Assessing The Suitability of New Film Laminates For Sustainable Insect Eradication By Modified Atmosphere In Museums

Manar Elkhial (manar_el_khial@yahoo.com)
Grand Egyptian Museum https://orcid.org/0000-0001-5143-0180

Nesrin Elhadidi
Faculty of Archaeology, Cairo University

Research article

Keywords: Plastic film, OTR, modified inert atmosphere, insect eradication, museums, permeability test

Posted Date: October 21st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-984239/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

The increasing demand for applying modified inert atmosphere (MIA) systems for insect eradication in museums has led to the desire for lower-cost consumable materials, particularly laminated plastic films. An ultra-low oxygen-permeable laminate is required for creating successful MIA systems to keep the oxygen concentration lower than 0.3%, which is commercially available but at a high cost. The wide use of local laminated films for food preservation makes them a perfect target for testing and improvement for MIA applications. However, the lack of laboratory oxygen permeability test methods to gauge the potential of local laminates for inclusion in MIA applications distracts attention from looking at them as alternatives and encourages the expense on extremely expensive imported ones. Therefore, the present work investigates the potential of employing two laminates (one local and one imported) to create a successful leak-proof MIA system. A laboratory easy-to-use test method was developed to assess the oxygen-gas retention property of each laminate by measuring its oxygen permeability and consequently oxygen transmission rate (OTR). The test method is a sealed static diffusion chamber separated in the middle by a known area (cm$^2$) of the test laminate to be tested. The test relies on measuring the concentration of oxygen in either sides of the laminate membrane within the sealed system and monitors the change over time to assess the OTR of the laminate. The specifications and design of the test chamber are adapted from the ASTM Designation: E2945 - 14, to meet the facilities of a typical artefact fumigation laboratory. The test is undertaken at standard MIA conditions (temperature of 25°C, relative humidity of 45%, and target oxygen concentration of 0.3). Results indicated that the new method is useful for an unlimited number of tests of an unlimited number of laminates. The conducted tests proved that the local laminate normally used for food packaging has superior advantages over the long-used imported ones.

Introduction

Flexible custom-made MIA systems are created using flexible plastic films that must have a low permeability to oxygen to retain the desired oxygen level, which is very low, over the treatment period. Other properties are required in plastic films for MIA applications; such as easily sealable and mild toughness. The properties of commercial thin layer plastic films are affected by many factors; such as the chemical nature of the film polymer; the distribution and concentration of its molecules; and the fabrication process itself (1). Although additives are used for optimizing some properties or adding new ones to plastic films, no physical or chemical modifications resulted in a perfect, thin layer film that meets all requirements for MIA applications. This emphatically means that the plastic film, that must combine a number of indispensable properties to fit MIA purposes, cannot be a single-layer film. Nowadays, a wide variety of film laminates are industrially available, which consist of layers of quite different films each with a particular superior property. A typical laminate for MIA applications must meet the following criteria (1,2):

Criterion 1. Flexibility: the MIA laminate must be flexible rather than brittle or too stiff to easily create custom-made bags or tents.
Criterion 2. Easily sealable: the laminate must be heat sealable to one another from one surface at a certain temperature that does not affect the other surface.

Criterion 3. Toughness: the non-sealable surface of the laminate must not be easily puncturable or scratchable.

Criterion 4. Oxygen permeability: the main characteristic of a MIA laminate is that oxygen does not transmit easily across it.

Criterion 5. Clarity: MIA is an insect-disinfestation treatment implemented to cultural artifacts that need to be monitored throughout the treatment. Therefore, MIA laminates must be transparent enough to see the artifacts through them.

Criterion 6. Cost: MIA laminates are consumable materials as they are cut and fabricated according to custom designs. They are also delicate materials and care must be taken when handling them (Criterion 3). Therefore, the cost of MIA laminate must be low to lower the labour cost and ensure sustainability in MIA application in the institution.

