Determining the Time for Oxygen-exposed Materials to Return to Reduced Flammability

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Catastrophic fires have occurred as a result of gaseous oxygen enrichment, even in low-pressure environments. Risk for localized oxygen-enriched areas can occur when textile and foam materials become saturated in enriched oxygen, making them more flammable and easier to ignite. Materials can also serve as barriers by trapping localized oxygen-enriched environments.

When materials are moved from a higher oxygen concentration environment to one with lower oxygen concentration, the corresponding flammability and ignitability risks are difficult to characterize. An industrial example of such a scenario would occur when a person performs liquid-oxygen-filling operations and is exposed to a high amount of oxygen vapor. An aerospace example would be when an astronaut completes an extravehicular activity performed in 100% oxygen and then moves into a spacecraft with a lower (e.g., 34%) oxygen concentration. In these scenarios, it is not known how long it takes for a person's garments to return to the normal flammability and ignitability expected in the lower oxygen concentration. Historically, the generally accepted rule of thumb has been to allow 30 minutes for diffusion to reduce oxygen concentrations. This rule of thumb is not based on data and could result in significant time lost, particularly in the case of an astronaut moving back and forth between different environments.

The NASA White Sands Test Facility developed a test methodology and conducted tests to relate oxygen permeation with the flammability of materials exposed to high levels of oxygen. This study examined two scenarios: (1) material *saturation* from exposure to oxygen-enriched environments, and (2) oxygen *entrapment* when materials function as a barrier to create localized high oxygen concentrations, particularly oxygen trapped between a material and a person's body.

NASA developed a list of realistic and applicable materials for testing. Thirteen materials were chosen and grouped into categories by function (extravehicular mobility unit materials, advanced crew escape suit equipment, cabin environment materials, and common/comparison fabrics). These materials were tested in their use thickness.

In both entrapment and saturation scenarios, when a material moves to a lower oxygen concentration environment, oxygen concentration decreases as a result of diffusion over time and flammability decreases correspondingly. The test methodology characterized flammability as a function of time, thereby relating flammability to the permeation of oxygen in entrapment and saturation scenarios. A two-phase approach consisted of permeability testing and flammability testing.

For the permeability phase, we used oxygen transmission rate data to perform calculations determining the time for materials to return to reduced oxygen concentrations. The permeation tests were performed per ASTM [American Society for Testing and Materials] F1927, *Standard Test Method for the Determination of Oxygen Gas Transmission Rate, Permeability and Permeance at Controlled Relative Humidity through Barrier Materials Using a Coulometric Detector*. This test method determines the transmission rate of oxygen gas at steady-state conditions at a given temperature and percent relative humidity. We conducted testing at conditions expected during use. The relationship between the oxygen transmission rate (absolute flux) and the concentration gradient is described by Fick's First Law of Diffusion when describing a steady-state stationary medium. Absolute flux can further be correlated with total amount of permeant.

The scenarios in question are not steady state due to their dependence on time for atoms to equilibrate from one region to another. Nonetheless, they can be evaluated at discrete time steps, each of which can be considered steady state. We used this method to determine the time needed for materials to return to reduced oxygen concentrations. For saturation scenarios, materials were assumed to be filled with oxygen. The extent to which a material can absorb a gas depends on the solubility of that gas in a solid. This relationship was used in conjunction with Fick's laws of diffusion in calculations of concentration decay.

The flammability phase of testing determined the maximum oxygen concentration (MOC) flammability limits for each material using NASA-STD-6001A Test 1 methodology. The test setup was a modified NASA-STD-6001A Test 1 configuration (figure 1) in which we performed non-edge ignition to better simulate a realistic ignition scenario. We conducted testing at a single worst-case pressure of 101 kPa (14.7 psia), while we varied the

oxygen concentration to determine the flammability MOC threshold. The MOC threshold established for each material is the desired oxygen concentration below which a material will have reduced flammability (i.e., safe for unrestricted use and continued operation).

