Modeling Respiration of Apple Slices in Modified-Air Atmosphere Packages

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ABSTRACT
Modified-atmosphere packaging was used to provide respiratory data for apple (Malus x domestica Borkh.) slices at 0, 5, 10 and 15°C. The maximum rate of O₂ uptake increased with increasing temperature. The lowest O₂ partial pressure to which fruit could be exposed without fermentation also increased with increasing temperature. A mathematical model of film permeability data characterized the effect of fruit mass, film permeability to O₂, activation energy of O₂ permeation, temperature, and the film type, area, and thickness on O₂ partial pressure for hermetically packaged apple slices. The model identified a minimum (fruit mass x film thickness)/(film area) ratio for apple slices, which would simplify package design calculations.

Key Words: fermentation, lightly processed, permeability, activation energy, apple

INTRODUCTION
FRESH APPLE SLICES HAVE THE POTENTIAL TO BE A HIGHLY popular lightly processed product (Hoag, 1995). Sliced apple products will likely be hermetically sealed in packages to maintain sterile conditions. Produce respiration inside a package with an air-tight seal alters the atmosphere within the package. For apple, modifying both O₂ and CO₂ may be useful to retard textural and flavor changes and reduce browning (Jurin and Karel, 1963). Similarly, steady-state CO₂ levels in the atmosphere on quality and physiology of the product. Ranges of nondamaging O₂ and CO₂ levels have been published for several commodities (Kader, 1993; Meheriuk, 1993; Salveit, 1993); however, the levels of O₂ and CO₂ required to avoid tissue damage or quality loss are unknown for apple slices.

Modified-atmosphere packaging (MAP) can be designed to maintain nondamaging partial pressures of O₂ and CO₂ over a range of temperatures (Beaudry et al., 1992; Cameron et al., 1994). According to Fick’s Law, the respiration-driven reduction in O₂ partial pressure and increase in CO₂ partial pressure creates gradients that cause O₂ to enter and CO₂ to exit the package at rates proportional to the gradient. Steady-state O₂ levels can be achieved in the package when the O₂ uptake by the product is equal to that permeating into the package (Jurin and Karel, 1963). Similarly, steady-state CO₂ levels in the package are achieved when CO₂ production by the product equals CO₂ flux out of the package. The steady-state levels of both gases are dependent on interactions of respiration of the product and permeability properties of packaging film (Cameron et al., 1989; Kader, 1989; Beaudry et al., 1992). Increases in temperature are related to decreases in O₂ partial pressure in modified-atmosphere packages (Beaudry et al., 1992; Cameron et al., 1994). This has been attributed to the higher temperature responsiveness of respiration relative to O₂ permeation (Beaudry et al., 1992; Cameron et al., 1994).

MAP design can be improved by developing mathematical descriptions of the effects of temperature and O₂ on respiration. A Michaelis-Menten type model has been used to describe the influence of temperature and O₂ on respiration of blueberries (Vaccinium corymbosum L.) (Cameron et al., 1992), strawberries (Fragaria x ananassa Duch.) (Joles, 1993), raspberries (Rubus idaeus L.) (Joles et al., 1994) and broccoli (Brassica oleracea L. Botrytis Group) florets (Talasila et al., 1994). Respiratory models incorporating Arrhenius equations describing the temperature sensitivity of film permeability to gases predict package O₂ partial pressure as a function of temperature, fruit mass, surface area and film thickness (Cameron et al., 1994; Cameron et al., 1995). This approach can be used to design an MA package that can generate aerobic O₂ partial pressures across a range of temperatures. The respiration of apple slices (O₂ uptake) as a function of temperature and O₂ partial pressure has not been reported.

Our objective was to collect data needed to design MA packages of sliced apple fruit that would generate an atmosphere minimizing fermentation. We collected data for development of a respiratory model for sliced apple, then combined package permeability characteristics with the respiratory model to develop a packaging model to predict effects of temperature, film thickness, and fruit mass on package O₂. We also attempted to develop a simplified approach for designing packages that would remain aerobic across a broad temperature range and validate the model by packaging sliced apple fruit, comparing resultant O₂ levels with those predicted.