Normally, a barrier laminate used for MIA is composed of at least three layers of polymer films (3). The internal layer is used to (heat) seal the barrier film together by melting these two layers together. The outer layer acts as a protective layer and serves to increase the barrier properties of the laminate. The intermediate layer provides a good barrier against oxygen from entering the MIA bag (2).

The selection of the suitable barrier for MIA depends mainly on the oxygen transmission rate (OTR) of the laminate, often expressed as the amount of material (cc of gas) that can pass through one square meter of the film membrane in 24 hours (4). A number of film laminates are commonly used for MIA applications worldwide for their low OTR (Fig. 1).

However, due to the disparate properties of each layer of a laminate, no laminate fulfils all the required criteria for MIA applications and therefore one has to balance between what is required and what is available. There are currently a number of commercially available film laminates which could be used in MIA applications; however, they are very expensive and are produced by certain companies located mainly in the U.S., Japan, and Germany, and must therefore be imported, which impedes their use, particularly when import restrictions occur and doubles their cost. In this context, the choice of certain film laminates may therefore question the sustainability of applying MIA treatments in flexible enclosures in museums and institutions. Consequently, there is a need to look for local alternatives to popular laminates to lower the cost and guarantee sustainability. Fortunately, the food packaging industry yields a huge number of diverse local film laminates. The only problem associated with these laminates in Egypt is that their oxygen permeability is generally unknown and they need to be tested to assess the potential of their use or even modification for MIA applications. As the required oxygen permeability is ultra-low for MIA laminates, suitable automated test devices are not locally available. In 2002, a simple method was developed to calculate the permeability of film laminates by calculating the transfer of
fumigant mass across the laminate (5). The method can be utilized to evaluate the permeability of the laminate to any kind of fumigants and has been applied to various organic fumigants and polyethylene films. The objectives of this study are: 1) establish an accurate oxygen permeability assessment strategy that can be easily applied in a laboratory, 2) assessing the potential of different laminates for MIA applications through measuring the oxygen permeability and consequently the oxygen transmission rate of known high barrier films as well as unknown local food packaging films, and 3) provide researchers with the requirements of MIA laminates as well as a simple strategy to choose among them to ensure sustainable implementation of their systems.

Materials And Methods

Plastic Films

Three film laminates were selected in this study for testing their oxygen permeability; a well-known MIA laminate, and other two laminates tested for their suitability for MIA applications; ESCAL™, the Cross-Barrier film, and a local polyamide-based film laminate.

ESCAL™

ESCAL™ is manufactured by Mitsubishi Gas Chemicals Inc., Japan. It is produced in sheet and tube rolls as well as in sachets. ESCAL™ is ceramic-coated polyvinyl alcohol (PVAL). The basic structure for this barrier film is orientated polypropylene (OPP) as a surface layer, silica deposited polyvinyl alcohol [(SiO)x/PVAL] as an intermediate layer and linear low-density polyethylene (LLDPE) as an inner layer. It is a superior oxygen and vapor barrier with an oxygen transmission rate of less than 0.1 cc/m².day.atm at 25°C and 60%RH (Long Life for Art 2021). It is optically very yellow and structurally thick (114 µm) (Fig. 2a).

Cross-Barrier

The laminate is manufactured by Nissin Kasei Co., Ltd., Saitama, Japan. It is produced in sheet rolls. Its thickness is 145 µm and weighs 115 g/m². It has been selected for the fact that it is a typical laminate as it consists of three layers; a surface layer, an intermediate layer, and a back-side layer. The surface layer consists of aluminium oxide [(ALO)x] deposited on polyethylene terephthalate (PET). The intermediate reinforcement layer is typically made of polyethylene (PE). The back-side layer consists of linear low-density polyethylene (LLDPE). The composition in ratios is approx. 13% PET; approx. 87% PE; and approx. 0.05% (ALO)x (Fig. 2b).