Once MOCs were determined and environments defined, we performed permeation rate calculations to determine the time required for each material to reach the MOC. Because porous materials exhibit diffusion rather than permeation, we used natural oxygen diffusion coefficients in calculations for porous materials, and we did not generate permeability data.

Analysis and correlation

The two scenarios examined were oxygen entrapment (as found between clothing and a person's body) and saturation of the material (common for cabin insulation and other materials exposed to an oxygen-enriched environment). Note: The proposed scenarios are meant to model only typical real-life situations. Data should therefore be used as an order-of-magnitude approximation for time in similar situations with similar materials.

The entrapment scenario assumed 100% oxygen contained in 1-cm depth behind permeable material, and a well-mixed environment of 20.9% oxygen outside the barrier. Calculations ascertained how well each barrier material "trapped" oxygen and determined the oxygen-concentration decay in the confined area with time. Table1 shows the amount of time each material needed to reach the MOC threshold. We assumed diffusion through all porous materials to be the same; the only variation was thickness. The time to reach decreased flammability for the thinnest to thickest porous materials tested ranged from 0.026 to 1 second.

The saturation scenario concerned larger, bulkier materials, as such materials hold the largest quantity

Material	Thickness (m)	MOC (%)	Time (t) to MOC or ambient (hr:min:sec)
Entrapment Scenario			
Tiburon® surgical microfiber composite drape (to 20.9)	0.00022	20	05:10:01
Spandex-covered Viton® (Mosite) fluoroelastomer closed-cell foam (to 20.9)	0.00794	18	447:18:21
ACES O_2 hose (silicone, stainless steel, Nomex®)	0.00567	49	11:55:00
Minicel® polyethylene closed-cell foam (to 20.9)	0.05100	20	36:55:01
Minicel® polyethylene closed-cell foam with Nomex® covering	0.05169	28	13:34:59
Zotek® F-30 PVDF closed-cell foam	0.0254	36	04:49:00
Saturation Scenario			
Spandex-covered Viton® (Mosite) fluoroelastomer closed-cell foam (to 20.9)	0.50	18	10,000:00:00
Minicel® polyethylene closed-cell foam (to 20.9)	0.50	20	3,050:00:00
Minicel® polyethylene closed-cell foam with Nomex® covering	0.50	28	350:00:00
Zotek® F-30 PVDF closed-cell foam	0.50	36	121:00:00
Pyrell® polyurethane open-cell foam (to 20.9)	0.50	19	00:02:10

Table 1. *Permeable materials oxygen permeation to low-flammability conditions*

Fig. 1. *Modified NASA-STD-6001A Test 1 on ACES layup.*

of oxygen. We assumed that cubes of bulk materials 0.5-m long have solubility equal to that of oxygen in rubber at 298 K. Each material was initially saturated in 100% mole fraction of oxygen.

Conclusions and future work

Our two-phase methodology succeeded in correlating time required for exposed materials to return to reduced flammability, and is recommended for future use in examining flammability risks for localized, oxygen-enriched environments. Validation testing will consist of burning materials at time intervals after removal from 100% oxygen environments, and correlating burn lengths and burn rates to known concentration testing.

Data show that oxygen entrapment and saturation is a concern, especially when dealing with nonporous materials. For porous materials, the 30-minute rule of thumb is overly conservative: an entrapped oxygen concentration will equilibrate with the new environment in a matter of seconds, and even large, bulky saturated porous material will take only a few minutes. In contrast, nonporous materials can trap and retain oxygen for many hours. In these cases, the 30-minute rule of thumb may not be sufficient. The risks must be weighed to not overly restrict operations while not ignoring increased flammability. Localized, enriched-oxygen concentrations should be considered in operational planning, especially as more closed-cell foams are used (e.g., Mosite in the astronaut liquid-cooled ventilation garment). Although these foams exhibit superb properties for use, they provide formidable barriers for oxygen permeation and act as retainers of oxygen saturation.

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