MATERIALS & METHODS

Film permeability
The permeability of 76.2 μm- and 101.6 μm-thick low density polyethylene (LDPE) film (LDF 550, The Dow Chemical Company, Midland, MI) and a polyolefin plastomer (POP) film made from a proprietary resin (Affinity PF 1140, The Dow Chemical Company, Midland, MI) to O₂ and CO₂ were determined on three random film samples at 0, 10 and 20±0.05°C according to the method of Beaudry et al. (1992). Concentration data were converted to partial pressures (1% O₂ (v/v) = 1.013 kPa at atmospheric pressure) to determine the permeability coefficients. Values of permeability as a function of temperature were fitted by the Arrhenius equation:

\[ P_j = P_{0j} \exp(-E_aP_j/RT) \]  

where \( P_j \) is the permeability coefficient (mol m⁻² Pa⁻¹ s⁻¹) of gas j, \( P_{0j} \) is the Arrhenius constant (mol m⁻² Pa⁻¹ s⁻¹), R is the gas constant (8.3144 J mol⁻¹ K⁻¹), Eₐj is the activation energy (J mol⁻¹) and T is the temperature (K).

Plant material
Apple fruit of the numbered selection ‘NY 674’ were harvested at

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commercial maturity from plantings at the New York State Agricultural Experiment Station (Geneva, NY) and shipped overnight (no temperature control) to Michigan State University in October, 1993 for collecting respiratory data to construct the packaging model. ‘NY 674’ fruit for the model validation test were harvested at the Clarksville Horticulture Experiment Station (Clarksville, MI) in October, 1994. In both years, harvested fruit were held under elevated humidity (RH >85%) at 3±0.5°C for 7 days prior to use. Apples were cut into wedges using a stainless steel knife and the core material was removed. The skin was not removed from the wedge. Each piece was 1.5 cm wide measured at the skin side.

Package design

The initial step in the designing process involved determining rate of O2 uptake \( (r_{O2}) \) for apple slices at ambient O2 partial pressure (20.7 kPa, 20°C). Apple slices (100g) were placed in a glass jar ventilated with air at a flow rate of 30 mL min\(^{-1}\) and the rate of CO2 production \( (r_{CO2}) \) measured. We assumed that \( r_{O2} \) was similar to \( r_{CO2} \) and was estimated to be 278, 194, 139 and 83 pmol g\(^{-1}\) s\(^{-1}\) at 15, 10, 5 and 0°C, respectively, by assuming a Q\(_{10}\) of 2 (Hardenburg et al., 1986). Using these estimates of \( r_{O2} \), the fruit mass and film area for 76 µm-thick LDPE packages needed to generate 16 kPa O2 in the package headspace for each temperature was calculated using Eq (2).

The O2 partial pressure of 16 kPa was assumed to saturate the respiratory demand for O2. To achieve a range of lower O2 levels, packages for the study possessed combinations of greater fruit mass, greater film thickness and/or decreased area. Film thicknesses were 76 and 102 µm, film areas were 800 and 1250 cm\(^2\) and fruit mass varied from 19 to 587g. Four replications of each of 12 different combinations of film thickness, film area, and fruit mass were made for each temperature.

Respiration rate of apple slices

Apple wedges were placed on a plastic tray and inserted into packages subsequently hermetically sealed using a heat sealer. A small amount of silicone adhesive on a short strip of electrical tape was attached to the surface of the package for gas sampling (Boylan-Pett, 1986). To accelerate steady-state gas concentrations, a portion of the headspace air was removed by vacuum and replaced with N2 prior to placing packages in controlled temperature chambers. Initial atmospheres contained 5 kPa O2. Packages with holes or containing fruit with decay lesions were discarded and no fungicide treatment was used.

Gas samples were drawn from each package through the self-sealing silicone septum using a 0.5-mL syringe. Two 100-L gas samples were analyzed from each package at each evaluation using a paramagnetic O2 analyzer (Series 1110, Servomex Co., Sussex, England) and CO2 analyzer (225-MK3, Analytical Development Co., Hoddesdon, England) connected in series, with N2 as the carrier gas (flow rate = 100 mL min\(^{-1}\)). A third gas sample was taken if any of the package variables \( (m, l, A \text{ and } p_{O2}) \) were changed while the other package variables \( (m, l, A \text{ and } p_{O2}) \) remained constant. A gas chromatograph (Carle AGC series 400, Carle Instruments Company, Fullerton, CA) fitted with a packed column (Haysep N, 3 mm i.d., 45.7 cm length, with gas flow rates of 40, 40 and 200 mL min\(^{-1}\) for H2, He and air, respectively) and an FID was used for analysis. The column was maintained at 120°C.

