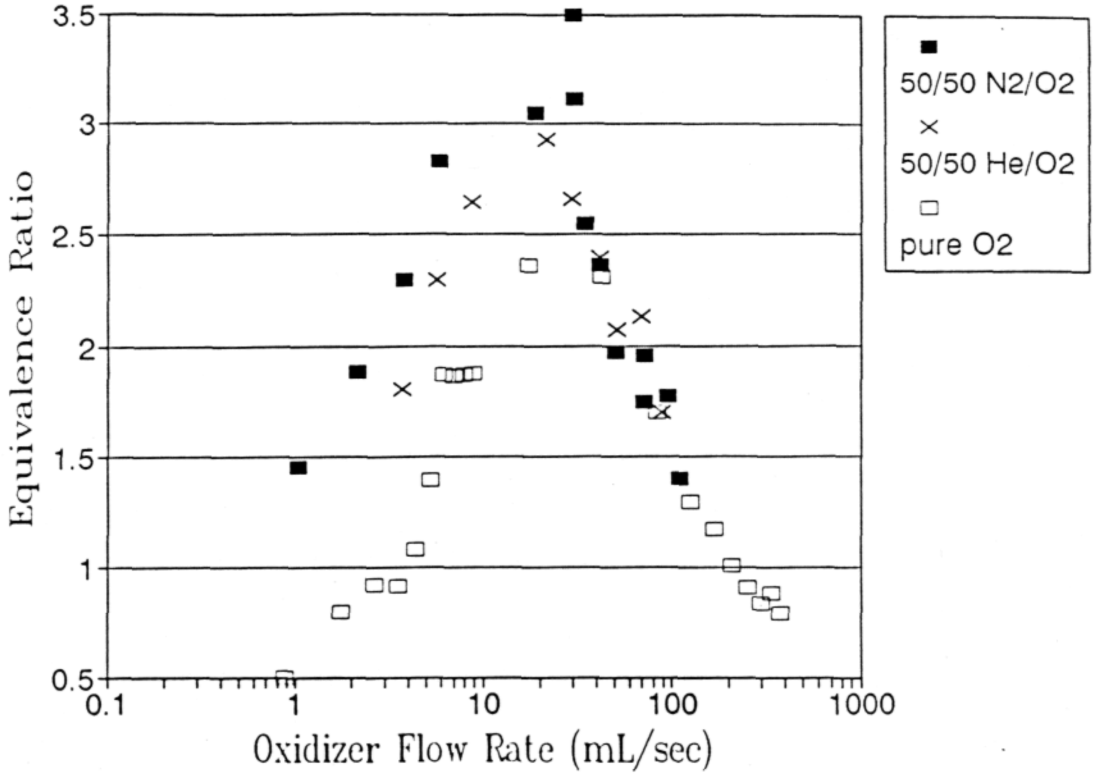

Fig. 4-- Equivalence ratio versus oxidizer flow rate. Data for 0.25-inch inner diameter, 0.5-inch outer diameter PVC tubes are presented.

The decrease in ER with increasing flow rate could be due in part to end effects. The intraluminal flame can be considered to have a length defined as the axial distance between the flame anchor at the fuel surface and where the gaseous flame "closes" on the centerline, the flame tip. This flame length increases with increasing flow rate. When the flame length is greater than the distance from the free end to the location of the flame anchor, the flame tip emerges from the tube. Therefore, less of the solid material is exposed to the heat of the flame than when the advancing flame is further from the free end. Efforts were made to minimize these effects (by using the longest tube samples possible) but could not be eliminated. Nevertheless, the general trend of decreasing ER with increasing flow seems reasonable as blow-out is approached.

Secondary Jet Diffusion Flame

Interpretation of the nature of the secondary flames (seen in Figure 1 emerging from the free end and ignition hole) is aided by the equivalence ratio data of Figure 4. Since the advancing intraluminal flame spread is overall fuel rich (more solid fuel is vaporized than the supplied oxygen can consume), the products which emerge from the tube contain combustible components such as, but not limited to, carbon monoxide, hydrogen gas and vinyl chloride. The higher the measured equivalence ratio, the higher the concentration of the combustible components. Therefore, wherever flow emerges from the tube downstream of the intraluminal flame, a classic jet diffusion flame can exist if the ambient environment is a suitable oxidizer. In addition to the combustibles mentioned, the products of the intraluminal flame consist of inerts ($N2$ or He, $CO2$, $H2O$), many other combustibles in small concentrations, toxics (HCl, CO, soot, aromatics, many others), and $O2$ in certain cases (especially when $ER < 1$).

The secondary flame will not exist if the concentration of the combustibles is too low, and/or the exit flow velocity is too high. For many cases, particularly for reduced oxygen concentrations, the secondary flame will initially exist but then blow-out as the primary flame moves away from the end. If there is no secondary flame, the products of the intraluminal flame are simply emitted into the environment.

Visually, when the secondary flame does not exist, copious amounts of black smoke are observed which indicates that the intraluminal flame generates soot. When there is a secondary flame, it is observed as an intense yellow flame, the yellow being attributed to incandescent radiation of soot particles which are heated as they approach the secondary flame.

In addition, the existence of the secondary jet diffusion flame depends on the distance from the ignition hole to the free end; if the hole is too far from the free end, the secondary flame will not be established [8]. In cases where the ignition hole was further from the free end than this minimum distance, the secondary flame could be lit if the pilot flame was placed near the free end. These results confirm that the secondary flame requires an ignition source, which can either be an externally applied source, or from the primary intraluminal flame itself.

It would be possible to measure a limiting oxygen index of the ambient environment, below which the secondary flame would not be established. It is intriguing that although the solid fuel will not support a candle-type flame in air, the products of the primary intraluminal flame spread in many cases have an LOI less than 21% oxygen (because they support a jet diffusion flame in air). This result can be explained by noting that the primary flame gasifies the fuel, which requires considerable energy; the energy released in the secondary flame need only heat the reactant gases up to a suitable "ignition temperature."

Extraluminal Flame

An extraluminal flame can exist if the concentration of oxygen outside the tube exceeds the LOI. In this case, even in a stagnant environment, if an ignition source is held near the tube, a flame can be established which spreads along the outside surface of the tube. This experiment is essentially that used as a standard to measure the LOI, and the flame appearance is similar [9]. If a flow were established inside the tube, the intraluminal and secondary jet diffusion flames could exist simultaneously. Unlike the intraluminal flame, the extraluminal flame does not require a forced flow but can be driven by natural convection.

CONCLUSIONS

The nature of the flame dynamics which can occur during existing operating room procedures have been investigated. We conclude that a flame spread process characterizes most if not all endotracheal tube fires which involve polyvinylchloride tubes [7].

The dynamics of opposed flow flame spread in tubes are similar to those for flame spread over solid fuels in other geometries (such as flat plates or rods). However, the intraluminal flame is unique because it is underventilated (except at high and low flows), and therefore the oxidizer cannot be considered infinite in extent. The diffusion flame can close on the axis, and thereby consume all the incoming oxygen.

The products of the intraluminal flame fuel the secondary jet diffusion flame which is anchored wherever flow emerges from the tube into an oxidizing environment. Visually, the secondary jet diffusion flame is the most apparent, and in the context of operating room fires, has the potential to do the most direct damage. However, it exists only as a result of the primary intraluminal flame spread.

If the oxygen concentration of the external environment is above the LOI of the material, flame spread can occur over the outer surface of the tube. Unlike the intraluminal flame, bouyancy creates the flow necessary to support extraluminal flame spread.

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