THEORETICAL STUDY OF PRODUCT-GENERATED ATMOSPHERE PACKAGES FOR FRUIT

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ABSTRACT

THEORETICAL STUDY OF PRODUCT-GENERATED ATMOSPHERE PACKAGES FOR FRUIT

By

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This thesis investigates the possibility of replacing controlled atmosphere storage of fruits with a product-generated atmosphere package. The investigation is comprised of an economic analysis and a computer model. The McIntosh apple is the product. Internal package conditions are generated for three films and temperatures between 3.5°C and 7°C.

Results of the economic analysis and computer model support the feasibility of product-generated storage costs for product-generated storage packages are less than either cold storage or controlled atmosphere storage. Apples stored in low density polyethylene had significantly lower respiration rates than cold storage apples.

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By

Thomas James Bussell

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CHAPTER I

INTRODUCTION

Section 1: Background

Packaging fruits and vegetables in transparent plastic bags has become popular commercially. These packages provide efficient distribution and attractive display at point of sale.[1]

This package is utilizing the three basic functions of a package--that is, the package: (1) communicates to the consumer, (2) provides utility, and (3) provides protection and containment of the product.

Extending storage life, which is part of the protection function, is economically important. The major storage life benefit derived from the familiar polyethylene fruit bag is that it hinders water loss and subsequent shriveling of the fruit.

Greater gains in extending storage life of fruits are today achieved by modifying the storage atmosphere prior to the packaging and distribution of the polyethylene bag. An atmosphere with low concentration of

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[1] R. G. Tomkins, "The Conditions Produced in Film Packages by Fresh Fruits and Vegetables and the Effect of These Conditions on Storage Life," Jrnl. Applied Bacteriology (1962), 25(8):290.

oxygen and a high concentration of carbon dioxide retards the fruits' ripening process. This increases the storage life.

Section 2: Purpose

The objective is to study if it is theoretically possible to achieve and maintain favorable storage conditions within a fruit package and in that way eliminate the necessity of controlled atmosphere storage. If this is possible, the package will be analyzed from an economic standpoint.

Section 3: Limitations

Fruit and Variety

The McIntosh apple (*Malus pumilu*, Mill.) is the particular fruit and variety that this theoretical study focuses on. The McIntosh was chosen on the basis of its commercial importance in Michigan's fruit industry and that it is commonly stored under modified atmospheres.

Storage Function

The movement of apples from harvest to consumer sales encompasses numerous handlings and environments. The scope of this thesis is limited to the storage function (Figure 1). The emphases of this paper are not concerned with the apples' distribution system, but are concerned with package design and an economic analysis of storage methods.

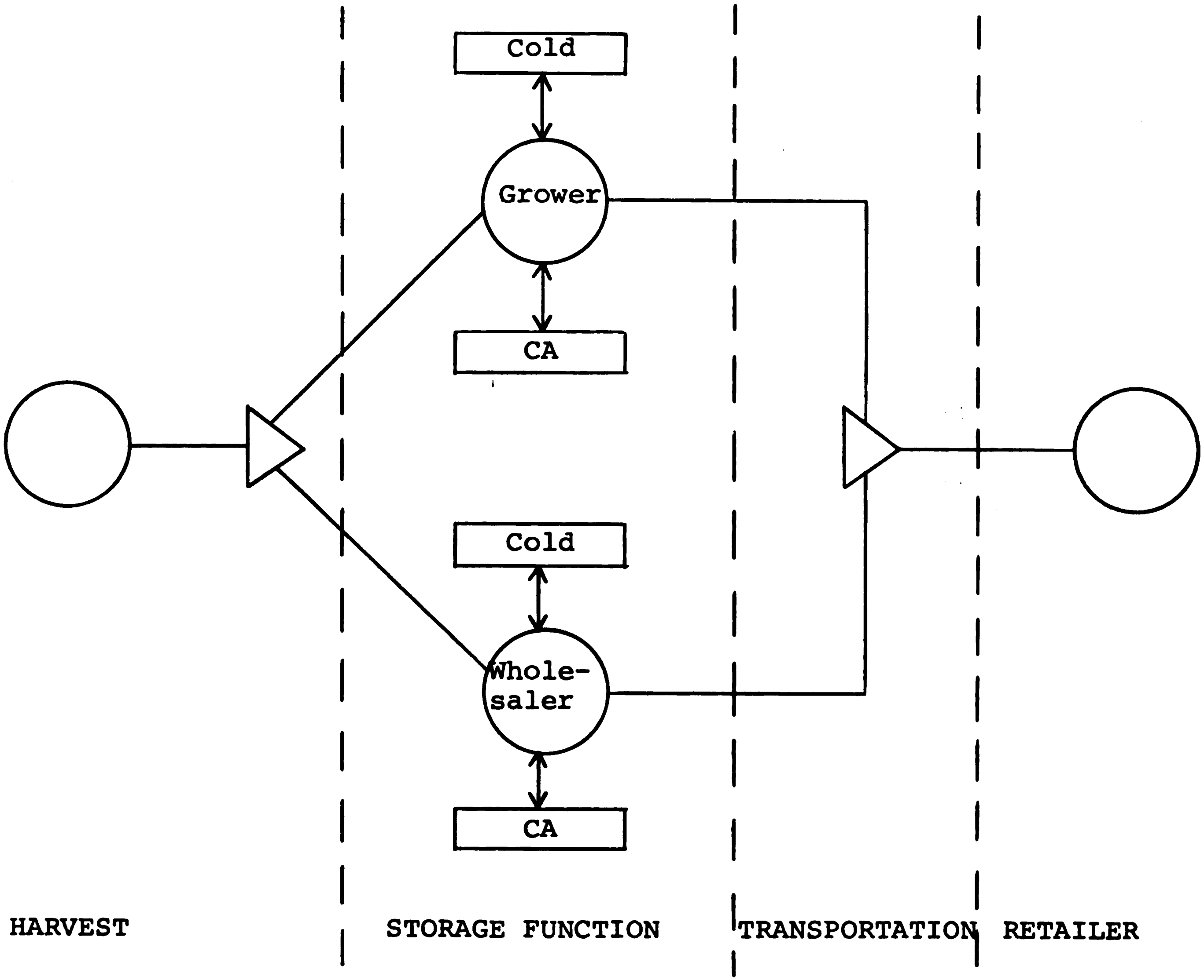

Figure 1.--Distribution System from Point of Harvest.

Storage Life

Storage life is dependent on numerous factors. Some of the factors are: metabolism, moisture loss, physiological disorders, chemical treatments, maturity at harvest dates and rate of cooling.[2] Of these factors, controlling the apple's metabolism is the most critical.

The metabolism, or respiration rate, of the apples is affected by the fruits' environment. It is the control of respiration (and, therefore, storage life) that is of concern to this problem.

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[2] A. VanDoren, "Physiological Studies with McIntosh Apples in Modified Atmosphere Cold Storage," Proc. Am. Soc. Hort. Sci. (1937), 37:453.

CHAPTER II

DEFINITIONS

Listed below are terms that are frequently used in this paper. Several terms and definitions may only be correct within the context of this paper. Most of the terms are particular to the apple or its storage.

Aerobic respiration: Respiration that occurs in an adequate supply of oxygen. This is the typical form of respiration and is referred to as simply "respiration."

Activation energy: A coefficient, particular to the film, that quantifies the effect of temperature on the permeability.

Anaerobic respiration: Fermentation--respiration in the absence of oxygen with by-products of ethyl alcohol, carbon dioxide and acetaldehyde.

Carbon dioxide scrubbers: Chemicals or processes that remove excess carbon dioxide from controlled atmosphere rooms.

Climacteric: Ripening process, evidenced by increasing respiration rate. The high respiration rate supplies energy for the conversion of starch to hexose, the production of ethylene and the distinction of cell wall material.[3]

Cold storage: Synonymous with "regular storage"--warehouse storage units that maintain a low temperature in an air atmosphere. The temperature is usually near 0°C.

Controlled atmosphere (CA) storage: Airtight storage units which control oxygen concentration, carbon dioxide concentration and temperature.

Cultivar: Variety.

Extinction point: Minimum oxygen level needed to sustain aerobic respiration.

Intercellular spaces: Void spaces between cells within the apple pulp. The oxygen in these spaces provide the immediate supply of oxygen for metabolism.

Ontogeny: The life cycle of a single organism.

Packing density: Ratio of product volume to package volume.

Permeability constant: A measure of grams of specific gas that pass through one square centimeter of material that is one millimeter thick, in one hour.

Product-generated atmosphere package: A sealed, flexible film package that contains a living, respiring

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[3] F. Kidd and C. West, "Recent Advances in the Work on Refrigerated Gas--Storage of Fruit," Jrnl. of Pomology (Hort. Sci.) (1936), 14:306.

organism (the product), where the respiratory process of the organism produces (generates) concentrations of oxygen and carbon dioxide within the package (atmosphere) that are in different quantities than is found in air.

Permeability rate: A measure of grams of specific gas that pass through one square centimeter of material one millimeter thick, in one hour, at a temperature other than 0°C.

Respiration: The uptake of oxygen to convert sugar into carbon dioxide, water and energy. The reaction is:

$$6\ O_2 + C_6H_{12}O_6 \longrightarrow 6H_2O + 6CO_2 + 673\ \text{Kcal}$$

Respiration rate: Measure of oxygen uptake or carbon dioxide output. Typically, carbon dioxide is used, such as: CO_2 grams/kilogram apple/hour.

Respiratory quotient (R.Q.): Volume of carbon dioxide produced divided by volume of oxygen simultaneously consumed.[4]

Senescence: Post-maturity stage, an aging process.

Storage life: Period of time from harvest to 10 percentage wastage of the fruit.

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[4] W. O. James, Plant Respiration (1953), p. 82.

Temperature coefficient (Q_{10}): This is the rate of respiration at a given temperature, divided by the respiration rate at 10°C lower.

Transmission rate: A measure of grams of a specific gas that pass through a package per period of time.

CHAPTER III

PRODUCT DESCRIPTION

This chapter is divided into three sections. The first section discusses the general ontogeny of apples. It focuses on apples from time of harvest to ultimate degradation. Harvest corresponds to the beginning of storage life.

The second area discusses anaerobiosis. Anaerobiosis is an important concept to understand if apples are to be stored in modified atmospheres.

The final section describes specific characteristics of the McIntosh apple relevant to this analysis. The effect of oxygen, carbon dioxide and temperature on the respiration rate are given special attention.

Section 1: Ontogeny

An apple is a living, respiring biological system which is constantly undergoing physical, chemical and structural changes as it develops, ripens and dies.[5]

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[5] A. Jabbari, N. N. Mohserin and W. S. Adams, "Analog Computer Model for Predicting Chemical and Physical Properties of Selected Food Materials," *Transactions, American Soc. Agri. Eng.* (1971), 14(2):319.