Local Commercial Nylon Film

The laminate is manufactured by M2Pack Co., Cairo, Egypt. It is produced in different size sachets. The sachet used in this experiment measures 25cmX30cm. Its thickness is 92 µm and weighs ~77.33 g/m². It has been selected for the fact that it is a low-cost, widely locally available laminate as it consists of two
layers; a surface layer, and an inner layer. The surface layer consists of polyamide (PA). The inner layer is typically made of linear low-density polyethylene (LLDPE). The interesting fact about this laminate is that it is recyclable (Fig. 2c).

**Test Chamber**

Chamber construction

A test system consists of two well-sealed chambers; a source chamber and a collecting chamber (Fig. 3). The chambers are long and cuboid to suit all grades of permeable films (high to low) and are made out of 6mm-thick Plexiglas® sheets for the availability and workability of the material. The chamber walls are glued using chloroform. Each chamber has an internal volume of 3 L (10cmX10cmX30cm), allowing a surface area of 100cm to attach the laminate membrane. One end of each chamber was closed by gluing it to a 10cmX10cm piece of Plexiglas®. 11mm-diameter holes were drilled in the test chambers at the mid-point height; two opposite holes in opposite sides in the source chamber; one as a gas insertion port and one as a pressure-relief and sampling port, and one hole as a sampling port in the collecting chamber. The holes were fitted with leak-proof connectors (see Chamber Fittings).

Chamber Fittings

All drilled holes were fitted with one \( \frac{1}{4} \)in Brass Swagelok® Male O-Seal Connector (Part #: B-400-1-OR). The connection point between the first O-seal connector and the acrylic sheet is fitted with a washer on the outer surface to enhance the seal-off. At the sampling ports, two septa are fixed at the inner opening of the connector and plugged with a Brass Swagelok® Plug for \( \frac{1}{4} \)in (Part #: B-400-P) for sealing off the port. The O-Seal Connectors at the gas introduction port was connected, through a \( \frac{1}{4} \)in Brass Swagelok® Port Connector (Part #: B-401-PC), to a \( \frac{1}{4} \) Two-Way Brass Ball Valve (Part #: B-42S4) to allow or shut off the gas purge process and enhance sealing off the port after shutting off the purge (Fig. 4).

**Selection and Source of Inert Gas**

Nitrogen was selected as the inert fumigant in this experiment because it is the most utilized gas and at the same time the most difficult to maintain (after helium) at very high concentrations (≥99.7%) due to leak problems. The gas was obtained from a high-pressure (250 bar) prepurified N\(_2\) cylinder, T size, containing about 8m\(^3\) of N\(_2\) (10kg). The cylinder is equipped with a MUJELLI OX – AC one-stage Nitrogen-Argon regulator, with a built-in nitrogen-argon flow meter (2).

**Experimental Procedure**

Installation of Test Laminate

The test film was glued to the open side of one chamber using epoxy glue mixed with its hardener and spread as a thin layer onto the 6mm rim of the open side. After drying, a small amount of epoxy glue was evenly spread onto the rim of the other chamber that is directly placed onto the test film aligning and joining the two chambers together with the test film in the middle. The contact line between the two
chambers was later tapped with a 2cm-wide strip of high-pressure aluminium tape to guarantee tight sealing.

Conditioning of Test Laminate

After installation, the film laminates were conditioned for a minimum of 40 h at standard laboratory conditions (23±2°C and 50±5 % relative humidity) immediately prior to testing according to ASTM D618 Practice for Conditioning Plastics for Testing (6). The conditions were controlled and monitored using the HVAC system of the laboratory.

Source Chamber Gas-Purge

The source chamber was totally purged with the pure, dry N\textsubscript{2} gas, following the dynamic purge process described by Elkhial (2), but using dry rather than humidied N\textsubscript{2} gas. Gas was purged through the inlet port fitted with the on/off valve. At this stage, the sampling port of the source chamber remains open. After a complete purge, reaching 100% N\textsubscript{2}, the septa and plug are installed at the sampling port, followed by a quick shutdown of the ball valve then the gas regulator to avoid pressure build-up and guarantee an O\textsubscript{2}-free gas path.