Package ethanol

The ethanol content of the package headspace was measured as described (Beaudry et al., 1993). Two 1-mL gas samples were withdrawn after packages had reached steady-state for O2 and CO2. Quantitation was by comparison to a gaseous standard. The standard gas sample was from a static headspace that was in equilibrium with a solution of water and ethanol of known concentration and temperature (Pesis and Avissar, 1990). A gas chromatograph (Carle AGC series 400, Carle Instruments Company, Fullerton, CA) fitted with a packed column (Haysep N, 3 mm i.d., 45.7 cm length, with gas flow rates of 40, 40 and 200 mL min\(^{-1}\) for H2, He and air, respectively) and an FID was used for analysis. The column was maintained at 120°C.

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The mathematical model of Cameron et al. (1994) was used to describe the dependence of package O2 levels on temperature and package characteristics for apple slices. Initially, O2 flux through the package \( (\text{Eq} \ 2) \) was set equal to the respiratory rate determined from the respiratory model \( (\text{Eq} \ 4) \) such that:

\[
(P_{O2}/A/mL)[p_{O2} - p_{O2}] = \left[ \left( V_{\text{max}} p_{O2} \right) / K_{\text{O2}} + p_{O2} \right] \]

which is valid only under steady-state conditions. This relationship was solved for \( p_{O2} \):

\[
P_{O2} = \frac{1}{2} \left[ \left( K_{\text{O2}} + (m/L)A V_{\text{max}} + p_{O2} \right)^2 \right] - \left[ K_{\text{O2}} + (m/L)A V_{\text{max}} - p_{O2} \right]

\]

Equation (6) was used to determine the effect of temperature on \( p_{O2} \) when the activation energy of film permeability to O2 \( (E_{P02}) \) was changed while the other package variables \( (m, L, A) \) and \( p_{O2} \) were constant. Equation (6) was also used to evaluate film types for their film thickness suitability for gas exchange design criteria of 100g of sliced fruit in a 120 cm\(^2\) package. The package model was used to predict the effects of varying the mL/A ratio for packages composed of LDPE containing apple slices.

RESULTS

Film permeability

An Arrhenius plot of permeability data indicated that ln(permeability) for both gases depended linearly on the reciprocal of temperature (Fig. 1, inset) with \( r^2 = 0.99 (P<0.01) \) for both O2 and CO2. Regression analysis of the Arrhenius plots, \( P_{O2} \) and \( P_{CO2} \) of LDPE yielded the following equations:

\[
P_{O2} = 2.49E - 9e^{(-37000/RT)} \text{ (mol m m}^{-2} \text{ Pa}^{-1} \text{ s}^{-1})

\]

where \( V_{\text{max}} (\text{mol g}^{-1} \text{ s}^{-1}) \) is the maximal rate of O2 uptake and \( K_{\text{O2}} \) (Pa) is the O2 partial pressure at one half of \( V_{\text{max}} \). The respiratory quotient (RQ) was calculated as \( r_{CO2} / r_{O2} \). Data were plotted as the dependence of \( r_{O2} \) and RQ on \( p_{O2} \) at four temperatures. The fermentation threshold was determined as the O2 partial pressure below which the RQ was estimated to increase above 1.3. The temperature dependence of \( V_{\text{max}} \) and \( K_{\text{O2}} \) was determined by fitting the respiratory data for all four temperatures to Eq (4) using SAS statistical analysis software (SAS Institute Inc., Cary, NC) as described (Cameron et al., 1994).
\[ P_{CO_2} = 4.14 \times 10^{-9} e^{-\frac{-35000}{RT}} \text{ (mol m}^{-2}\text{s}^{-1}\text{Pa}^{-1}) \quad (8) \]

\[ E_{aP_{CO_2}} \text{ for LDPE was 37 kJ mol}^{-1}. \text{ The activation energy of the permeation of } CO_2 (E_{aP_{CO_2}}) \text{ through LDPE was 35 kJ mol}^{-1}. \text{ The permeability of the POP (Affinity PF 1140) film to } O_2 \text{ and } CO_2 \text{ was, respectively, 3.5 and 4-fold higher than for LDPE (data not shown). The activation energy for } O_2 \text{ and } CO_2 \text{ permeation through the POP film was 37.4 and 33.1 kJ mol}^{-1}, \text{ respectively.} \]