Respiration rate is an ideal parameter for determining the physiological age of the apple. The respiration rate has a definite trend through the ontogeny of the apple (Figure 2).

Pre-climacteric Minimum

The harvest date is at the pre-climacteric minimum (point A in fig. 2). At this stage of ontogeny, the apple is fully developed and the respiration rate is at a minimum. Harvesting at or just prior to the pre-climacteric minimum will provide the greatest storage potential.[6]

Climacteric

The next stage of ontogeny is the climacteric, which is the ripening process. At this point, the apple is converting its energy supply of starch into sugar, oxygen, carbon dioxide, ethylene and heat. This will cause a change in color of the skin and a softening and sweetening of the flesh.[7]

The climacteric is critical to storage-life. Once the climacteric starts, the ultimate storage-life is

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[6] D. R. Dilley, "Prediction and Verification of Proper Harvest Date for Storage Apples," Mich. St. Hort. Soc. (1965), 95:48.

[7] F. Kidd and C. West, "Recent Advances in the Work on Refrigerated Gas--Storage of Fruit," p. 306.

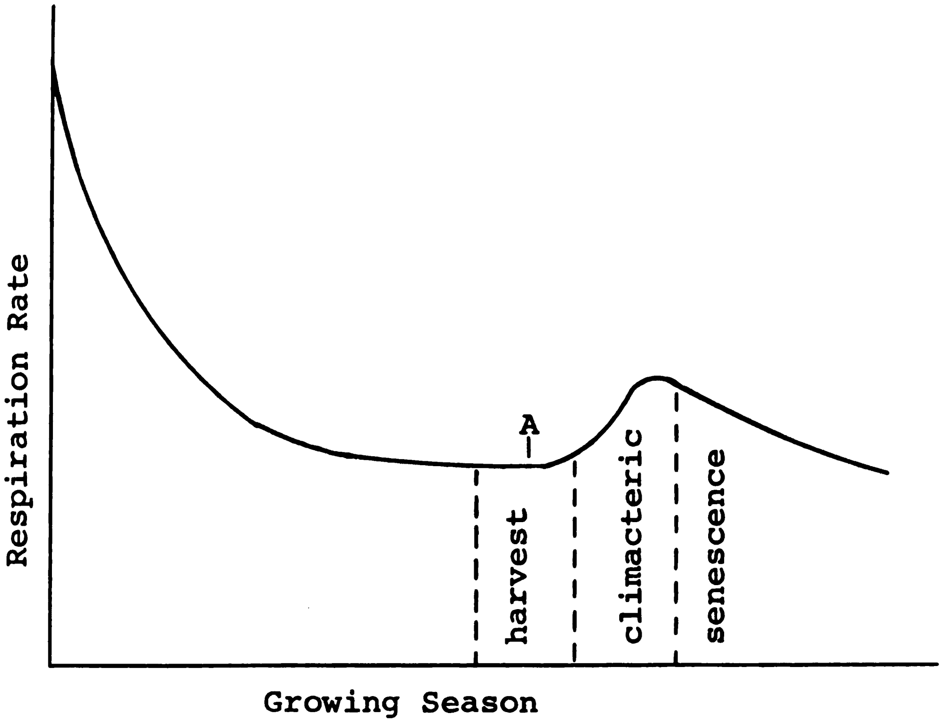

Figure 2.--Ontogeny of Apples as Represented by Respiration Rate.

Source: Fidler, J.C.; Wilkenson, B.G.; Edney, K.L.; and Sharples, R.O. (1973), The Biology of Apple and Pear Storage. Headley Brothers, Ltd., London. Page 4.

limited. If the climacteric can be delayed or suppressed, the storage-life will be increased.[8] A low temperature environment will delay the climacteric. A modified atmosphere can suppress the climacteric to the extent that the respiration rate is not affected.[9]

At one time, the onset of the climacteric was believed to be initiated by the presence of ethylene. It appeared that the increase in ethylene production by the apple triggered the chemical reactions associated with the climacteric. This has been proven false based on two findings: (1) ethylene production follows the respiratory peak of McIntosh apples by about four days at 20°C,[10] and (2) initial studies were done in air at 20°C, where low temperatures and a modified atmosphere negate any ethylene effect on the climacteric.[11]

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[8] F. Gangerth, "Hypobaric Storage of Vegetables," Acta Horticulturae (1974), 1(6):23.

[9] F. Kidd and C. West, "Recent Advances in the Work on Refrigerated Gas--Storage of Fruit," p. 308; and J. C. Fidler, "Studies of the Physiological-Active Volatile Organic Compounds Produced by Fruit II. The Rate of Production of Carbon Dioxide and of Volatile Organic Compounds by King Edward VII Apples in Gas Storage, and the Effect of Removal of Volatiles from the Atmosphere of the Store on the Incidence of Superficial-Scald," Jrnl. Hort. Sci. (1950), 25(2):104.

[10] R. M. Smock, "The Influence of One Lot of Apple Fruit on Another," Proc. of the Am. Soc. Hort. Sci. (1942), 40:187.

[11] J. C. Fidler, B. G. Wilkenson, K. L. Edney and R. O. Sharples, The Biology of Apple and Pear Storage (1973), p. 8.

Senescence

The final stage of the apple's life is called "senescence." The apple pulp or flesh becomes mealy and loses its flavor. At this point, storage-life and market value are very limited. The respiration rate during senescence is characterized by a downward drift.

Section 2: Anaerobiosis

Preventing anaerobic respiration is critical to apple quality. The by-products of anaerobic respiration are carbon dioxide, ethyl alcohol and acetaldehyde. Ethyl alcohol and acetaldehyde will remain in the apple, which results in an "off" flavor. Quality of apples will be severely affected after approximately one week in anaerobic conditions.[12]

Oxygen is necessary for the normal respiratory process. Decreasing the available supply of oxygen will have a retarding effect on the rate of respiration. There is, however, a limit to the amount that oxygen can be reduced and still maintain respiration. This lower limit (concentration) for oxygen is referred to as the extinction point. Extinction point is dependent on temperature and apple variety. For the McIntosh apple,

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[12] J. C. Fidler and C. J. North, "The Effect of Periods of Anaerobiosis on the Storage of Apples," J. Hort. Sci. (1971), 45:220; and R. G. Tompkins, "The Conditions Produced in Film Packages by Fresh Fruits and Vegetables and the Effect of These Conditions on Storage Life," p. 304.

the extinction point is 2% oxygen at 3.5°C,[13] and 3.5% oxygen at 20°C.[14]

When the oxygen supply falls below the extinction point, respiration is replaced by anaerobic respiration as the oxygen concentration approaches zero (Figure 3).[15] Anaerobiosis results in total depletion of oxygen supply within the fruit which will disrupt and accelerate the metabolic processes.[16] An increase in carbon dioxide evolution is associated with anaerobic fermentation.

Section 3: Apple Cultivar--McIntosh

The design of a product-generated package is affected by the characteristics of the product.[17] The product traits that must be determined are: (1) physical characteristics, (2) optimum storage conditions, (3) effect of oxygen on respiration rate, (4) effect of

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[13] A. Van Doren, "Physiological Studies with McIntosh Apples in Modified Atmosphere Cold Storage," p. 454.

[14] V. Jurin and M. Karel, "Studies on Control of Respiration of McIntosh Apples by Packaging Methods," Food Technology (1963), 17(6):106.

[15] H. E. Street and W. Cockburn, Plant Metabolism (1972), p. 90.

[16] J. C. Fidler and C. J. North, "The Effect of Periods of Anaerobiosis on the Storage of Apples," Jrnl. Hort. Sci. (1971), 46:213.

[17] R. G. Tomkins, "The Conditions Produced in Film Packages by Fresh Fruits and Vegetables and the Effect of These Conditions on Storage Life," J. Applied Bacteriology (1962), 25(8):305.

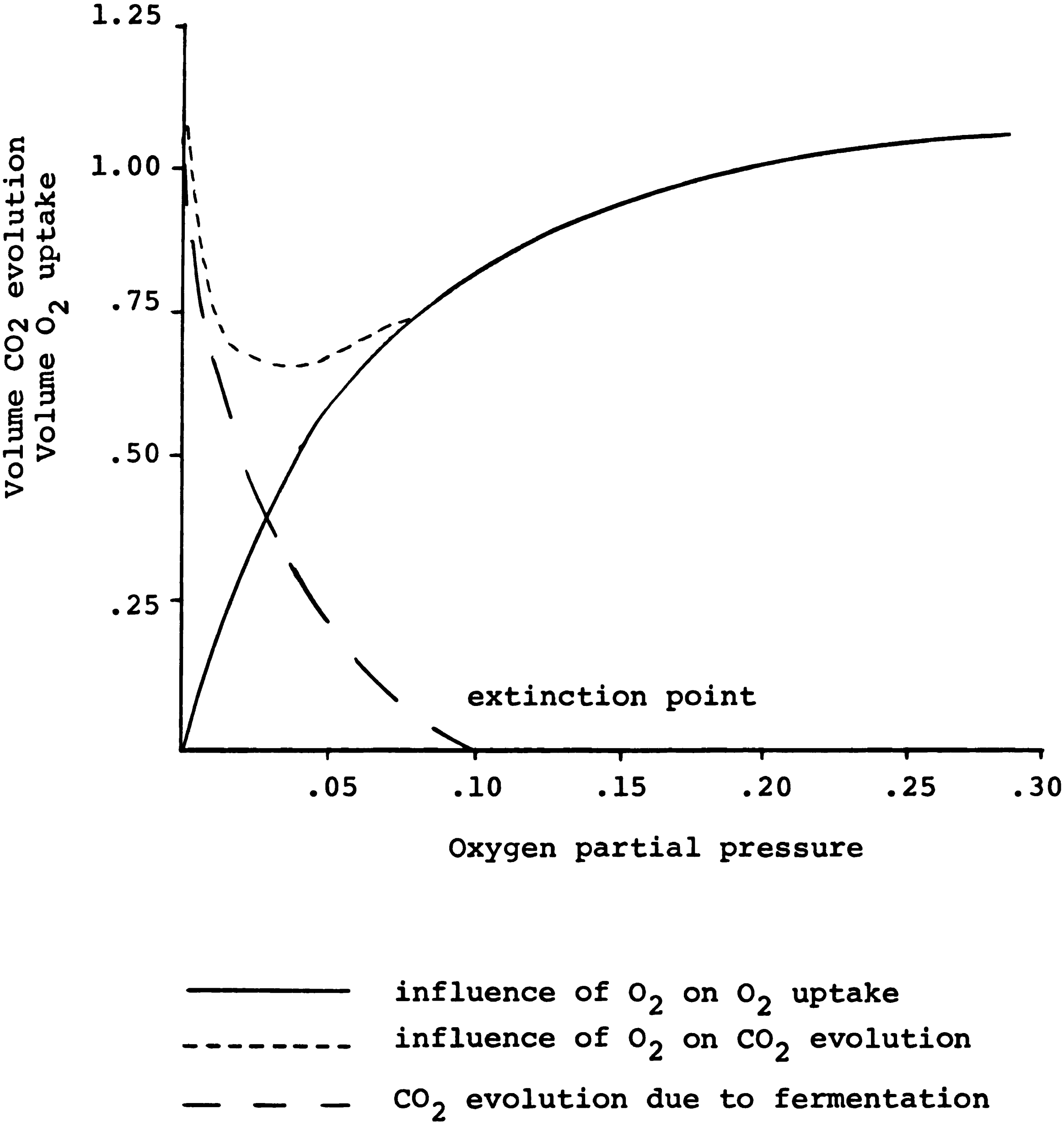

Figure 3.--Effect of the Partial Pressure of Oxygen on Subsequent Oxygen Uptake and Carbon Dioxide Output.

