Journal of ASTM International, October, 2009, Vol. X No. X
Paper ID: JAI102306-08
Available online at www.astm.org

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Determination of Time Required for Materials Exposed to Oxygen to Return to Reduced Flammability

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ABSTRACT: Increased material flammability due to exposure to high oxygen concentrations is a concern from both a safety and operational perspective. Localized, high oxygen concentrations can occur when exiting a higher oxygen concentration environment due to material saturation, as well as oxygen entrapment between barrier materials. Understanding of oxygen diffusion and permeation and its correlation to flammability risks can reduce the likelihood of fires while improving procedures as NASA moves to longer missions with increased extravehicular activities in both spacecraft and off-Earth habitats. This paper examines the time required for common spacecraft materials exposed to oxygen to return to reduced flammability after removal from the increased oxygen concentration environment. Specifically, NASA-STD-6001A maximum oxygen concentration testing and ASTM F-1927 permeability testing were performed on Nomex®[4] HT90-40, Tiburon®[5] Surgical Drape, Cotton, Extravehicular Mobility Unit (EMU) Liquid-Cooled Ventilation Garment, EMU Thermal Comfort Undergarment, EMU Mosite Foam with Spandex Covering, Advanced Crew Escape Suit (ACES) Outer Cross-section, ACES Liquid Cooled Garment (LCG), ACES O_2 Hose Material, Minicel®[6] Polyethylene Foam, Minicel® Polyethylene Foam with Nomex® Covering, Pyrell Polyurethane Foam, and Zotek®[7] F-30 Foam.

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[4] Nomex® is a registered trademark of E. I. Du Pont de Nemours and Company, Wilmington, DE.

[5] Tiburon® is a registered trademark of Allegiance Corporation, McGraw Park, IL.

[6] Minicel® is a registered trademark of Sekisui Voltek, Lawrence, MA.

KEYWORDS: Flammability, Nonmetals, Diffusion, Permeability, Permeation, Maximum Oxygen Concentration (MOC), Gaseous Oxygen Enrichment, Textiles, Extravehicular Mobility Unit, Crew Escape Suit

[7] Zotek® is a registered trademark of Zotefoams plc, Walton, KY.

Introduction

Catastrophic fires have occurred as a result of gaseous oxygen enrichment, even in low pressure environments. One contributing factor is that textile materials become more flammable and easier to ignite after exposure to gaseous oxygen enrichment or saturation. In addition, these materials can serve as barriers by trapping localized oxygen-enriched environments.

When materials are moved from a higher oxygen concentration environment to an environment 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 of such a scenario would occur when an astronaut completes an extravehicular activity (EVA) performed in 100% oxygen, and then moves into a spacecraft with a lower oxygen concentration (such as 34% oxygen). In each of these scenarios, it is not known how long it would take for the person's garments to return to the flammability and ignitability expected in the lower oxygen concentration. The generally accepted rule of thumb used in such a scenario has historically been to allow 30 minutes for materials to return to their flammability and ignitability in the lower oxygen concentration (and essentially to avoid any potential ignition sources during that 30-minute time frame). 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.

NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) developed a test methodology and conducted tests to relate oxygen permeation with flammability of materials that have been exposed to oxygen enrichment or saturation. This report examines both the scenario of saturation of materials exposure to oxygen-enriched environments, and the scenario of entrapment when materials function as a potential barrier to create localized high oxygen concentrations. The entrapment scenario is particularly focused on simulating oxygen trapped between a material and a person's body.

Test Methodology

The test methodology characterized flammability as a function of time, thereby relating the flammability to the permeation of oxygen in entrapment and saturation scenarios. It was determined that a two-phase approach could be used and data correlated. The two phases of the methodology were permeability testing and flammability testing.

Permeability Phase of Methodology

When a material is moved from a high oxygen concentration to a low oxygen concentration, the oxygen concentration in the material decreased over time through diffusion. Mass transfer is mass in transit as the result of a species concentration difference in a mixture as a driving potential for transport. This transport process is called diffusion. Permeation is the flux of a species through a material due to species concentration differences on either side normalized to the pressure gradient. For simplification, only oxygen transport was considered in our models. Nitrogen transport was assumed to be reasonably negligible due to a significantly smaller concentration gradient that would drive transport, and transport rates that tend to be two to three times slower than those for oxygen.

