Standard Test Method for Oxygen Gas Transmission Rate Through Plastic Film and Sheeting Using a Coulometric Sensor

1. Scope

1.1 This test method covers a procedure for determination of the steady-state rate of transmission of oxygen gas through plastics in the form of film, sheeting, laminates, coextrusions, or plastic-coated papers or fabrics. It provides for the determination of (1) oxygen gas transmission rate (O₂ GTR), (2) the permeance of the film to oxygen gas (P'O₂), and (3) oxygen permeability coefficient (P'O₂) in the case of homogeneous materials.

1.2 This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

1.3 This test method does not purport to be the only method for measurement of O₂ GTR. There may be other methods of O₂ GTR determination that use other oxygen sensors and procedures.

2. Referenced Documents

2.1 ASTM Standards:
D 1434 Test Method for Determining Gas Permeability Characteristics of Plastic Film and Sheeting
D 1898 Practice for Sampling of Plastics
F 1927 Test Method for Determination of Oxygen Gas Transmission Rate, Permeability and Permeance at Controlled Relative Humidity Through Barrier Materials Using a Coulometric Detector

3. Terminology

3.1 Definitions:

3.1.1 oxygen permeability coefficient (P'O₂)—the product of the permeance and the thickness of film. The permeability is meaningful only for homogeneous materials, in which case it is a property characteristic of the bulk material. This quantity should not be used, unless the relationship between thickness and permeance has been verified on tests using several different thicknesses of the material. The SI unit of oxygen permeability is the mol/m·s·Pa. The test conditions (see 3.1.3) must be stated.

3.1.2 oxygen permeance (P'O₂)—the ratio of the O₂ GTR to the difference between the partial pressure of O₂ on the two sides of the film. The SI unit of permeance is the mol/(m²·s·Pa). The test conditions (see 5.1) must be stated.

3.1.3 oxygen transmission rate (O₂ GTR)—the quantity of oxygen gas passing through a unit area of the parallel surfaces of a plastic film per unit time under the conditions of test. The SI unit of transmission rate is the mol/(m²·s). The test conditions, including temperature and oxygen partial pressure on both sides of the film must be stated.

3.1.3.1 A commonly used unit of O₂ GTR is the cm³(STP)/m²·d at one atmosphere pressure difference where 1 cm³(STP) is 44.62 µmol, 1 atm is 0.1013 MPa, and one day is 86.4 × 10³ s. The O₂ GTR in SI units is obtained by multiplying the value in inch-pound units by 5.160 × 10⁻¹⁰.

4. Summary of Test Method

4.1 The oxygen gas transmission rate is determined after the sample has equilibrated in a dry test environment. In this context, a “dry” environment is considered to be one in which the relative humidity is less than 1%.

4.2 The specimen is mounted as a sealed semi-barrier between two chambers at ambient atmospheric pressure. One chamber is slowly purged by a stream of nitrogen and the other chamber contains oxygen. As oxygen gas permeates through the film into the nitrogen carrier gas, it is transported to the coulometric detector where it produces an electrical current, the magnitude of which is proportional to the amount of oxygen flowing into the detector per unit time.
5. Significance and Use

5.1 The O₂ GTR is an important determinant of the packaging protection afforded by barrier materials. It is not, however, the sole determinant, and additional tests, based on experience, must be used to correlate packaging performance with O₂ GTR. It is suitable as a referee method of testing, provided that the purchaser and the seller have agreed on sampling procedures, standardization procedures, test conditions, and acceptance criteria.

5.2 Limited statistical data on correlations with Test Method D 1434 methods are available; however, the oxygen transmission rate of a standard reference material (see 12.1) as determined manometrically by NIST, is in good agreement with the values obtained in the coulometric interlaboratory test using material from the same manufacturing lot. Thus, this test method may be used as a referee method.

6. Interferences

6.1 The presence of certain interfering substances in the carrier gas stream may give rise to unwanted electrical outputs and error factors. Interfering substances include free chlorine and some strong oxidizing agents. Exposure to carbon dioxide should also be minimized to avoid damage to the sensor through reaction with the potassium hydroxide electrolyte.