Source: James, W.O. (1953). Plant Respiration. Oxford Claredon Press, England. Page 90.

carbon dioxide on respiration rate, and (5) effect of temperature on respiration rate.

Physical Characteristics

Following is a brief description of the physical characteristics of the McIntosh that are relevant to this study:

1. Density is .814.[18]
2. 30% - 35% of volume is intercellular spaces.[19]
3. Approximately 4% of intercellular space is carbon dioxide.[20]
4. Approximately 17% of intercellular space is oxygen. The accumulation of carbon dioxide is almost balanced by the depletion of oxygen.[21]
5. 85% of the weight of the apple is assumed to be water.[22]
6. 0.5 is the packing density for plastic bags.[23]

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[18] B. A. Stout, D. H. Dewey, and R. F. Mrozek, "Mechanical Orientation of Apples and Related Fruit Characteristics," Agr. Exp. Stn. Mich. St. Univ. Research Bulletin (1971), No. 32, p. 13.

[19] S. P. Burg and E. A. Burg, "Gas Exchange in Fruits," Physiologia Plantarum (1965), 18:876.

[20] Ibid., p. 879.

[21] Ibid., p. 878.

[22] J. C. Fidler, "Studies of the Physiological Active Volatile Organic Compounds Produced by Fruit II," p. 89.

[23] R. G. Tomkins, "The Biological Effects of the Conditions Produced in Sealed Plastic Containers by Pre-packaged Fresh Fruit and Vegetables," Bull. Int. Inst. Refrig, Annexe. (1960), 1:237.

Optimum Storage Conditions

The optimum storage conditions for McIntosh are a temperature of 3.5°C and an atmosphere of 5 percent carbon dioxide and 3 percent oxygen. This atmosphere can be stated as 5:3. These ideal storage conditions are quite typical among common Michigan apple cultivars (Table 1).[24]

TABLE 1.--Storage Conditions for Some Michigan Apple Cultivars.

Cultivar	Conditions			Rates of Respiration in 1/1,000 kg day
	T°	%CO_2	%O_2	CO_2
Golden Delicious	3.5	5	3	20
Delicious	0	5	3	18
Jonathan	3.5	7	13	33
McIntosh	3.5	5	3	35

Oxygen Effect

The effects of both oxygen and carbon dioxide partial pressures on the respiration rate of McIntosh apples have been measured by Jurin and Karel.[25] This

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[24] J. C. Fidler and G. Mann, Refrigerated Storage of Apples and Pears--A Practical Guide (1972), p. 34.

[25] V. Jurin and M. Karel, "Studies on Control of Respiration of McIntosh Apples by Packaging Methods," p. 107.

study was conducted at a constant 20°C. The effects of the gases are illustrated in Figures 4 and 5.

Jurin and Karel found that the oxygen effect on the rate of respiration was practically linear between the extinction point concentration of .035 and .21. In this span of oxygen concentrations, the respiration was suppressed from 10 cc O_2/Kg•hr to 6 cc O_2/Kg•hr at the extinction point. The respiration rate fell sharply when the oxygen supply was below the extinction point.

Carbon Dioxide Effect

Increasing the partial pressure of carbon dioxide had a retarding effect on respiration rate (Figure 5). The retarding effect was minor at the lower concentrations.

The effect of decreasing the respiration rate by changing the partial pressures of oxygen and carbon dioxide are additive.[26] When the atmosphere is oxygen deficient and carbon dioxide rich, the gases will have a combined retarding effect on the respiration rate.

It is not completely understood how the concentrations of oxygen and carbon dioxide affect metabolism. The probable dictating factor is the quantity of the two

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[26] J. C. Fidler and C. J. North, "The Effect of Conditions of Storage on the Respiration of Apples," Jrnl. Hort. Sci. (1967), 42:203.

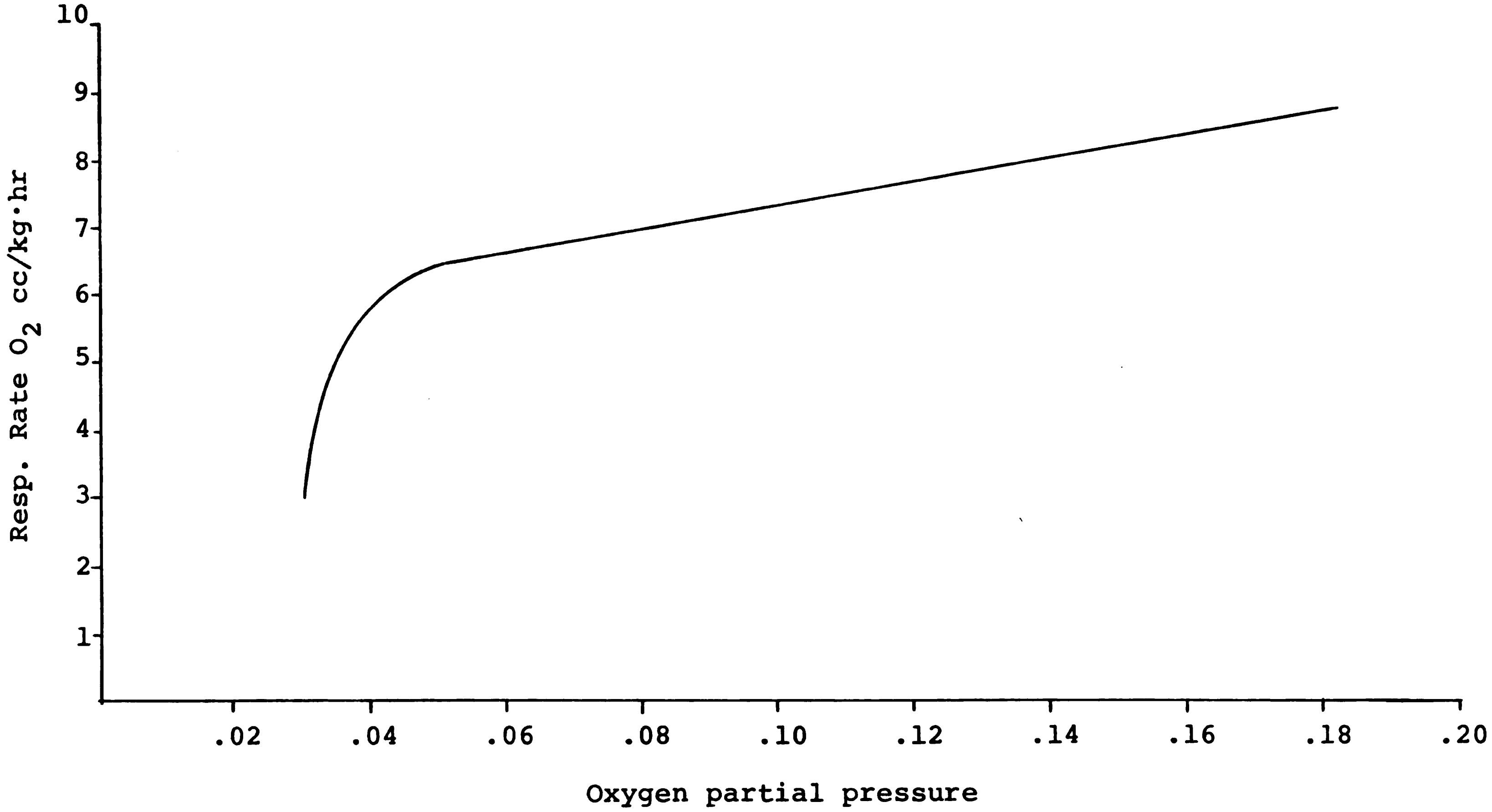

Figure 4.--Oxygen Effect on Respiration Rate of McIntosh Apples.

Source: Jurin, V. and Karel, M. (1963). "Studies of Control of Respiration of McIntosh Apples by Packaging Methods." Food Technology 17(6):107.