Gas Sampling and Analysis

The concentration of fumigant (N\textsubscript{2}) is measured by monitoring the concentration of O\textsubscript{2} inside the bag using Dansensor® Checkmate® 3 Headspace O\textsubscript{2} analyser, measuring range 0-100%, accuracy ±0.01%, and measuring three numbers after the decimal point. The utilised O\textsubscript{2} sensor is headspace Dansensor® CheckMate 3, MOCON, Inc., USA, the most accurate modified atmosphere packaging gas analyser. It uses the latest zirconia O\textsubscript{2} sensor, which has the inherent benefits of low cost, fast response, high sensitivity, and feedback control (7). The analyser was calibrated using fresh air at 20,9460% O\textsubscript{2}.

Test Duration

Each experiment was repeated three times and the mean values are considered. The duration of each iteration was one month at constant laboratory conditions (23±2°C and 50±5 % relative humidity).

Calculations and Data processing

For easily calculating the oxygen permeability and the OTR of the test membrane, the Film Permeability Evaluation System, FilmPC software, v. 3.0.4, 2011, United States Department of Agriculture, CA, the US, was utilized to obtain graphical and statistical data, especially as a report comprising all analytical data about the test film.

The software was provided with the sampling time and concentration data for each chamber sampled at the same time of the day. As high oxygen gas barriers were used in this experiment, the time is measured in days and the duration of each experiment was 30 days. The initial concentration of oxygen in the
source chamber was 0.000% and the fumigant (N\textsubscript{2}) concentration was 100% and the fumigant subsequent measurements (the source room concentrations) were the actual measurements of oxygen concentration (%) subtracted from 100%. As for the collecting chamber, the initial value of oxygen (20.9%) was normalised to 0.000%, and the difference between the actual initial value and measured values due to oxygen transmission was recorded (the collecting room concentrations). After data entry, the run button was pressed to start the calculations automatically, recording the measurements in the form of a graph, and preparing a Rich Text report of the film permeability analysis, which can be saved, printed, or copied and pasted elsewhere. Afterwards, the OTR was calculated by multiplying the oxygen permeability by 100 to relate the permeability to one squared metre of a laminate.

Experiment Termination

After completing each test duration, the valve in the source chamber was opened and the chamber vented. The system was then disassembled by removing the aluminium tape, softening the silicon glue, disengaging the collecting chamber, removing the tested film, and cleaning the chamber rims.

\#Swagelok® Company, OH, U.S.

\$Septa are not installed until the gas concentration is reached and a tight sealing is to start (after completion of step 2.1.4.32.1.4.3. Source Chamber Gas-Purge).

"This software is developed by Scott Yates of ARS, USDA at Riverside, CA, and is available at: https://data.nal.usda.gov/dataset/lmpc.

**Results And Discussion**

The permeability of three laminates of different chemical structures and thicknesses to oxygen (OTR) was measured using the sealed test system. Measurements of oxygen concentration on both sides of each laminate allowed for assessing its OTR.

**Acquired Data Analysis**

The modified design of the test chamber resulted in a completely leak-proof system and allowed for measuring very low oxygen permeability values. The oxygen permeability of the tested area of ESCAL™ laminate was found to be 0.00060 cm/day (Fig. 6 and 7). The correspondent OTR for one squared meter is 0.060 cc/m\textsuperscript{2}/day. Cross-Barrier data showed an oxygen permeability of the tested area of 0.02018 cm/day (Fig. 8 and 9) with correspondent OTR for one squared meter of 2.018 cc/m\textsuperscript{2}/day. Nylon, however, showed oxygen permeability of 0.04134 cm/day (Fig. 10 and 11), with a correspondent OTR of 4.134 cc/m\textsuperscript{2}/day. The oxygen permeability graph of double-layered Nylon showed a rate of 0.01950 cm/day of oxygen permeability which corresponds to 1.950 cc/m\textsuperscript{2}/day OTR (Fig. 12 and 13).
The highest barrier property was recorded by ESCAL™, followed by Cross-Barrier, then Nylon. The attempt to increase the barrier property of Nylon laminate by doubling the layer of the film during the permeability test showed a reduction in the resultant oxygen permeability by half (Fig. 12 and 13), almost evening out the OTR of double-layered Nylon and single-layered Cross-Barrier laminates.