7. Apparatus

7.1 Oxygen Gas Transmission Apparatus, as diagrammed in Fig. 1 with the following:

7.1.1 Diffusion Cell shall consist of two metal halves, which, when closed upon the test specimen, will accurately define a circular area. The volume enclosed by each cell half, when clamped, is not critical; it should be small enough to allow for rapid gas exchange, but not so small that an unsupported film which happens to sag or bulge will contact the top or bottom of the cell. The diffusion cell shall be provided with a thermometer well for measuring temperature.

7.1.1.1 O-Ring—An appropriately sized groove, machined into the oxygen (or test gas) side of the diffusion cell, retains a neoprene O-ring. The test area is considered to be that area established by the inside contact diameter of the compressed O-ring when the diffusion cell is clamped shut against the test specimen. The area, A, can be obtained by measuring the inside diameter of the imprint left by the O-ring on the specimen after it has been removed from the diffusion cell.

7.1.1.2 The nitrogen (or carrier gas) side of the diffusion cell shall have a flat raised rim. Since this rim is a critical sealing surface against which the test specimen is pressed, it shall be smooth and flat, without radial scratches.

7.1.1.3 Diffusion Cell Pneumatic Fittings—The diffusion cell shall incorporate suitable fittings for the introduction and exhaust of gases without significant loss or leakage.

7.1.1.4 It is desirable to thermostatically control the diffusion cell. A simple heating or heating/cooling system regulated to ±0.5°C, is adequate for this purpose. A thermistor sensor and an appropriate control circuit will serve to regulate the cell temperature unless measurements are being made close to ambient temperature. In this case, it is desirable to provide cooling capability to remove some of the heat.

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3 Supporting data for this test method can be obtained from ASTM Headquarters. Request RR:D20-1085.
7.1.1.5 Experience has shown that arrangements using multiple diffusion cells are a practical way to increase the number of measurements which can be obtained from a coulometric sensor. Valving connects the carrier gas side of each individual diffusion cell to the sensor in a predetermined pattern. Carrier gas is continually purging the carrier gas sides of those cells that are not connected to the sensor. Either test gas or carrier gas, as is appropriate, purges the test gas chamber of any individual cell.

7.1.2 Catalyst Bed—A small metal tube with fittings for attachment to the inlet on the nitrogen side of the diffusion cell shall contain 3 to 5 g of 0.5 % platinum or palladium catalysts on alumina\(^4\) to provide an essentially oxygen-free carrier gas.

7.1.3 Flowmeter—A flowmeter having an operating range from 5 to 100 mL/min is required to monitor the flow rate of the nitrogen carrier gas.

7.1.4 Flow Switching Valves—Valves for the switching of the nitrogen and test gas flow streams.

7.1.5 Coulometric Sensor—An oxygen-sensitive coulometric sensor\(^5\) operating at an essentially constant efficiency shall be used to monitor the quantity of oxygen transmitted.

7.1.6 Load Resistor—The current generated by the coulometric cell shall pass through a resistive load across which the output voltage is measured. Typical values for the load resistor are such that the values yield a convenient relationship between the output voltage and the oxygen transmission rate in standard units (cm\(^3\)/(STP)/m\(^2\)/d).

7.1.7 Voltage Recorder—A multirange, potentiometer strip chart recorder may be used for measuring the voltage developed across the load resistor. The recorder should be capable of measuring a full-scale voltage of 50 mV. It should be capable of measuring voltages as low as 0.100 mV and have a resolution of at least 10 µV. An input impedance of 1 megohm or higher is acceptable.

8. Reagents and Materials

8.1 Nitrogen Carrier Gas shall consist of a nitrogen and hydrogen mixture in which the percentage of hydrogen shall fall between 0.5 and 3.0 volume %. The carrier gas shall be dry and contain not more than 100 ppm of oxygen. A commercially available mixture known as “forming gas” is suitable.

8.2 Oxygen Test Gas shall be dry and contain not less than 99.5 % oxygen (except as provided in 14.11).

8.3 Sealing Grease—A high-viscosity silicone stopcock grease or a high-vacuum grease is required for sealing the specimen film in the diffusion cell.