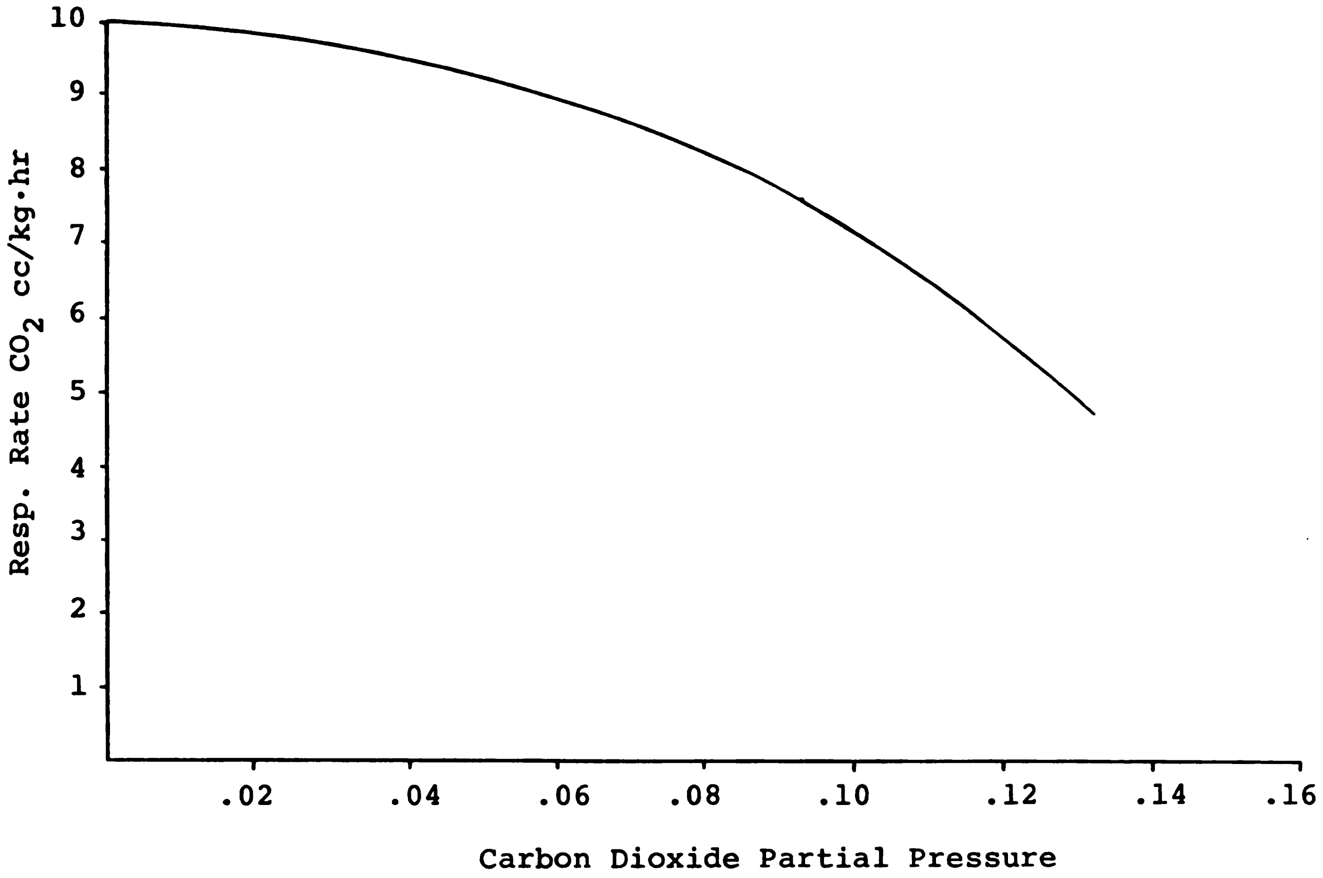

Figure 5.--Carbon Dioxide Effect on Respiration Rate of McIntosh Apples.

Source: Jurin, V. and Karel, M. (1963) "Studies of Control of Respiration of McIntosh Apples by Packaging Methods." _Food Technology._ 17(6):107.

gases that is dissolved in the apple sap.[27] The amount of soluble gas in the sap is dependent on physiological age of the apple, temperature and the atmosphere in the intercellular spaces. This atmosphere is dependent on the apple's external atmosphere and current respiration rate.[28] When the external atmosphere is altered, the respiration rate may not reach equilibrium for several days.

Research in measuring and controlling the solubility of oxygen and carbon dioxide in apple sap has been limited. Most horticulturalists have remained satisfied with quantifying the effects of external conditions on the apple's respiration. This theoretical study is based on their experimental findings.

Jurin and Karel also studied the effects of oxygen and carbon dioxide on the respiratory quotient (R.Q.). It was found that at 20°C, the R.Q. was 1.0 and remained at that relationship until the oxygen supply

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[27] J. C. Fidler and C. J. North, "The Effect of Conditions of Storage on the Respiration of Apples V. The Relationship Between Temperature, Rate of Respiration and Composition of Internal Atmosphere of the Fruit," Jrnl. Hort. Sci. (1971), 46:233.

[28] E. G. Hall, F. E. Huelin, F. M. V. Hackneys, and J. M. Bain, "Gas Exchange in Granny Smith Apples," VIII Congrés International Botanique (1954), p. 405.

fell below the extinction point (Figure 6).[29] Carbon dioxide did not effect the R.Q. (respiratory quotient) at any concentration.

Temperature Effect

Temperature has a great impact on respiration rate. A change of several degrees can have a significant effect on metabolism.[30]

There is a direct relationship between respiration rate and temperature. This relationship is commonly expressed in terms of Q_{10} coefficient. The Q_{10} for specific varieties, such as McIntosh, could not be obtained. Instead, the average Q_{10} for apples based on information from Recommended Conditions for Cold Storage of Perishable Produce (Table 2)[31] will be substituted for the unknown Q_{10} for McIntosh.

Table 3 has the calculated Q_{10} for temperature in three ten-degree ranges. The Q_{10} used for McIntosh is 2.77, the average Q_{10} of the Q_{10}'s in Table 3. A Q_{10} of 2.77 means that the respiration rate at 15°C is 2.77 times greater than the respiration rate at 5°C

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[29] V. Jurin and M. Karel, "Studies on Control of Respiration of McIntosh Apples by Packaging Methods," p. 107.

[30] F. Kidd and C. West, "The Gas Storage of Fruit II. Optimum Temperatures and Atmospheres," Jrnl. of Pomology (Hort. Sci.), (1930), 13:74.

[31] Recommended Conditions for Cold Storage of Perishable Produce, International Institute of Refrigeration (1967), p. 47.

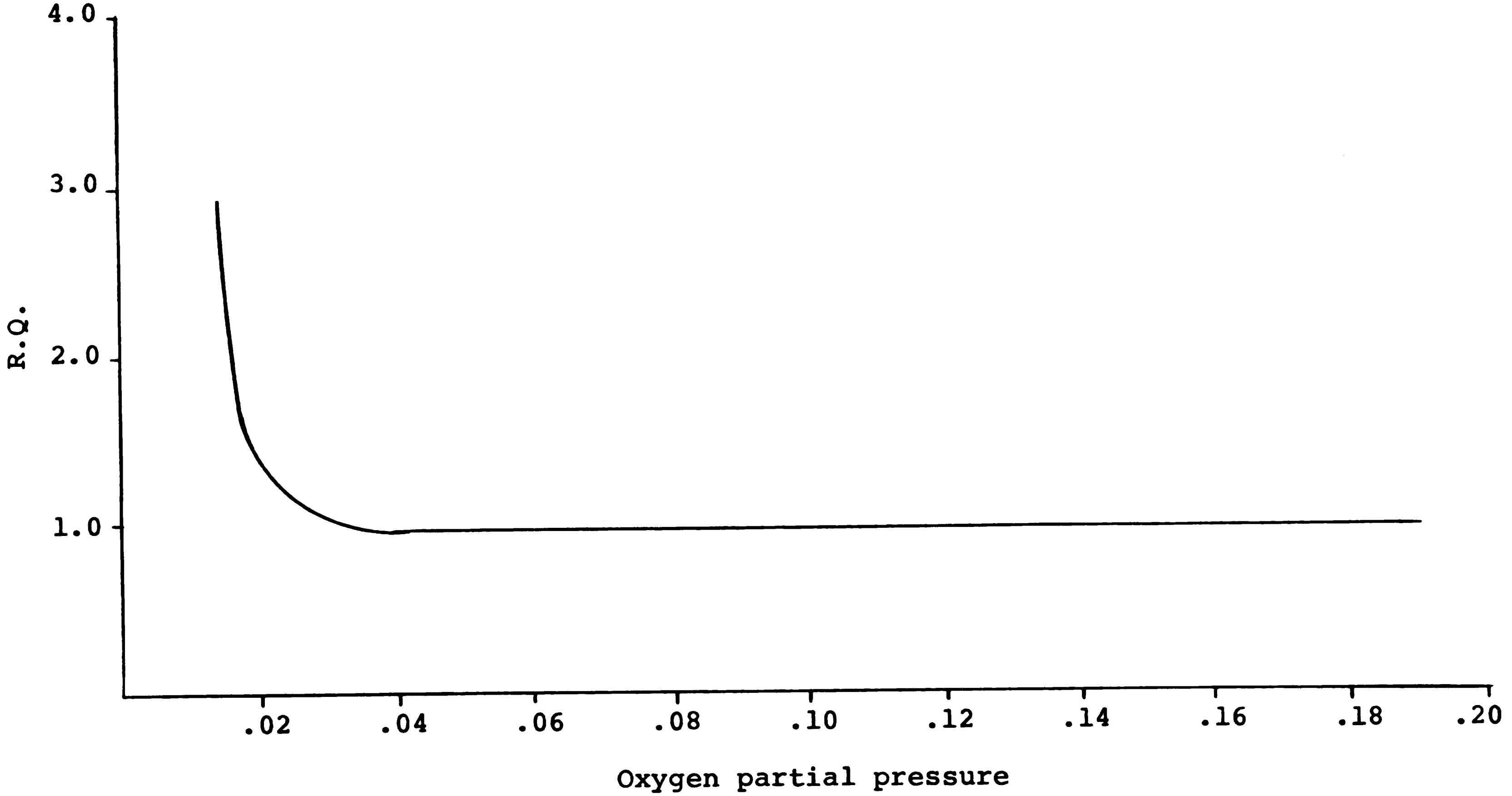

Figure 6.--Effect of Oxygen on Respiration Quotient.

Source: Jurin, V. and Karel, M. (1963). "Studies on Control of Respiration of McIntosh Apples by Packaging Methods." Food Technology. 17(6):107.

(10° less). The Q_{10} corresponds well with the data in the Agriculture Handbook,[32] which has an average Q_{10} of 2.85 in the same temperature range (Table 3).

TABLE 2.--Respiration Rates for Apples at Several Temperatures.

	Temperature				
	0°C 273°K	5°C 278°K	10°C 283°C	15°C 288°K	20°C 293°K
Early Ripening	800- 1420	1280- 2600	3400- 5000	4400- 7600	4800- 10000
Late Ripening	440- 880	1120- 1720	1680- 2560	2280- 4800	3600- 6000

Source: Agriculture Handbook 66, U.S. Department of Agriculture, Oct. 1968, pg. 8.

Heat of Respiration in BTU./ton/day.

TABLE 3.--Q_{10} of Apples for Different Temperature Ranges.

	Q_{10} 0°-10°	Q_{10} 5°-15°	Q_{10} 10°-20°	Ave. Q_{10}
Early Ripening	3.78	3.09	1.76	2.77
Late Ripening	3.21	2.49	2.26	

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[32] Agriculture Handbook 66, U.S. Department of Agriculture (October, 1968), p. 8.

CHAPTER IV

STORAGE

The duration of market life is primarily dependent upon physiological changes already accrued during the storage period.[33] Different methods of storage suppress the apple's physiological changes in varying degrees. The duration of maximum storage connotates the effectiveness of different storage methods.

In the following discussion, the two main methods of commercial storage will be described and compared.

Cold Storage

The temperature is held slightly above the temperature that would initiate low temperature breakdown, a physiological disorder.[34] The temperature is typically between -2°C and 1°C.

The cold storage temperature for McIntosh is 0°C. This temperature coincides with the lowest respiration

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[33] G. D. Blanpied and D. H. Dewey, "Quality and Condition Changes in McIntosh Apples Stored in Controlled Atmospheres," Quarterly Bulletin of Mich. Agr. Exp. Stn. (1960), 42(4):778.