Permeability testing was performed to generate oxygen-transmission rate data that was then used to perform calculations determining the time necessary for materials to return to reduced oxygen concentrations. The permeation tests were performed in accordance with ASTM-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 rate of transmission of oxygen gas at steady-state conditions at a given temperature and percent relative humidity (% RH) through films, sheeting, laminates, coextrusions, or plastic-coated papers and fabrics. 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 as shown in equation 1. Absolute flux can further be correlated with total amount of permeant using equation 2. [2]

$$J = -D\frac{\partial C}{\partial x}$$

(1)

Equation 1: Fick’s First Law for a steady-state stationary medium is where J is the flux per unit area of permeant through the polymer, D is the diffusion coefficient, and δc/δx is the concentration gradient of the permeant across a thickness δx.

$$J = \frac{Q}{At}$$

(2)

Equation 2: Correlation of absolute flux (J) to amount of permeant (Q) that has passed through area (A) during time (t).

The scenarios in question are not steady state due to their dependence on time for atoms to accumulate in a region and correspondingly deplete from another a region. Nonetheless, equation 2 can be evaluated at discrete time steps, which can be considered steady state within each time step. By using this method, the time needed for materials to return to reduced oxygen concentrations was determined [8]. For saturation scenarios we assume materials are filled with oxygen. The extent to which a material can absorb a gas is dependent on the solubility of that gas in a solid. This relationship is shown in equation 3 and is used in conjunction with Fick’s laws for diffusion in calculations of concentration decay [2, 8].

Equation 3: Concentration equation and relationship to solubility and partial pressure of gas adjoining to the surface of solid material.

$$C_A(0) = S \cdot p_A$$

(3)

Flammability Phase of Methodology

Flammability testing was conducted to determine the Maximum Oxygen Concentration (MOC) flammability limits for each material. The MOC method uses NASA-STD-6001A, Test 1 methodology to determine oxygen concentration thresholds for which a material will pass NASA's criteria for acceptable flammability in a specified environment. Acceptable flammability is determined to be a burn length of less than 6 inches before self-extinguishment occurs with no drip or burning that propagates fire to K-10 paper set below the sample. The test setup was a modified NASA-STD-6001A, Test 1 configuration, as shown in Figure 1. Non-edge ignition was performed to better simulate a realistic ignition scenario. To achieve this scenario, materials were angled at 15° from vertical with the igniter positioned 2 in. above the bottom of the sample and 1/4 inch below the surface.

Passing of this test can be considered conservative as it is meant to identify materials that will self-extinguish with only minimal burning and limited possibilities for propagation to surrounding materials. The MOC threshold established for each material can be considered to be the desired oxygen gas concentration below which a material will have reduced flammability. When this concentration is reached, the material will not need any additional special restrictions for use and continued operation

In both entrapment and saturation scenarios, once a material configuration is moved to a lower oxygen-concentration environment, the oxygen concentration will begin to decrease as a result of diffusion with respect to time, and flammability will decrease correspondingly. Once MOCs were determined and environments defined, permeation calculations based on Fick's First Law were performed to determine the time required for each material to reach the MOC.

Test Materials

The NASA groups that encounter potentially oxygen-enriched entrapment and saturation scenarios collaborated to develop a list of realistic and applicable materials for testing. Groups involved in material selection were: the Johnson Space Center Material and Process Branch, the Extravehicular Activity Office, and the Crew Escape Suit and Systems Group. Some materials not used in NASA scenarios were chosen for their comparison with past data [1].The materials chosen were grouped into separate categories by function and tested in their use thickness. Table 1 describes the thirteen materials and layups that were tested.

Test Results & Discussion

Results from the two phases of testing are discussed in the following sections, as well as the analysis and correlation of test data.

Permeability Phase of Methodology

ASTM-F1927 was conducted at a specified temperature, and % RH expected during material usage. Results of these tests are shown in Table 2 and Figure 2. In inspecting materials for permeation testing it was determined that porous materials would not exhibit resistance to natural diffusion, and so it was assumed that these materials would exhibit diffusion rather than permeation. Therefore, for porous materials, natural oxygen diffusion coefficients were used in calculations and permeability data was not generated [2]. Porous materials were identified by holding the material up to light to determine if there were any holes large enough to allow light to show through. The ACES layup was questionable and was tested for porosity using ASTM-F1927. Testing showed that the layup was indeed porous. Results for ASTM-F1927 Testing and Corresponding Permeability Coefficients are found in Table 2. Materials that were determined to be porous and their diffusion coefficient are shown in Table 3.