9. Precautions

9.1 Extended use of the test unit, with no moisture in the gas stream, may in some older systems result in a noticeable decrease in output and response time from the sensor (equivalent to an increase in the calibration factor, \(Q\)). This condition is due to drying out of the sensor.

9.2 Temperature is a critical parameter affecting the measurement of O\(_2\) GTR. Careful temperature control can help to minimize variations due to temperature fluctuations. During testing, the temperature shall be monitored to the nearest 0.5°C. The average temperature and the range of temperatures found during a test shall both be reported.

9.3 The sensor will require a relatively long time to stabilize to a low reading characteristic of a good barrier after it has been used to test a barrier such as low-density polyethylene. For this reason, materials of comparable gas transmission qualities should be tested together.

9.4 Back diffusion of air into the unit is undesirable. Care should therefore be taken to ensure that there is a flow of nitrogen through the system at all times. This flow can be low when the instrument is not being used.

9.5 Elevated temperatures can be used to hasten specimen outgassing, provided that the treatment does not alter the basic structure of the specimen (crystallinity, density, and so forth). This can be accomplished by the use of the heaters in the diffusion cells.

10. Sampling

10.1 The sampling units used for the determination of O\(_2\) GTR shall be representative of the quantity of product for which the data are required, in accordance with Practice D 1898. Care shall be taken to ensure that samples are representative of conditions across the width and along the length of a roll of film.

11. Test Specimens

11.1 Test specimens shall be representative of the material being tested and shall be free of defects, including wrinkles, creases, and pinholes, unless these are a characteristic of the material being tested.

11.2 Average thickness shall be determined to the nearest 2.5 µm (0.0001 in.), using a calibrated dial gage (or equivalent) at a minimum of five points distributed over the entire test area. Maximum, minimum, and average values shall be recorded.

11.3 If the test specimen is of an asymmetrical construction, the two surfaces shall be marked by appropriate distinguishing marks and the orientation of the test specimen in the diffusion cell shall be reported (for example, “side II was mounted facing the oxygen side of the diffusion cell”).

12. Calibration

12.1 General Approach—The oxygen sensor used in this test method is a coulometric device that yields a linear output as predicted by Faraday’s Law. In principle, four electrons are produced by the sensor for each molecule of oxygen that passes into it. Considering that the sensor is known to have a basic efficiency of 95 to 98 %, it may be considered an “intrinsic” standard\(^6\) that does not require calibration, and can thus be used as a reference method.

12.2 Experience has shown, however, that under some circumstances the sensor may become depleted or damaged to

\(\text{---}^4\) A suitable catalyst can be obtained from Englehard Industries Division, Chemical Dept., 429 Delaney Street, Newark, N.J. 07105.

\(\text{---}^5\) It is deemed advisable upon initial setup of the voltage recorder and periodically thereafter to check the response of the recorder on all ranges to a suitable voltage input.

the extent that efficiency and response are impaired. For that reason, this test method incorporates means for a periodic sensor evaluation. This evaluation is derived from measurements of a known-value “reference package”. Experience indicates however, that a specimen-to-specimen variability of the reference material is such that a change should never be made in the calibration factor, as the result of a measurement using a single sheet of the reference material.

12.3 Establishing a System Calibration Constant (Used only on systems using a chart recorder to determine $O_2 \text{GTR}$)—Determine the exposed area, $A$, of the calibration reference film (see 7.1.1.1). Using the permeance value furnished with the film, determine the $O_2 \text{GTR}$ through that film of that area ($A$). Use this value to determine the calibration constant, $Q$:

$$Q = \frac{O_{2 \text{GTR}} \times R_L}{E_o - E_e}$$  \hfill (1)

where:

$O_{2 \text{GTR}} = \text{Oxygen transmission rate through a film of area, } A$, as calculated from data supplied with the reference film,

$R_L = \text{value of load resistance,}$

$E_o = \text{observed steady-state zero-level before oxygen gradient is applied, and,}$

$E_e = \text{observed steady-state voltage with oxygen gradient across test film.}$

Repeat the calibration using additional sheets of the reference film until the confidence interval for $Q$ defined by the measurements is within acceptable limits.