[34] J. C. Fidler and C. J. North, "The Effect of Conditions of Storage on the Respiration of Apples," p. 204.

rate attainable without midifying the atmospheric conditions. The maximum cold storage life for McIntosh is two to four months.[35]

Cooling is rapid in cold storage. The temperature of the fruit is cooled from 20°C to 3°-4°C within five days. It is essential to establish storage conditions within a week.[36]

Cold storage aids in suppressing respiration, aging due to ripening, water loss and spoilage due to bacteria, fungi and yeast.[37] If the temperature is 2° or 3° above the optimum temperature, there is an increased danger of increased decay and unnecessary ripening.[38]

Controlled Atmosphere (CA) Storage

The atmospheric concentration of oxygen and carbon dioxide of CA storage will hinder the respiration of the organism. CA is used extensively for apples to extend storage life and marketability.[39]

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[35] *Agriculture Handbook 66*, p. 23.

[36] J. C. Fidler, et al., *The Biology of Apple and Pear Storage*, p. 33.

[37] *Agriculture Handbook 66*, p. 2.

[38] Ibid., p. 2.

[39] P. Veiraju and M. Karel, "Control of Atmosphere Inside a Fruit Container," *Modern Pkg.* (1967), 40(2):168; and A. Van Doren, "Physiological Studies with McIntosh Apples in Modified Atmosphere Cold Storage," p. 453.

Controlled atmosphere storage facilities consist of airtight store rooms that control oxygen concentration and carbon dioxide, as well as temperature. Apples are pre-cooled before being sealed in the storage rooms. The ideal atmospheric conditions are either achieved by artificial means or by letting the apples' respiratory process generate ideal conditions. The effect of these partial pressure changes is to decrease the respiration rate. Product-generated and artificially-generated atmospheres give identical storage results.[40] It may require two to three weeks to attain CA conditions.[41] The desired conditions are maintained by venting with cooled air and using carbon dioxide scrubbers.

The oxygen concentration is kept slightly above the extinction point to reduce the possibility of incurring anaerobic conditions. The temperature maintained in CA storage is generally several degrees higher than found in cold storage. The change in gas concentration elevates the temperature at which low temperature breakdown starts to appear.[42]

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[40] Fidler, et al., The Biology of Apple and Pear Storage, p. 33.

[41] Agriculture Handbook 66, p. 17.

[42] G. D. Blanpied and D. H. Dewey, "Quality and Condition Changes in McIntosh Apples Stored in Controlled Atmospheres," p. 774.

CA offers several advantages over cold storage. They are:

1. Carbon dioxide retards not only respiration, but also the germination and growth of fungi.[43]
2. Brown core, storage scald and mealy breakdown is retarded.[44]
3. Firmness is better maintained.
4. Ripening is significantly slowed down.[45]
5. Shelf-life after removal from storage is greatly lengthened.
6. Storage life is extended to 6-8 months.[46]
7. Climacteric is suppressed.

The retention of flesh firmness during CA storage is apparent from the results shown in Figure 7. The storage temperature was 3.5°C. Cold storage is associated with the greatest loss of flesh firmness, while all of the various modified atmospheres indicate some degree of maintaining firmness. The atmosphere 5:2 preserved the most firmness.

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[43] F. Kidd and C. West, "The Gas Storage of Fruit II. Optimum Temperatures and Atmospheres," p. 77.

[44] G. D. Blanpied and D. H. Dewey, "Quality and Condition Changes in McIntosh Apples Stores in Controlled Atmospheres," p. 778.

[45] F. Kidd and C. West, "Recent Advances in the Work on Refrigerated Gas-Storage of Fruit," p. 303.

[46] <u>Agriculture Handbook 66</u>, p. 23.

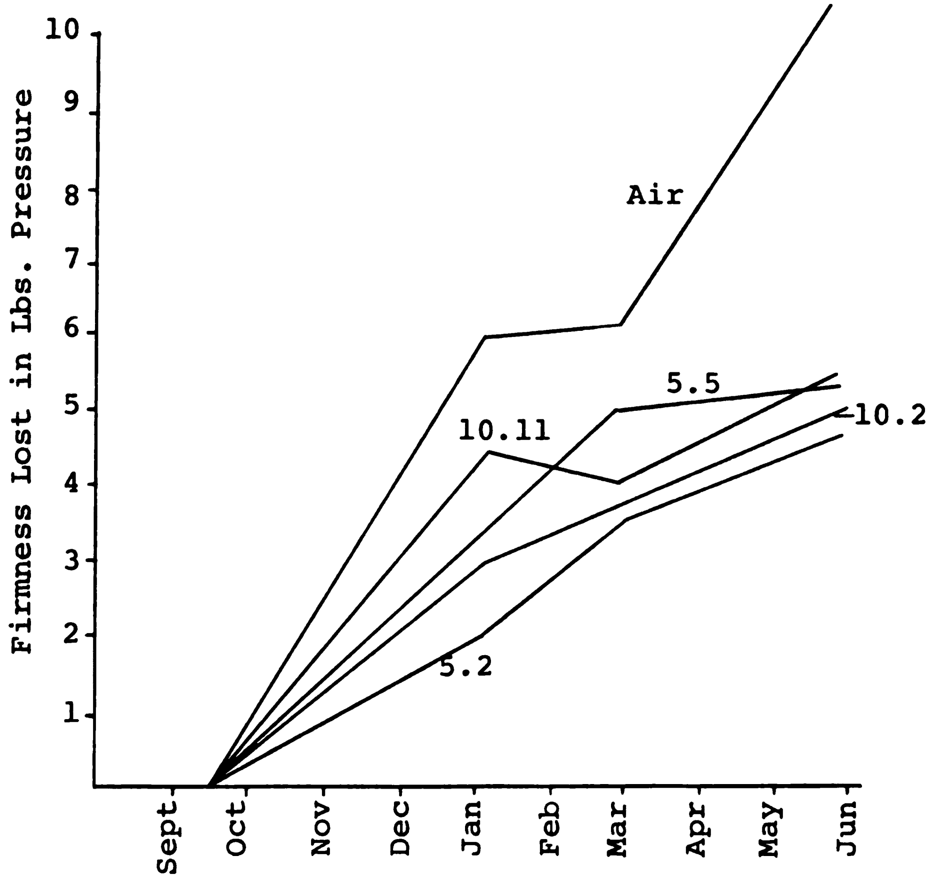

Figure 7.--Firmness losses of McIntosh apples at 40°F. Initial firmness approximately 15 pounds.

Source: Van Doren, A. (1937) "Physiological Studies with McIntosh Apples in Modified Atmosphere Cold Storage." <u>Proc. Am. Soc. Hort. Sci</u>. 37:455.

The atmosphere of 5:2 is sometimes used in lieu of 5:3 for McIntosh. However, this is not the general commercial practice. The risks of anaerobiosis offset the possible gains gotten at 5:2 rather than at 5:3.

Extending the market life after removal from storage (Figure 8) is almost as important commercially as extending the storage period. Extending the storage period only to have the quality to maintain for several weeks would hardly justify the added costs of CA storage. Fortunately, this is not the case with CA stored McIntosh apples. Modifying the atmosphere consistently preserves apple quality[47] and marketing life in comparison to cold storage.

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[47] T. Murata and T. Minamide, "Studies on Organic Acid Metabolism and Ethylene Production During Controlled Atmosphere Storage of Apples (Mallus pumila Miller, cv. Rolls)," Plant and Cell Physiology (1970), 11(3):857

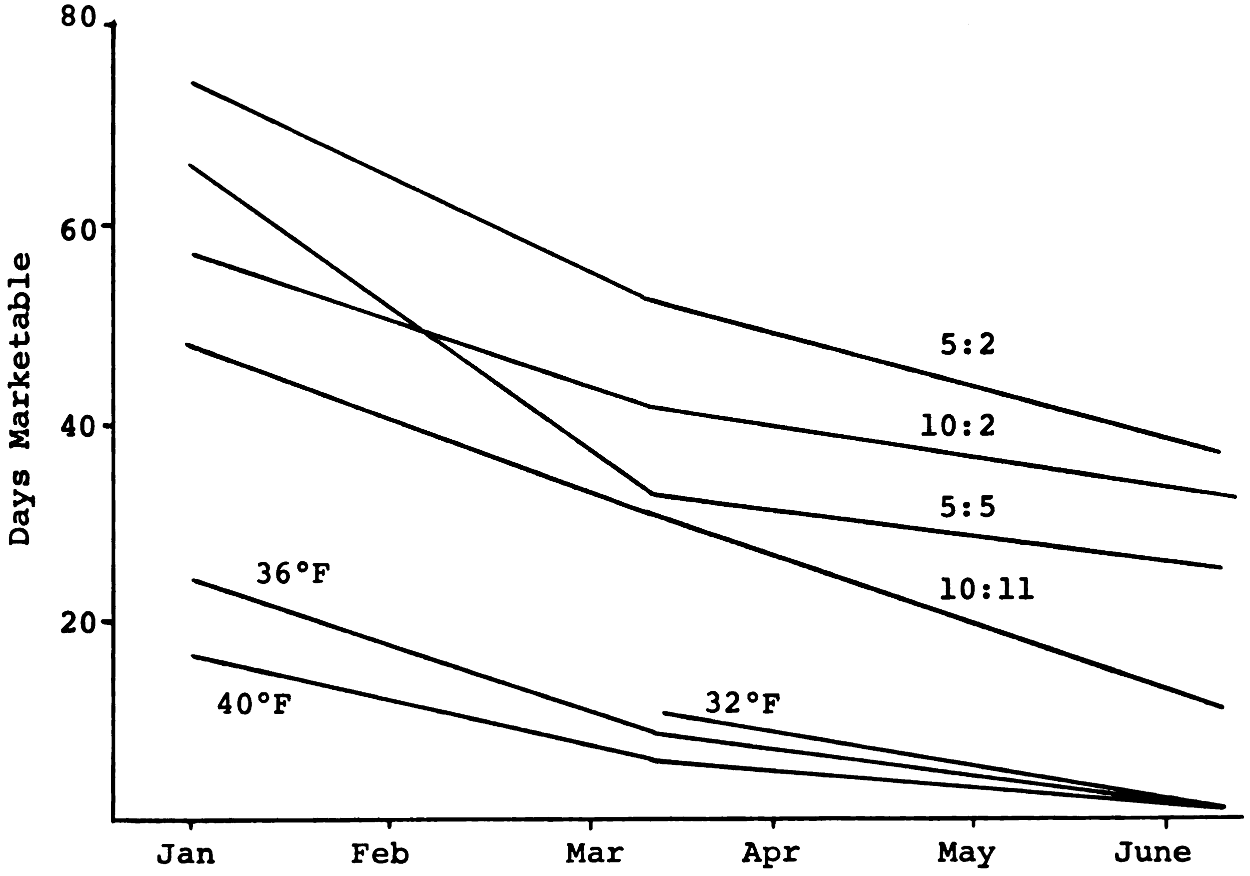

Figure 8.--Number of days McIntosh remain marketable after removal from storage and placed in air at 70°F.