Comparing the resultant OTR of the tested laminates (Fig. 14), the present study confirmed the ultra-high oxygen barrier property of ESCAL™ showing the lowest OTR among the tested plastics, however, it also confirms that there are promising alternatives to such a highly expensive laminate. It casts a new light on local film laminates that, despite the fact that little is known about their composition, they could perform significantly well and be considered effective alternatives. The measured OTR of Nylon film showed that it is of an exceptional capital quality in terms of the OTR, as generally the OTR of polyamide laminates ranges from 18-40 cc/m²/day (8) and goes up to 60 (9,10) or 110 cc/m²/day (1,11). A superior result, however, was achieved by doubling the layer of the local barrier film, Nylon, to cut down its OTR to almost a half. This result is comparable to published data, as the OTR linearly decreases with the increase in the laminate thickness (12,10,13). Although the cost is doubled by multiplying the local film layers, it is still far beyond the cost of a single layer of other imported ones that were tested. Table 1 summarizes the properties of the three tested laminate films and compares their composition, OTR (mentioned in datasheet vs tested), and sale price in Egypt.

Table 1 Properties of tested laminated films.

| Film Laminate          | Manufacturer                  | Composition | Thickness (mm) | OTR (cc/m²/day) | Price EGP/m² |
|------------------------|-------------------------------|-------------|----------------|-----------------|--------------|
| ESCAL™                 | Mitsubishi Gas Chemical Co., Japan | (SiO)x/PET PE | 0.11-0.12      | <0.1 0.05       | 500.45       |
| Cross-Barrier          | Nissin Kasei Co., Ltd., Japan | (AlO)x/PET PE/LLDP | 0.14          | NA 2.02         | 50           |
| Nylon                  | M2Pack Co., Cairo, Egypt      | PA/PE       | 0.092          | NA 4.13         | 5            |
| Double-Layered Nylon   | Alternate PA/PE               | 0.184       | NA 1.95        | 10              |

It is worth noting that the methodological approach for testing the OTR of the film laminates is fairly straightforward and comes up with good results. The chambers are easy to create and assemble and could be easily replicated using any inert, leak-proof materials. Additionally, the analyser is easy to use, is normally available in museums, and is available in modern versions to measure oxygen and carbon
dioxide at the same time, allowing for performing two tests at once. The sole apparent concern about using this system could be the possibility of having leaky locations. Therefore, one must make sure that the whole system (materials; connections; joints; paths; etc.) is leak-proof. For precise data analysis, experiments should be iterated.

**Benefit-Cost Analysis**

The decision on the type of laminate is based on six criteria as previously mentioned in the Introduction. Therefore, a simple evaluation procedure giving the laminate one of three grades; positive (+), average (±), and negative (-), was generated in Table 2. Positive was given to a laminate only when it highly functions at the category; average when its performance is only tolerable; negative when its performance is either unacceptable, undesirable, or unaffordable.

|                | Flexibility | Easily sealable | Toughness | OTR | Clarity | Cost | Ranking |
|----------------|-------------|-----------------|-----------|-----|---------|------|---------|
| ESCAL™         | +           | +               | +         | +   | ±       | -    | 2       |
| Cross-Barrier  | ±           | +               | ±         | ±   | -       | -    | 3       |
| Nylon          | +           | +               | ±         | -   | +       | +    | 2       |
| Double-layered Nylon | +       | +               | ±         | ±   | +       | +    | 1       |

Ranking the results, it is providential that double-layered Nylon is ranked first followed by ESCAL™ and single-layered Nylon. The superior low cost and local availability enhanced its rank among other laminates. As for Cross-Barrier, it was ranked third (last) due to its high cost and poor clarity. Although ESCAL™ is superior in terms of OTR, it dropped to the second level because of its extremely high cost.