**Respiratory model**

Steady-state \( p_{i,O_2} \) was reached for all packages for each temperature and ranged from approximately 0.1 to 15 kPa (Fig. 2). The \( r_{O_2} \) (Fig. 2) and \( r_{CO_2} \) (data not shown) calculated from film permeability to \( O_2 \) and \( CO_2 \), respectively, increased with increasing temperature and \( p_{i,O_2} \): \( V_{\max} \) increased exponentially with temperature, while \( K_{1/2} \) increased linearly:

\[ V_{\max} = 1.67 \times 10^{0.069T} - 1.06 \times 10^{-1} \text{ (mol g}^{-1}\text{s}^{-1}) \quad (9) \]

\[ K_{1/2} = 50T + 660 \text{ (Pa)} \quad (10) \]

where T is temperature in °C. The data fit the respiratory model with a coefficient of determination (\( R^2 \)) of 0.94. The \( V_{\max} \) for ‘NY-674’ apple slices was calculated to be 64, 139, 222 and 367 pmol g\(^{-1}\)s\(^{-1}\) for apple slices held at 0, 5, 10 and 15°C, respectively. This increase in respiration was equivalent to \( Q_{10} < 3. \)

At \( p_{i,O_2} < 1 \text{ kPa}, \text{ RQ increased above its aerobic value (Fig. 3). Ethanol concentration in the package headspace increased when the RQ was } \geq 1.3 \text{ (data not shown) indicating fermentative metabolism. The } p_{i,O_2} \text{ at which the RQ increase occurred increased as temperature increased. Fermentation threshold estimates for 0, 5, 10, and 15°C were 0.2, 0.25, 0.3 and 0.4 kPa } O_2 \text{ (Fig. 3) and empirically fitted the exponential equation:} \)

\[ p_{i,O_2} = 195 e^{(0.047T)} \text{ (Pa)} \quad (11) \]

where T is temperature in °C (\( r^2 = 0.99 \)). A ‘practical’ lower \( O_2 \) limit three times higher than the fermentation threshold was established (Fig. 4).

**Package model**

The respiratory data enabled calculation of an apparent activation energy of respiration (apparent \( E_{aO_2} \)), expressing the respiratory tem-
perature sensitivity comparable to that for O₂ permeability (inset, Fig. 4). The apparent \( E_a^{pO_2} \) for fruit at 16 kPa O₂ was 75 kJ mol⁻¹ and at 0.5 kPa O₂ was 55 kJ mol⁻¹. Thus, the \( E_a^{pO_2} \) of LDPE (37 kJ mol⁻¹) was lower than the apparent \( E_a^{pO_2} \) of apple slices for O₂ partial pressures from 0.5 to 16 kPa.

The package model developed from apple slice data was used to determine how \( E_a^{pO_2} \) affects \( p_{i,O_2} \) and temperature-induced anaerobiosis by substituting differing values of \( E_a^{pO_2} \) for the permeability coefficient in Eq (6). When predictions for \( p_{i,O_2} \) were constrained to yield 1.2 kPa at 15°C, as \( E_a^{pO_2} \) decreased, the \( p_{i,O_2} \) predicted at 0°C increased (Fig. 4). When the permeability coefficient \( E_a^{pO_2} \) was near that of the respiratory response (60 kJ mol⁻¹), a low O₂ partial pressure was predicted across the temperature range. This was slightly higher than the practical lower O₂ limit established, and remained above the fermentation threshold.

Predictions of film thickness needs were made based on \( P_{O_2}^{0} \) and \( E_a^{pO_2} \) data from Pauly (1989) for Saran® (poly[vinylidene chloride]), PVC (polyvinyl chloride) and PP (polypropylene) and from laboratory measurements on LDPE and POP (Affinity PF 1140) for theoretical packages (Fig. 5). Predicted film thickness ranges needed to maintain aerobic conditions across the temperature range of 0 to 15°C were 0.0066 to 0.109 µm for Saran®, 0.0775 to 0.96 µm for PVC, 0.533 to 5.51 µm for PP, 0.858 to 14.1 µm for LDPE and 3.15 to 25.4 µm for POP (Affinity PF 1140).