Source: Van Doren, A. (1937). "Physiological Studies with McIntosh Apples in Modified Atmosphere Cold Storage." Proc. Am. Soc. Hort. Sci. 37:456.

CHAPTER V

THEORY FOR PRODUCT-GENERATED ATMOSPHERE PACKAGE

The hypothesis of this thesis is that it is possible to design a flexible package system that will provide longer storage life for fruits and vegetables (specifically, apples) than is possible with cold storage. If an atmosphere within a package is oxygen deficient and/or carbon dioxide rich, the metabolism will be suppressed. Metabolism is inversely related to storage life.

The intensity of metabolism is evidenced by the respiration rate. The rate of respiration is altered by changing temperature and partial pressure in the apples' environment. Metabolism can be depressed in a number of ways: decreasing oxygen concentration, increasing carbon dioxide concentration, decreasing temperature, or any combination of the three.[48]

This chapter is divided into five sections. The first section will present the variables that effect

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[48] F. Kidd and C. West, "The Gas Storage of Fruit II. Optimum Temperatures and Atmospheres," p. 67.

equilibrium concentrations. The next three sections quantify three of the variables: oxygen effect, carbon dioxide effect and temperature effect. The other variables are quantified in the Appendix. The final section depicts these variables in two theoretical equations. A computer simulation based on the two equations is presented in the Appendix.

Equilibrium conditions may not be achieved. Respiration has a minimum rate that corresponds with the extinction point in oxygen. If the net transmission rate for oxygen is less than the respiration rate when the partial pressure of oxygen is at the extinction point, the partial pressure will continue to decrease. Reducing the oxygen partial pressure below the extinction point will cause anaerobic respiration. Fermentation increases the respiration rate (Figure 9). This will cause a greater imbalance in the system because the oxygen supply is further depleted. Equilibrium will not be attained.

Section 1: Equilibrium Variables

The equilibrium is approached by two actions, a declining respiration rate and an increasing net transmission rate (Figure 10).[49] The barrier qualities and a

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[49] R. G. Tompkins, "Film Packaging of Fresh Fruit and Vegetables--the Influence of Permeability," The Inst. of Packaging Conference Guide, 1962, p. 66.

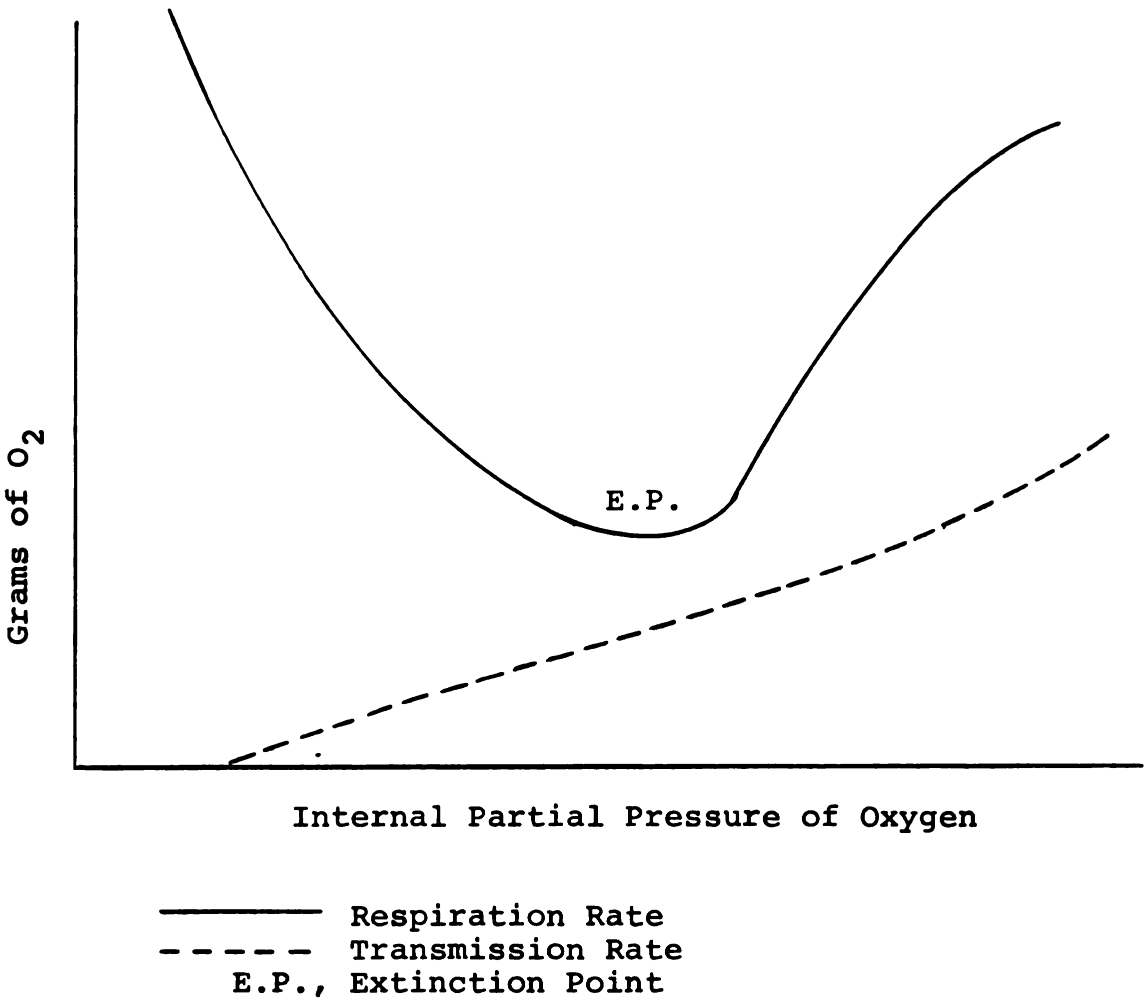

Figure 9.--Unbalanced System.

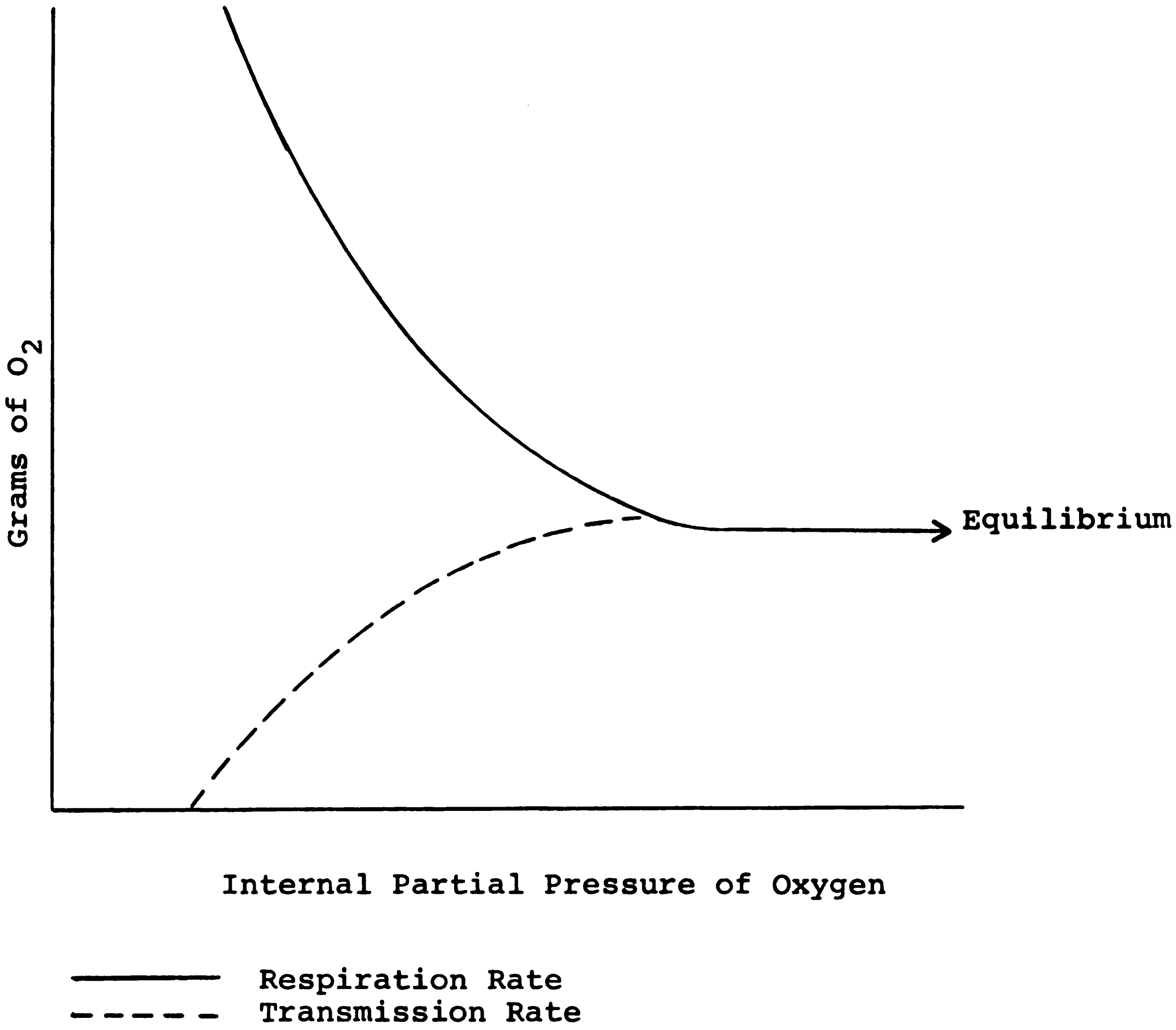

Figure 10.--Equilibrium Conditions.

respiring organism will provide a dynamic environment system that will continue to evolve until equilibrium conditions are reached. Equilibrium conditions are reached when the respiration rate is equal to the package's transmission rate of oxygen and carbon dioxide.[50]

The transmission rate and respiration rate are dependent upon a number of variables. The variables affecting transmission rate are:

1. permeability constant
2. film thickness
3. temperature
4. package surface area
5. activation energy for the film
6. concentration of oxygen
7. concentration of carbon dioxide
8. head space in the package.

The variables affecting respiration rate are:

1. apple variety
2. concentration of oxygen
3. concentration of carbon dioxide
4. temperature
5. respiratory quotient
6. total apple weight.

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[50] Ibid.