Flammability Phase of Methodology

NASA- STD-6001A Maximum Oxygen Concentration (MOC) flammability testing was conducted at specified environmental pressure while the oxygen concentration was varied to determine the flammability threshold. Though the actual materials are used in a variety of pressure and concentration combinations, a single worst-case pressure of 101 kPa (14.7 psia) was chosen for consistency and ease of data comparison [7]. MOC threshold results are shown in Tables 4 and 5 for permeable and porous materials, respectively.

Analysis and Correlation of Permeation and Flammability Data

Two scenarios are examined in the following section. One scenario represents oxygen entrapment as found between clothing and a person's body, and the other scenario represents saturation of the material itself as would be common for cabin insulation and other materials exposed to an oxygen-enriched environment. It should be noted that any type of permeation calculations are dependent on configuration and that scenarios in real life will vary in their specific configuration from those modeled here. Nonetheless, the scenarios proposed are meant to model typical situations that may be encountered in real life. Therefore, data should be used as an order of magnitude approximation for time data in similar situations with similar materials.

In the entrapment scenario, the model situation has oxygen trapped between an impermeable surface (human body) and that of a barrier material. The volume of gas was determined through an assumed 1 cm of depth between the barrier material and the impermeable surface. Calculations were performed to ascertain how well each barrier material "traps" oxygen and to determine the oxygen-concentration decay in the confined area. It was assumed that the initial concentration between the barrier and the impermeable surface was 100% and that the oxygen concentration on the outside of the barrier was a well-mixed environment of 20.9%. Figures 3 and 4 are example plots showing the decay of the oxygen concentration in the trapped area as permeation progresses with time. Tables 6 and 7 show the amount of time needed for the trapped area to reach the MOC threshold determined in flammability testing or to reach 20.9% oxygen if the MOC was determined to be below 20.9% oxygen.

Because the diffusion through all porous materials is assumed to be the same, the only variation in time for these materials is dependent on their thickness. Table 7 presents the thickest and thinnest porous materials tested to give a range of time for decreased flammability.

For the saturation scenario, the model situation represents a potential situation of oxygen saturating a material and the time associated for this saturated material to permeate out enriched oxygen to equilibrate with surrounding concentration. Saturation is a great concern for larger, bulkier materials as they can hold the largest quantity of oxygen when saturated. Therefore, for the saturation scenario, bulk materials were modeled. The saturated material was an assumed cube of bulk material with a length of 0.5 m. Due to limited solubility information, materials were assumed to have solubility equal to that of oxygen in rubber at 298K. The saturation scenario shows how well saturated materials retain oxygen and the decay function of oxygen concentration was determined for each material. It was assumed that each material was initially saturated in 100% mole fraction of oxygen permeating out into a well-mixed 20.9% oxygen environment. Tables 8 and 9 show the times required for each material to reach the MOC, or 20.9% oxygen if the MOC was determined to be below 20.9% oxygen.

Conclusions and Future Work

The two-phase methodology consisting of NASA-STD-6001A MOC flammability testing and ASTM F-1927 permeability testing was successful in correlating time required for materials exposed to oxygen to return to reduced flammability. This methodology is recommended for future use in examining flammability risks for localized, enriched-oxygen environments. Validation testing will be performed to confirm modeled scenarios, but were not completed in time for this publication. Validation testing will consist of burning materials at time intervals after being removed from 100% oxygen environments, and their burn lengths and burn rates will be correlated to known concentration testing.