13. Conditioning

13.1 Trim the test specimen to a size appropriate for the diffusion cell in which it will be mounted. In general, this means that the seal around the edge of the diffusion cell should not be impaired if the specimen bulges or sags slightly. After trimming, condition the specimens in a desiccator over calcium chloride or another suitable desiccator for a minimum of 48 h. This does not imply that 48 h will be sufficient to bring the specimen to a condition where their measured $O_2 \text{GTRs}$ will be obtained. At this time, the sensor output will usually increase abruptly, indicating that oxygen is entering the sensor with the carrier gas. The most likely sources of this oxygen are (1) outgassing of the sample, (2) leaks in the system, or (3) a combination of (1) and (2). The operator shall observe the recorder trace until the sensor output current stabilizes at a constant value with no significant trend in either direction. Thick samples may require a purge of several hours, or even overnight, before a steady low value of sensor current is obtained. On older systems, the sensor should be bypassed except for brief periods when the zero level is being checked. Once a steady low value of sensor current has been obtained, the sensor may be inserted to monitor the zero level and left there until a stable zero level is obtained. At this time, the zero level is recorded and labelled $E_o$. It has been found helpful to periodically test the $O_2 \text{GTR}$ of a piece of brass shim stock in order to ascertain that no leaks or contamination of the carrier gas have developed.

14. Procedure

14.1 Preparation of Apparatus—If preceding tests have exposed the apparatus to high moisture levels, it will be necessary to outgas the system, particularly the catalyst bed, to desorb residual moisture. Water shall be removed from the nitrogen and test gas humidifiers. The system can then be dried by slowly purging overnight using dry carrier gas and with the sensor bypassed. Heating the apparatus will speed the drying and outgassing process.

14.2 Inserting the Specimen—With the sensor bypassed, unclamp the diffusion cell and open it. Apply a thin layer of sealing grease (see 8.3) around the raised rim of the lower half of the diffusion cell. Remove the test specimen from the desiccator and place it upon the greased surface, taking care to avoid wrinkles or creases. Set the movable half of the diffusion cell into place and clamp both halves tightly together.

14.3 Purging the System—Place the system in the CARRIER PURGE mode and purge air from the upper and lower diffusion cell chambers, using a flow rate of 50 to 60 mL. After 3 or 4 min, reduce the flow rate to the desired value between 5 and 15 mL/min. Maintain this configuration for 30 min.

14.4 Establish $E_o$—After the system has been flushed with nitrogen for 30 min, INSERT THE SENSOR so that the carrier gas which has passed through both sides of the diffusion cell is diverted into the sensor. Note 1—$E_o$ is often referred to as “individual zero.”

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14.5 Once $E_o$ has been established, switch OXYGEN into the test-gas side of the diffusion cell. This action will be automated on newer systems.

14.6 The sensor output current should increase gradually, ultimately stabilizing at a constant value. While some thin films with high diffusion coefficients may reach equilibrium in 30 to 60 min, thicker or more complex structures may require a number of hours to reach a steady state of gas transmission. The steady-state voltage value of the oxygen transmission rate shall be recorded and labelled $E_e$.

Note 2—If, after attainment of an apparent steady-state condition, any doubt exists as to whether this is a true steady-state condition, perform a check as follows: (1) bypass the sensor; (2) allow the unit to stabilize for an additional period of time (minimum of 6 h); and, (3) insert the sensor again, and monitor the transmission rate. An increased output indicates that steady-state conditions have not been reached, while the same output (no increase) indicates that steady-state conditions have been initially obtained.

14.7 Temperature shall be obtained by monitoring the temperature as close as possible to the specimen.

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7 Reference material available from Mocon Inc., has been found satisfactory.
15. Calculation

15.1 If using a chart recorder, determine the O₂GTR as follows:

\[
O₂GTR = \frac{(E_e - E_o) \times Q}{A \times R_L} \tag{2}
\]

where:
- \(E_e\) = steady-state voltage level (see 14.6),
- \(E_o\) = zero voltage level (see 14.4),
- \(A\) = specimen area (see 7.1.1.1),
- \(Q\) = calibration constant (see Section 12), and
- \(R_L\) = value of load resistance (see 7.1.6).

Newer, computer-controlled systems will automatically record the O₂GTR, and possibly the permeance and permeation coefficient.