The interaction of these variables will determine the eventual atmosphere within a product-generated atmosphere package.[51]

Section 2: Oxygen Effect

Respiration rate is a function based on the effect of oxygen, carbon dioxide and temperature and can be written as $RR(P_{O_2}, P_{CO_2}, T)$. The effect of oxygen is based on Figure 4. This figures is simplified into a straight line (Figure 11). The oxygen effect can be written as:

$$6 + (22.2 \cdot \text{partial pressure of } O_2) \qquad (1)$$

based on line points (6.0, 0.03) and (10.0, 0.21).

Section 3: Carbon Dioxide Effect

The depressing effect of carbon dioxide is based on Figure 5. The results are represented by two connecting straight lines (Figure 12). The carbon dioxide effect for line AB can therefore be written as:

$$1.0 - 2.25 \cdot CO_2 \text{ partial pressure} \qquad (2)$$

based on points (1.0, 0.0) and (0.82, 0.08).

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[51] R. G. Tomkins, "The Conditions Produced in Film Packages by Fresh Fruits and Vegetables and the Effect of these Conditions on Storage Life," p. 293.

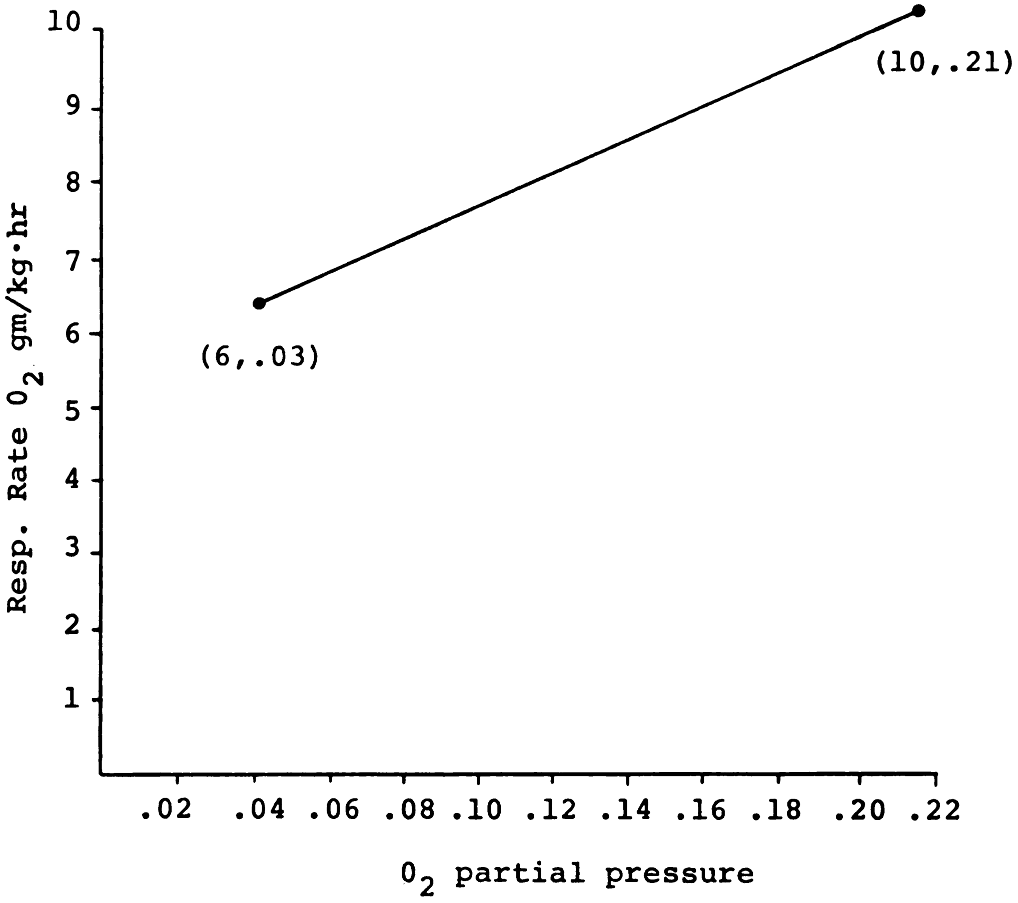


Figure 11.--Oxygen Effect on Respiration Rate of McIntosh.

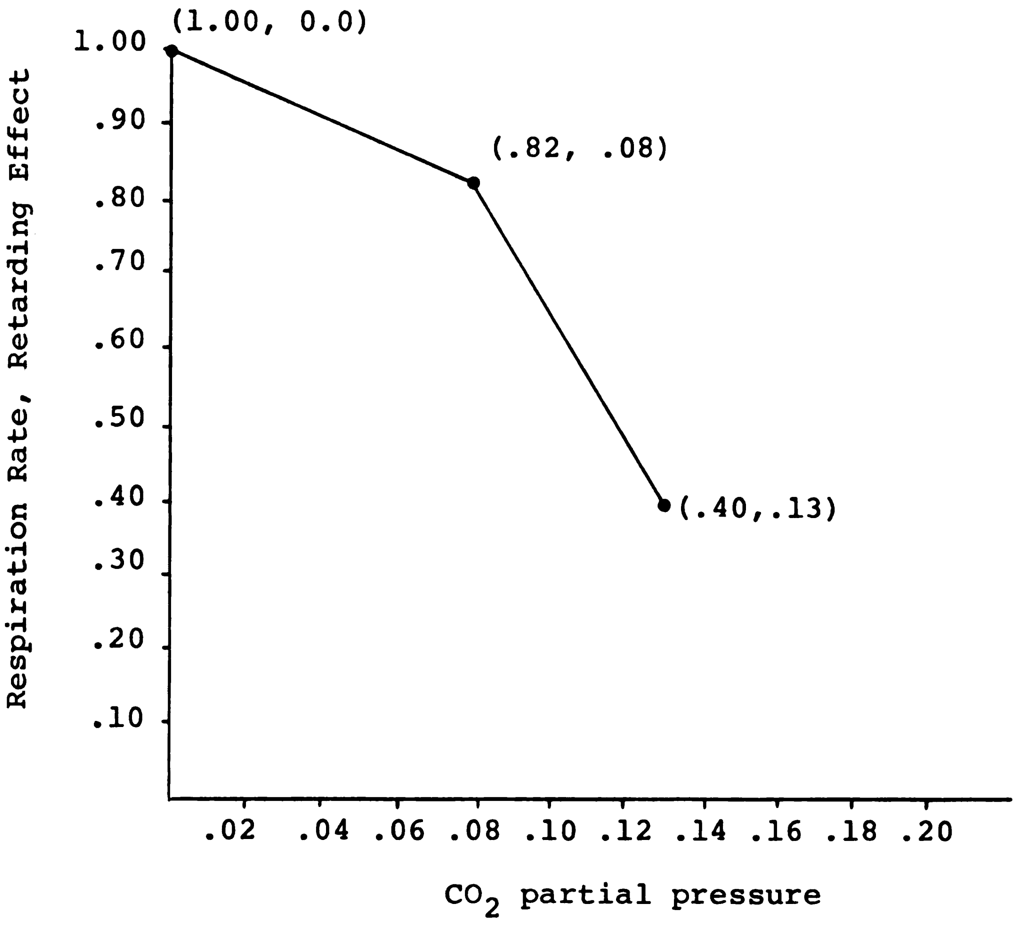


Figure 12.--Carbon Dioxide Effect on Respiration Rate of McIntosh.

The second line represents the effect of carbon dioxide of a partial pressure at or above 0.08. The equation for line BC based on points (0.82, 0.08) and (0.40, 0.13) is:

$$.82 - 6.6 \cdot (CO_2 \text{ partial pressure}) - 0.08 \qquad (3)$$

The values generated from equations (2) and (3) are in the form of percentages. The product of equations (2) or (3) with equation (1) reflect the additive effect of carbon dioxide and oxygen on the respiration rate.

Section 4: Temperature Effect

The temperature effect is based on a Q_{10} of 2.77. The following statement is made to quantify the temperature effect on respiration rate:

$$e^x \left[-8181 \cdot \left(\frac{1}{T} - \frac{1}{293}\right)\right] \qquad (4)$$

if $$\frac{RR_{293°K}}{RR_{283°K}} = 2.77 \qquad (5)$$

then $$\frac{RR_{283°K}}{RR_{293°K}} = 0.36 \qquad (6)$$

$$0.36 = e^x \left[\frac{\Delta H}{R} \cdot \left(\frac{1}{283} - \frac{1}{293}\right)\right] \qquad (7)$$

$$\frac{\Delta H}{R} = \frac{\ln 0.36}{\frac{1}{283} - \frac{1}{293}} \qquad (8)$$

$$\frac{\Delta H}{R} = -8470$$

This is the temperature effect between 10°C and 20°C. The temperature effect between 0°C and 10°C is:

$$.36 = e^{x}\left[\frac{\Delta H}{R} \cdot \left(\frac{1}{273} - \frac{1}{283}\right)\right] \qquad (9)$$

$$\frac{\Delta H}{R} = -7892$$

The average of the two $\frac{\Delta H}{R}$ is -8181.

Section 5: Theoretical Equations

The definitions of symbols used in this discussion are:

A = surface area of package in square centimeters.

dp_{CO_2} = derivative of partial pressure of carbon dioxide.

dp_{O_2} = derivative of partial pressure of oxygen.

dt = derivative of time

$p_{CO_2}^{e}$ = external partial pressure of carbon dioxide.

$p_{CO_2}^{i}$ = internal partial pressure of carbon dioxide.

$\tilde{P}_{CO_2(T)}$ = permeability constant for carbon dioxide at temperature T°K, where "K" is degrees absolute.

p_O = atmospheric pressure.

$p_{O_2}^{e}$ = external partial pressure of oxygen.

$p_{O_2}^{i}$ = internal partial pressure of oxygen.

$\tilde{P}_{O_2(T)}$ = permeability constant for oxygen at T°K.

R = gas constant

$RR(p_{O_2}, p_{CO_2}, T)$ = respiration rate in grams of carbon dioxide per kilogram product per hour as a function of the partial pressure of oxygen and carbon dioxide and the temperature.

$S_{CO_2(T)}$ = solubility of carbon dioxide in apple sap in grams carbon dioxide per kilogram apple sap as a function of temperature.

$S_{O_2(T)}$ = solubility of oxygen in apple sap in grams oxygen per kilogram apple sap as a function of temperature.

T_o = standard temperature, 0°K.

W_A = weight of apples in kilograms.

x = film thickness in centimeters.

V = combined void volume of gas in cubic centimeters of package head space and intercellular spaces in the apples.

32 = molecular weight of oxygen.

44 = molecular weight of carbon dioxide.