It is clear 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, and it can be expected that oxygen concentration will equilibrate with the new environment in a matter of seconds when considering entrapment scenarios. For saturation scenarios, even large, bulky sections of porous material will take only a few minutes to equilibrate. In contrast, nonporous materials are excellent at trapping and retaining oxygen, even for many hours. In these cases, there will be localized, enriched-oxygen areas with higher flammability risks for a substantial length of time, and the 30-minute rule of thumb may not be sufficient. With nonporous materials, the risks must be weighed to not overly restrict operations, nor to ignore the increased flammability. Localized, enriched-oxygen concentrations should be considered in operational planning, especially as there is a move toward a greater quantity of closed-cell foams. An example is the use of Mosite in the astronaut Liquid-Cooled Ventilation Garment (LCVG) that can be worn after a mission is complete and suit is removed and where the astronaut would retain enriched-oxygen concentrations in direct contact with his body for extended periods of time. Although these foams exhibit superb properties for use, here they are evidenced to be excellent barriers for oxygen permeation and retainers of oxygen saturation.

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TABLE 1—*Test materials.*

Material	Description
Common/Comparison Fabrics	
Nomex® HT90-40	Aramid fabric with high-performance heat- and flame-resistant properties. L/N 7254
Tiburon surgical drape	Microfiber composite consisting of three layers: an absorbent fluid-control layer made of microfiber fabric, an impermeable cast-extruded polyethylene membrane laminated to the non-woven components, and a patient comfort layer
Cotton Fabric	Cellulose fabric in 100% cotton Hanes Beefy T-shirt
Extravehicular Mobility Unit Materials	
EMU Liquid-Cooled Ventilation Garment (LCVG)	Polyamide Material Nylon Tricot ST11N791-01
Thermal Comfort Undergarment (TCU)	Polyester-based Material TCU Bottom, P/N SKD38114488-01. 100% Polyester
Spandex-Covered Viton (Mosite) Foam	Polyurethane/Polyethylene Glycol Elastomeric Spandex ST11N117-07 Covered Viton (Mosite) Fluoroelastomer Closed-cell Foam ST66V2590-01 is used in a variety of pads available for use in the EMU. These pads were designed to reduce hot-spots created by suit contact with the shoulders, elbows, ribs, or knees. The pads are inserted into spandex pockets that are form-fitted to each pad, and these are whip-stitched to the LCVG. [5]

Advanced Crew Escape Suit(ACES)/Equipment	
ACES Suit Layup	Layup consisting of two outer layers of ACES, the outer material being composed of the Aramid fiber-based Nomex® and the inner material composed of a Polytetrafluoroethylene (PTFE) based Gore-Tex® for use as a bladder.
ACES Liquid-Cooled Garment (LCG)	An assembly composed of thick, polypropylene-based undergarment with plastic tubing stitched in. This garment is worn under the outer ACES garment for temperature control [6].
O_2 Hose	Oxygen hose, SN-NA (Class 3) for supply of oxygen to astronauts during ascent in case of depressurization or escape. The hose is composed of a silicone liner, stainless-steel interstitial-weave braid, and a Nomex® aramid material cover.
Cabin Environment Materials	
Minicel® Polyethylene Foam	L-200 Minicel® Polyethylene Foam. This foam is extremely fine-celled, chemically cross-linked closed-cell foam, commonly used in the various space vehicles. This foam is commonly covered an Aramid (Nomex) to mitigate fire risk.
Minicel® Polyethylene Foam with Nomex® Covering	HT90-40 Nomex® Covered L-200 Minicel® Polyethylene Foam. This foam is closed-cell foam, commonly used in the various space vehicles.
Pyrell Polyurethane Foam	Pyrell Polyurethane Foam. This foam is open-celled foam.

Zotek® F-30 Foam	Polyvinylidene Flouride (PVDF), highly non-reactive and pure thermoplastic fluoropolymer closed-cell foam; a foam being considered for extensive use in future NASA vehicles.

TABLE 2—*Permeable materials and their permeability coefficients.*

Material	Analysis Conditions			Permeability Coefficient $\frac{Mol \cdot m}{m^2 \cdot S \cdot Pa}$
	Temp (F)	Test Gas (O_2) Humidity (RH %)	Carrier Gas (N_2) Humidity (RH %)	
Tiburon Surgical Drape	75	35%	35%	1.4018E-14
Spandex-Covered Viton (Mosite) Foam	72	47%	35%	4.1486E-15
ACES O_2 Hose	75	0%	0%	7.3413E-15
Minicel Polyethylene Foam	75	35%	35%	1.3362E-13
Minicel Polyethylene Foam with Nomex Covering	75	35%	35%	1.3543E-13
Zotek F-30 Foam	75	35%	35%	3.4117E-13