*Long Life for Art: ESCAL NEO oxygen barrier film (llfa.eu)

†(1)

‡Price converted from US-Dollar in 2021 (tax included, import expenses excluded)

§Price converted from Yen in 2021 (tax included, import expenses excluded)

**Conclusion**

For successful application of MIA systems, the selection of consumable flexible film laminates is a main challenge that must be overcome to attain the pest eradication objective and ensure sustainability. In this study, a methodological approach adapted from the ASTMD 618-05 (6) was developed and utilised to
measure the oxygen permeability, and consequently the OTR, of three film laminates in four replicated experiments using a highly sensitive oxygen analyser.

Results showed that ESCAL™ laminate, which is based on silicon dioxide has the highest oxygen-barrier ability. Cross-Barrier, which is based on aluminium oxide has almost the same OTR as double-layered Nylon, which is based on alternate polyamide/polyethylene layers. Although Nylon by default has the lowest OTR compared to other tested laminates, the tested local type showed consummate oxygen barrier property which adds to its improved flexibility, due to its thickness and lack of strengthening layers. It also has the best clarity over the other tested laminates and, therefore, allows for better observation of the object under treatment. Furthermore, its competitive price and local availability in Egypt make it a superior choice for wide-range, sustainable MIA applications in Egyptian institutions and hereby accomplishes the main aim of this study.

Additionally, the utilised test system allows for an unlimited number of tests on an unlimited number of laminates using the normally available oxygen sensors, leak-proof fittings, and ultra-low- or non-permeable materials such as glass or thick Plexiglas, which brings OTR testing system in house and allows for easy, consistent, and time-managed tests.

**Abbreviations**

MIA: Modified inert atmosphere; OTR: Oxygen transmission rate; ASTM: international standards organization, formerly American Society for Testing and Materials; PVAL: polyvinyl alcohol; OPP: orientated polypropylene; LLDPE: linear low-density polyethylene; PE: polyethylene.

**Declarations**

**Acknowledgements**

The experiments were performed at the Fumigation Laboratory at the Grand Egyptian Museum. The authors are grateful for the sincere scientific research encouragement by the GEM which allowed for using the laboratory facilities and equipment, particularly we are grateful to Dr. Hussein Kamal, General Director of the Conservation Centre, for facilitating this work and for his useful advice.

**Authors’ contributions**

Conceptualization, methodology, experiment, validation, analysis, discussions and writing- ME, supervision, writing-review and editing-NE. All authors have read and approved the manuscript.

**Funding**

Not applicable
**Availability of data and materials**

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

**Competing interests**

The authors declare that they have no competing interests.

**Author details**

1 Head of Fumigation and Environmental Management, Conservation Centre, the Grand Egyptian Museum, Giza, Egypt. 2 Professor of Wood Conservation, Department of Conservation, Faculty of Archaeology, Cairo University, Giza, Egypt.

**References**

1. Maekawa S, Elert K. The Use of Oxygen-Free Environments in the Control of Museum Insect Pests Los Angeles: Getty Conservation Institute; 2003.

2. Elkhial MM. Study on Some Operational Problems of Modified Inert Atmosphere Fumigation and their Solutions - Applied on a Selected Wooden Artifact Cairo: Faculty of Archaeology, Cairo University; 2019.

3. Selwitz C, Maekawa S. Inert gases in the control of museum insect pests Maekawa S, Selwitz C, editors. California: The Getty Conservation Institute; 1998.