15.2 Determine the permeance (\(P'O₂\)) of the specimen as follows:

\[
P'O₂ = \frac{O₂GTR}{p} \tag{3}
\]

where \(p\) = partial pressure of oxygen, which is the mol fraction of oxygen multiplied by the total pressure (normally, one atmosphere), in the test gas side of the diffusion cell. The partial pressure of O₂ on the carrier gas side is considered to be zero.

15.3 Determine the oxygen permeability coefficient (\(P'O₂\)) as follows:

\[
P'O₂ = P'O₂ \times t \tag{4}
\]

where \(t\) = average thickness of the specimen (see 11.2). Results should be expressed as permeabilities only in cases where materials have been determined to be homogeneous by investigation of the relationship between specimen thickness and permeance.

16. Report

16.1 Report the following information:

16.1.1 A description of the test specimen, including an identification of the two sides of the material if they are different, a statement as to which side was facing the test gas, the location of the specimen in the lot of material of which it is representative, and the dimensions of the test specimen.

16.1.2 The average thickness of the test specimens as determined in 11.2 and the standard deviation of the thickness values.

16.1.3 The barometric pressure at the time of the test and whether or not barometric pressure compensation is performed on the data, either manually or by computer. Barometric compensation is performed to standardize data to 760 MMHg (sea level).

Note 3—The barometric compensation factor may be calculated as follows:

\[
\frac{fBP}{BP} = \frac{BP_{760}}{760} \tag{5}
\]

where:
- \(fBP\) = barometric compensation factor
- \(BP_{760}\) = 760 MMHg, and
- \(BP\) = ambient barometric pressure in MMHg.

16.1.4 The partial pressure of the oxygen gas on the test-gas side of the diffusion cell and a statement as to how it was determined.

16.1.5 The rate of flow of the nitrogen carrier gas during the test.

16.1.6 The conditioning procedure used on the test specimens prior to testing.

16.1.7 The temperature of the test specimen (to the nearest 0.5°C) and the method used to determine the temperature.

16.1.8 The values of O₂GTR, permeance (if desired), and the permeability (if desired).

16.1.9 A description of the apparatus used including, if applicable, the manufacturer’s model number and serial number.

16.1.10 The calibration factor (\(Q\)) and a statement of the means used to obtain the calibration factor (only needed if a voltage recorder is being used to calculate O₂GTR).

16.1.11 The effective area for permeation, A, and a description of how it was obtained.

16.1.12 The time to reach steady-state after introduction of the oxygen gas into the test-gas side of the diffusion cell.
17. Precision and Bias

17.1 The data given were obtained at a temperature of 20 to 25°C from statistical analysis of an interlaboratory test program in which sheets of a polyester film nominally 23 µm thick were distributed to 17 participants. The participants used two different models of a commercially available coulometric gas transmission measuring instrument, corrected the data for atmospheric pressure and temperature fluctuations, and reported permeance values. No significant difference was found between results obtained from the two models, and the results from the two models were pooled.

17.2 Variability—The statistical analysis of the data took the unequal number of replicates from each respondent into account. The between-laboratory standard deviation, $S_b$, is 5.0 cm³(STP)/(m²·d·atm), and within-laboratory standard deviation, $S_w$, is 1.2 cm³(STP)/m²·d·atm. The standard deviation for the uncertainty of a single measurement is, therefore, 5.1 cm³(STP)/(m²·d·atm).

17.3 A weighted average material value, $X$, and its standard error were calculated from the data, taking the within- and between-laboratory variability into account. The weighted average material value was found to be 59.36 cm³(STP)/(m²·d·atm) and the standard error of 1.21 cm³(STP/m²·d·atm).

17.4 The material used in the interlaboratory test was from the same manufacturing lot as NIST Standard Reference Material 1470, which NIST has found to possess an O₂ GTR equal, at a pressure differential of one atmosphere (0.10133 MPa), to 63.8 cm³(STP)/(m²·d·atm) with a standard error of 0.4 cm³(STP)/(m²·d·atm). This discrepancy may be attributable to differences in sampling, test methodology, or analysis of the data.

18. Keywords

18.1 coulometric; oxygen transmission rate; permeability; permeation; plastic films