TABLE 3—*Porous materials and their diffusion coefficient.*

Material	Natural Oxygen Gas Diffusion Coefficient through air @ 278K and 1 atm (m^2/s)
Nomex HT90-40	2.1E-05
Cotton Fabric	2.1E-05
EMU Liquid-Cooled Ventilation Garment (LCVG)	2.1E-05
Thermal Comfort Undergarment (TCU)	2.1E-05
ACES Suit Layup	2.1E-05
ACES Liquid-Cooled Garment (LCG)	2.1E-05
Pyrell Polyurethane Foam	2.1E-05

TABLE 4—*Permeable materials maximum oxygen concentrations at 101kPa.*

Material	Test Pressure (pa)	Maximum Oxygen Concentration (%)
Tiburon Surgical Drape	101,325	20
Spandex-Covered Viton (Mosite) Foam	101,325	18
ACES O_2 Hose	101,325	49
Minicel Polyethylene Foam	101,325	20
Minicel Polyethylene Foam with Nomex Covering	101,325	28
Zotek F-30 Foam	101,325	36

TABLE 5—*Porous materials maximum oxygen concentrations.*

Material	Test Pressure (pa)	Maximum Oxygen Concentration (%)
Nomex HT90-40	101325	24
Cotton Fabric	101325	13
EMU Liquid-Cooled Ventilation Garment (LCVG)	101325	23
Thermal Comfort Undergarment(TCU)	101325	21
ACES Suit Layup	101325	34
ACES Liquid-Cooled Garment (LCG)	101325	18.1
Pyrell Polyurethane Foam	101325	19

TABLE 6—*Permeable materials oxygen permeation to low-flammability conditions for entrapment scenario.*

Material	Thickness (m)	MOC (%)	Time (t) to achieve MOC or ambient (hr:min:sec)
Tiburon surgical drape	0.00022	20	03:04:58
Spandex-Covered Viton (Mosite) Foam	0.00794	18	74:51:36
ACES O_2 Hose	0.00567	49	11:55:00
Minicel Polyethylene Foam	0.05100	20	16:30:00
Minicel Polyethylene Foam with Nomex Covering	0.05169	28	12:30:00
Zotek F-30 Foam	0.0254	36	04:30:00

TABLE 7—*Porous materials oxygen permeation to low-flammability conditions for entrapment scenario.*

Material	Thickness (m)	MOC (%)	Time (t) for MOC or ambient (hr:min:sec)
EMU Liquid-Cooled Ventilation Garment (LCVG)	0.00022	23	00:00:026
Pyrell Polyurethane Foam	0.0508	19	00:00:10

TABLE 8—*Permeable materials oxygen permeation to low-flammability conditions for saturation scenario.*

Material	Thickness (m)	MOC (%)	Time (t) for MOC or ambient (hr:min:sec)
Spandex-Covered Viton (Mosite) Foam	0.50	18	2029:30:00
Minicel Polyethylene Foam	0.50	20	334:30:00
Minicel Polyethylene Foam with Nomex Covering	0.50	28	159:30:00
Zotek F-30 Foam	0.50	36	52:30:00

TABLE 9—*Porous materials oxygen permeation to low-flammability conditions for saturation scenario.*

Material	Thickness (m)	MOC (%)	Time (t) for MOC or ambient (hr:min:sec)
Pyrell Polyurethane Foam	0.50	19	00:02:10