**DISCUSSION**

The respiratory rate of apple slices was about 2 to 3 times that reported for whole fruit (Gran, 1993; Kader et al., 1989), due to effects of wounding, not a reduction in diffusive resistance produced by slicing. Since diffusive resistance of whole fruit resulted in an O₂ partial pressure gradient of only 2 to 5 kPa (Rajapakse et al., 1989), the interior O₂ level was sufficiently high to very nearly saturate the respiratory response (Tucker and Laties, 1985). Thus, the reduced diffusive resistance provided by slicing should not have resulted in an increase in O₂ uptake relative to whole fruit. The shapes of the respiratory curves were similar to those reported for blueberry (Beaudry et al., 1992) since both the \( K_m \) and \( V_{max} \) increased with temperature in linear and exponential fashions, respectively.

The increase in RQ with declining \( p_{i,O_2} \) represents the lower O₂ limit in some studies and has been referred to as the RQ breakpoint, extinction coefficient or as the fermentation threshold (Beaudry et al., 1992; Gran and Beaudry, 1993; Yearsley et al., 1996). The fermentation threshold of apple slices was about half that of whole fruit reported by Gran and Beaudry (1993). The low fermentation threshold was likely not a function of the cultivar, but resulted from partial removal of the skin gas exchange barrier, coupled with a reduced diffusion path length. Hence, O₂ partial pressure in the surrounding atmosphere could be lower for a slice than for whole apple with internal O₂ partial pressure just above the fermentation threshold.

Like whole apple (Gran and Beaudry, 1993), blueberry (Beaudry et al., 1992), raspberry and strawberry (Joles, 1993; Joles et al., 1994) fruit, the fermentation threshold for apple slices increased with temperature. It was associated with the accumulation of ethanol in a manner consistent with previous results (Beaudry et al., 1992; Gran, 1993).

The hypothesis that fermentation was linked to off-flavors and/or tissue damage in apple slices was supported indirectly by the correlation between RQ and the development of off-flavors in highbush blueberry fruit in a MAP system (Dostal et al., 1991). Fermentation should probably be avoided in packaged apple slices.

The package model could be used to design a package to minimize fermentation and predict the headspace atmosphere composition for sliced apples in packages composed of any polymer film of known permeability, thickness, area and fruit mass. The fruit must physically fit within the container and with sufficiently small headspace to permit rapid attainment of steady state. In addition to providing a suitable headspace atmosphere during storage, package material should maintain non-injurious \( p_{i,O_2} \) and \( p_{i,CO_2} \) over a range of temperatures and limit CO₂ injury. Treatment of apple slices with CO₂ resulted in the development of brown lesions in the fruit cortex when \( p_{i,CO_2} \) was near 10 kPa (Lakakul, 1994). An optimal package design therefore, should maintain \( p_{i,O_2} \) in the aerobic range and \( p_{i,CO_2} \) below the range causing injury.

The commercially acceptable lower O₂ limit may be higher than the fermentation threshold (Fig. 4). Cameron et al. (1993) measured variation in product respiration and package permeability and modeled the effects on \( p_{i,O_2} \). They determined there was an estimable risk of the \( p_{i,O_2} \) falling below the O₂ limit, resulting in fermentation. They showed that for broccoli, packages must be designed to generate a \( p_{i,O_2} \) well above the fermentation threshold to ensure aerobic conditions. We used a practical lower O₂ limit 3 times higher than the fermentation threshold as a package design criterion (Fig. 4).

The apparent \( E_a^{pO_2} \) for blueberry fruit ranges from 40 to 60 kJ mol⁻¹ under aerobic conditions, similar to the range reported here (55 to 75 kJ mol⁻¹). The apparent \( E_a^{pO_2} \) for strawberry fruit is 60 kJ mol⁻¹, lettuce, ~53 kJ mol⁻¹ and broccoli, ~90 kJ mol⁻¹ (Cameron et al., 1995). It appears that the \( E_a^{pO_2} \) for many horticultural crops tends to be greater than the \( E_a^{pO_2} \) for LDPE. Thus, the flux of O₂ gas into the commodity has a higher temperature sensitivity than the flux of O₂ through the polymer film. Therefore as temperature increases, the respiration rate of the commodity would increase relatively more than \( P_{O_2} \). That is, packaging systems with higher \( E_a^{pO_2} \) would undergo smaller declines in \( O_2 \) as temperature increased. Generally, polymer...
films with lower temperature sensitivities are predicted to exert progressively less ‘control’ over \( P_{i,O_2} \) (Cameron et al., 1994; Cameron et al., 1995). A package that relies solely upon perforations would have an \( E_a^{P_{O_2}} \) of 5 kJ mol\(^{-1}\) and, thus less ‘control’ than systems relying on \( O_2 \) permeation through polymers, with greater fluctuations in \( P_{i,O_2} \) with temperature changes. A polymeric package with a \( E_a^{P_{O_2}} \) of 60 kJ mol\(^{-1}\) would be expected to maintain low \( O_2 \) levels across the range 0 to 15°C. The need for a temperature-adaptive package is minimized if temperature can be controlled within a range of 1 to 2°C of the target temperature (Cameron et al., 1994; Cameron et al., 1995).