4. Burke J. Anoxic Microenvironment: A Treatment for Pest Control. Conserve 0 Gram. 1999: p. 1-4.

5. Yates SR, Papiernik SK, Qian Y. Standard Test Method for Film Permeability Determination Using Static Permeability Cells. In International A. Pesticides, Antimicrobials, and Alternative Control Agents ; Environmental Assessment ; Hazardous Substances and Oil Spill Response.: The Society; 2021.

6. ASTMD618-05. Standard Practice for Conditioning Plastics for Testing. In. West Conshohocken: ASTM International; 2005.

7. Luo ZA, Xiao JZ, Xia F. Preparation and analysis of zirconia oxygen sensors. Transactions of Nonferrous Metals Society of China. 2006; 16: p. s82-s87.

8. Robertson GL. Optical, Mechanical and Barrier Properties of Thermoplastic Polymers. In Edition T, editor. Food Packaging: Principles and Practice. U. S.: CRC Press; 2016. p. 91-130.

9. Butler TI, Morris BA. PE based multilayer film structures. In Wagner JR, editor. Plastics Design Library: Multilayer Flexible Packaging.: William Andrew Publishing; 2010. p. 205-230.

10. Morris BA. Barrier. In Morris BA, editor. Plastics Design Library: The Science and Technology of Flexible Packaging.: William Andrew Publishing; 2017. p. 259-308.
11. Paine FA. Plastics. In The Packaging User's Handbook. Glasgow: Springer Science & Business Media; 2012. p. 102-120.

12. Goswami TK, Mangaraj S. Advances in polymeric materials for modified atmosphere packaging (MAP). In Lagarón JM(). Multifunctional and Nanoreinforced Polymers for Food Packaging: Woodhead Publishing; 2011. p. 163-242.

13. Allentown I. Case Study: Evaluating The Barrier Properties of a Membrane.; 2021 [cited 2021 July 7. Available from: https://www.intertek.com/pharmaceutical/barrier-properties-of-a-membrane-cs/.

Figures

![Graph showing Oxygen Transition Rate (OTR) of the most used oxygen barriers Log by 10 adapted from Elkhial (2).](image)

**Figure 1**

Oxygen Transition Rate (OTR) of the most used oxygen barriers (Log by 10) adapted from Elkhial (2).
Figure 2

Structure of laminates; left are cross-section microscopic images showing thicknesses, right are stratigraphic structure schematics.
Figure 3

Schematic of the test system; a side view.
Figure 4

Schematic of the sampling port fittings.
Figure 5

Schematic of the inlet port fittings.

Figure 6

Film Permeability Test Results

| Concentration (C/Co) | Time (day) |
|----------------------|------------|
| 100                  | 0          |
| 100                  | 5          |
| 100                  | 10         |
| 100                  | 15         |
| 100                  | 20         |
| 100                  | 25         |
| 100                  | 30         |
| 100                  | 35         |

ESCAL

OTR Test Chamber

h = 0.00060 cm/day

Co = 100.00046 C/Co

alf = 0.00000 1/day

Kp = 0.00000 cm

Source

Collection
ESCAL™ oxygen permeability analysis obtained from FilmPC software, showing oxygen permeability of 0.00049 cm/day.

![Graphs showing source and collection chamber measurements](image)

**Figure 7**

Details on the source and collection chamber measurements during testing ESCAL™ laminate.
Figure 8

Cross-Barrier oxygen permeability analysis obtained from FilmPC software, showing oxygen permeability of 0.02018 cm/day.
Figure 9

Details on the source and collection chamber measurements during testing Cross-Barrier laminate.
Figure 10

Nylon oxygen permeability analysis obtained from FilmPC software, showing oxygen permeability of 0.04134 cm/day.
**Figure 11**

Details on the source and collection chamber measurements during testing Nylon laminate.
Figure 12

Double-layered Nylon oxygen permeability analysis obtained from FilmPC software, showing oxygen permeability of 0.01950 cm/day.
Figure 13

Details on the source and collection chamber measurements during testing double-layered Nylon laminate.
A comparison between OTR results of the three tested laminates in the four experiments.