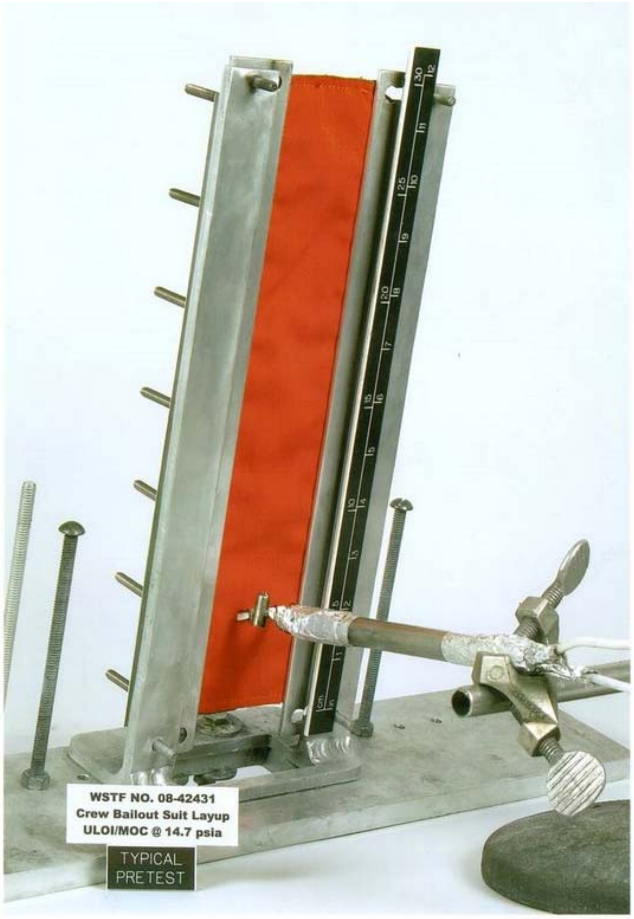

FIG.1—*Modified NASA-STD-6001A Test 1 on ACES Suit Layup.*

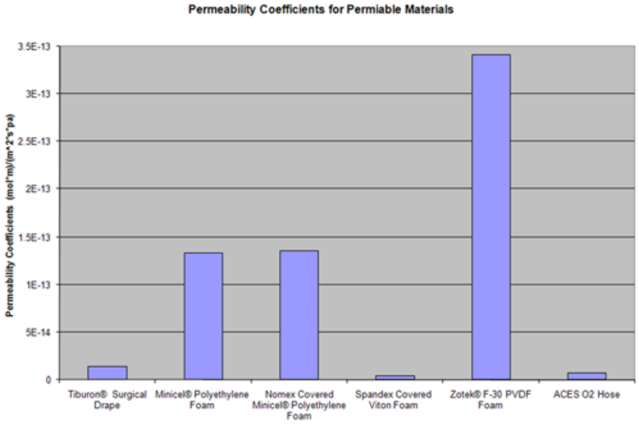

FIG. 2—*Permeation coefficients of materials.*

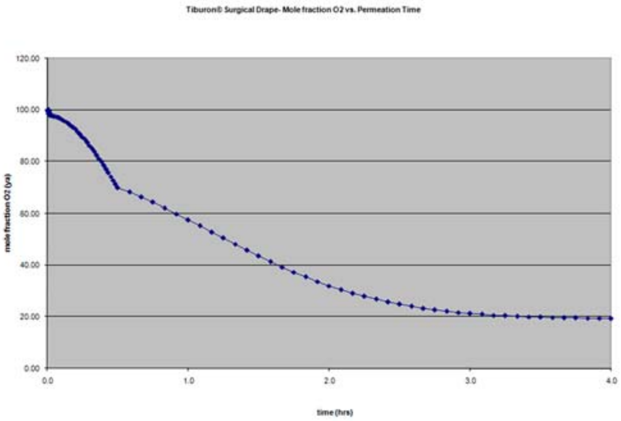

FIG. 3—*Permeation of oxygen through Tiburon Surgical Drape in entrapment scenario.*

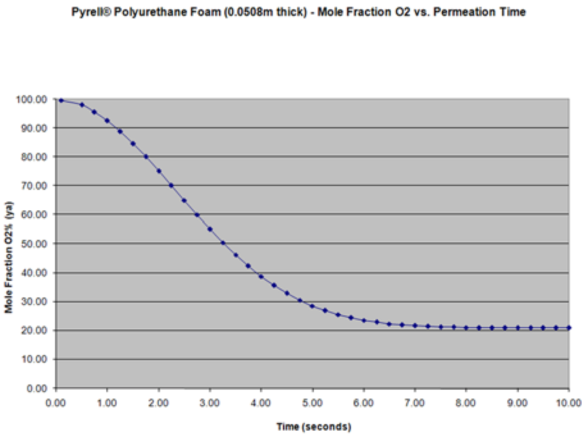

FIG. 4—*Permeation of oxygen through Pyrell Polyurethane Foam in an entrapment scenario.*