The package model could be rearranged to predict a suitable thickness range for packaging films for which design criteria have been established (e.g., 100g of fruit, 120 cm\(^2\)) such that the atmosphere in the package would remain aerobic from 0 to 15°C (Fig. 5). While many kinds of food-compatible polymer films are available, the predicted film thicknesses suggest not all would be suitable for apple slices. Among these polymers, a Saran® copolymer has a desirably high \( E_a^{P_{O_2}} \); however its \( P_{O_2} \) is very low, so film thickness would necessarily be much thinner than most machining capabilities (S. Jenkins, The Dow Chemical Company, Midland, personal communication) and use of Saran® copolymer would not be an option. Moreover, a thin monolayer film may not provide enough strength for the package. The POP film had a \( P_{O_2} \) about 3.5 times higher than that of LDPE, but a similar \( E_a^{P_{O_2}} \). The elevated \( P_{O_2} \) enables the use of greater film thickness than standard LDPE. For example, 25.4 µm-thick film would yield \( P_{i,O_2} \) of 6 kPa at 0°C (film area 120 cm\(^2\) and 100g of apple slices) and would safely remain aerobic up to 15°C.

A more generally applicable form of the model can be derived using a ratio of the ml/A of each polymer film type (e.g., LDPE, PVC, EVA, etc.) to predict \( P_{i,O_2} \) dependency on temperature. From our model, an apple slice package composed of LDPE would be predicted to maintain aerobic conditions within the range from 0 to 15°C when the ml/A ratio is less than 5.65E-2g m\(^{-1}\). For example, for a 100-g apple slice fruit pack using LDPE film thickness of 12.7 µm, the film area would have to be >225 cm\(^2\) to avoid risk of fermentation.

To validate the model, packages composed of LDPE with ml/A ratios of 2.0E-02 and 3.575E-02 g m\(^{-2}\) were constructed and stored at 0, 3, 5, 10, and 12°C. Package \( O_2 \) was expressed as a function of temperature (Fig. 6). The data were close to predicted values represented by the solid lines (\( r^2 = 0.76, P<0.05 \)), suggesting the model was functional and accurate.

Decay and browning remain as obstacles in the commercial production of apple slices (Lee and Smith, 1995). In our study or in parallel CA studies, neither decay nor browning were controlled by the atmospheres generated in the packages. Decay was observed on the apple slices in packages within 5 days at 15°C and 8 days at 10°C and browning was considered unacceptable within 24h of packaging at all temperatures.

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**Fig. 5—Interrelationship between film \( E_a^{P_{O_2}} \) and thickness on the ability of a theoretical package to maintain aerobic \( O_2 \) partial pressures between 0 and 15°C.** Thickness data are expressed as a function of \( P_{i,O_2} \) at 0°C. Curves were generated from Eq (6) with substitution of different \( P_{i,O_2} \) and \( E_a^{P_{O_2}} \) obtained experimentally or from Pauly (1989). The theoretical package film surface area was 120 cm\(^2\) and fruit mass was 100g.

**Fig. 6—Package headspace \( O_2 \) achieved in packages designed to have a ml/A of either 3.58E-02 or 2.0E-02.** The practical \( O_2 \) limit is 3\( \times \) the fermentation threshold and is represented by the exponential equation: Practical \( O_2 \) limit (kPa) = 0.587e\(^{0.047T}\), where \( T \) is temperature in °C.
CONCLUSIONS

MATHEMATICAL MODELS FOR RESPIRATORY RESPONSES TO O\textsubscript{2} and temperature and the permeation of O\textsubscript{2} through various films could be combined for the design of MA packages for apple slices. The effects of environmental factors such as temperature on O\textsubscript{2} partial pressure in the packages could be predicted, enabling the evaluation of film types without the need for conducting numerous packaging experiments. The simplified approach of using the film-specific ml/A ratio should facilitate package design for MAP.

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