The initial supply of oxygen and carbon dioxide within the package can be represented as:

$$\text{(initial } O_2 \text{ supply)} \quad S_{O_2(T)} \cdot W_A + \frac{32 \cdot V}{R \cdot T} \tag{10}$$

$$\text{(initial } CO_2 \text{ supply)} \quad S_{CO_2(T)} \cdot W_A + \frac{44 \cdot V}{R \cdot T} \tag{11}$$

The supply includes gas that is in apple sap, intercellular spaces and package headspace or void.

The transmission rate of oxygen is represented as:

$$\tilde{P}_{O_2(T)} \cdot \frac{32 \cdot P_O}{R \cdot T_o} \cdot \frac{A}{x} \cdot (p_{O_2}^{e} - p_{O_2}^{i}) \tag{12}$$

Carbon dioxide transmission rate is represented as:

$$\tilde{P}_{CO_2(T)} \cdot \frac{44 \cdot P_O}{R \cdot T_o} \cdot \frac{A}{x} \cdot (p_{CO_2}^{e} - p_{CO_2}^{i}) \tag{13}$$

Combining the respiration function (equations (1) and (2)), initial gas supplies (equations (10) and (11)), and the representations for transmission rates (equations (12) and (13)) can be simplified into two theoretical equations. The equation for oxygen is:

$$[S_{O_2(T)} \cdot W_A + \frac{32 \cdot V}{R \cdot T}] \cdot \frac{dp_{O_2}}{dt} = [\tilde{P}_{O_2(T)} \cdot \frac{32 \cdot P_O}{R \cdot T_o} \cdot \frac{A}{x} \cdot (p_{O_2}^{e} - p_{O_2}^{i})] - [RR(p_{O_2}, p_{CO_2}, T) \cdot W_A] \tag{14}$$

The second equation, which represents carbon dioxide evolution within the package, is:

$$[S_{CO_2}(T) \cdot W_A + \frac{44 \cdot V}{R \cdot T}] \cdot \frac{dp_{CO_2}}{dt} = [\tilde{P}_{CO_2}(T) \cdot \frac{44 \cdot P_O}{R \cdot T_o} \cdot \frac{A}{x} \cdot (p_{CO_2} - p_{CO_2})] + [RR(p_{O_2}, p_{CO_2}, T) \cdot W_A] \tag{15}$$

Equations (14) and (15) provide the basis for the computer model. The computer model is presented and described in the appendix.

CHAPTER VI

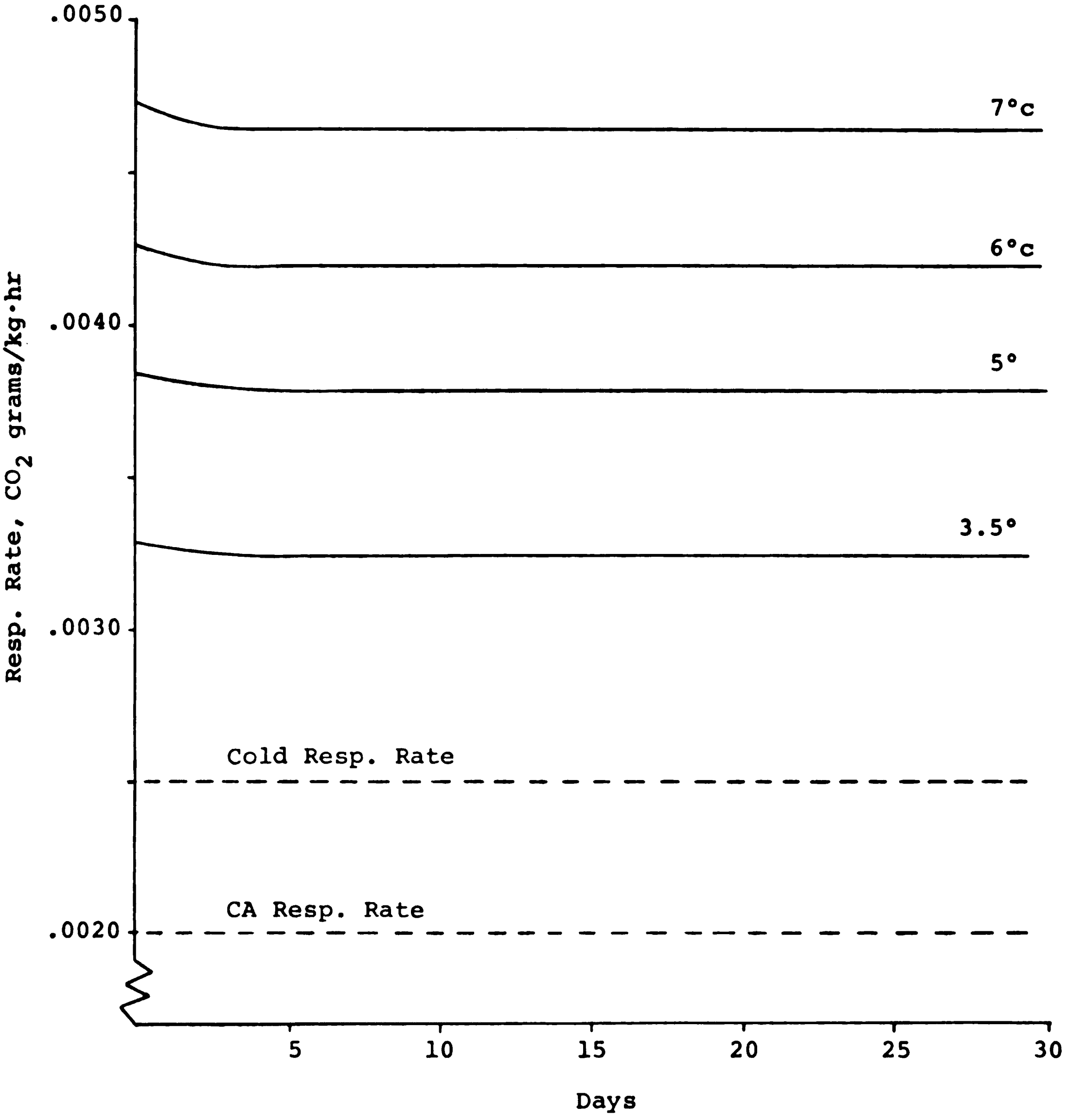
SIMULATION RESULTS

In this chapter the results from the simulation of the three films are presented. This is in Section 1. The following two sections discuss the effect of film thickness and pallet-sized product-generated atmosphere packages, respectively.

Section 1: Films

The respiration rate and package atmosphere are affected by the film used. Respiration rate at equilibrium is directly related to the permeability constants.

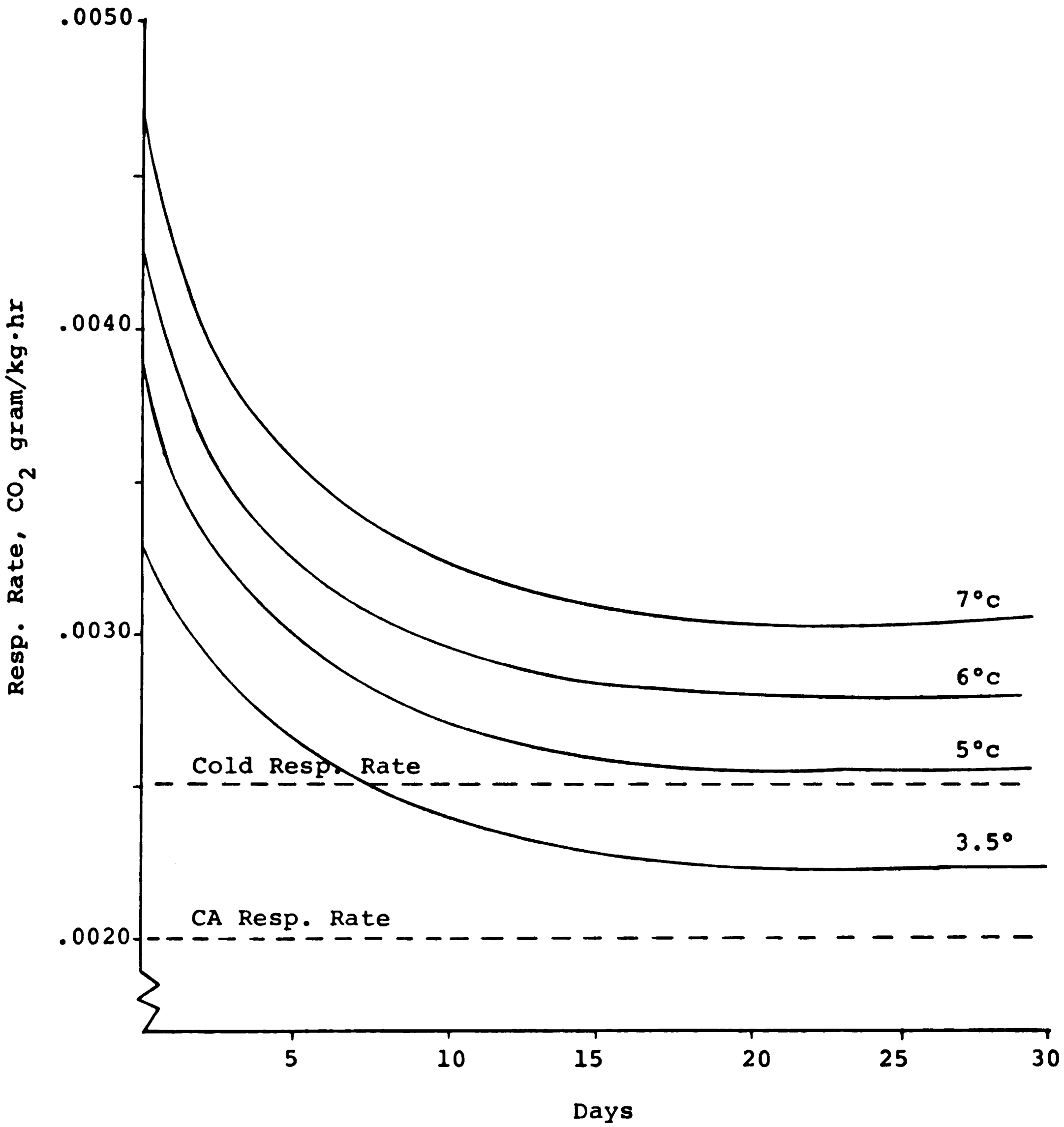
Figures 13, 14 and 15 denote the downward trend of respiration at the different temperatures over a thirty day period for the three films. The two horizontal lines in each figure represent the respiration rates of cold storage and CA storage. The cold storage respiration rate corresponds with .0025 grams CO_2/Kg x hr. The CA respiration rate is the lower of the two lines and represents a rate of .0020 grams CO_2/Kg x hr.



$\tilde{P}_{o2} = 2.44 \times 10^{-4}$

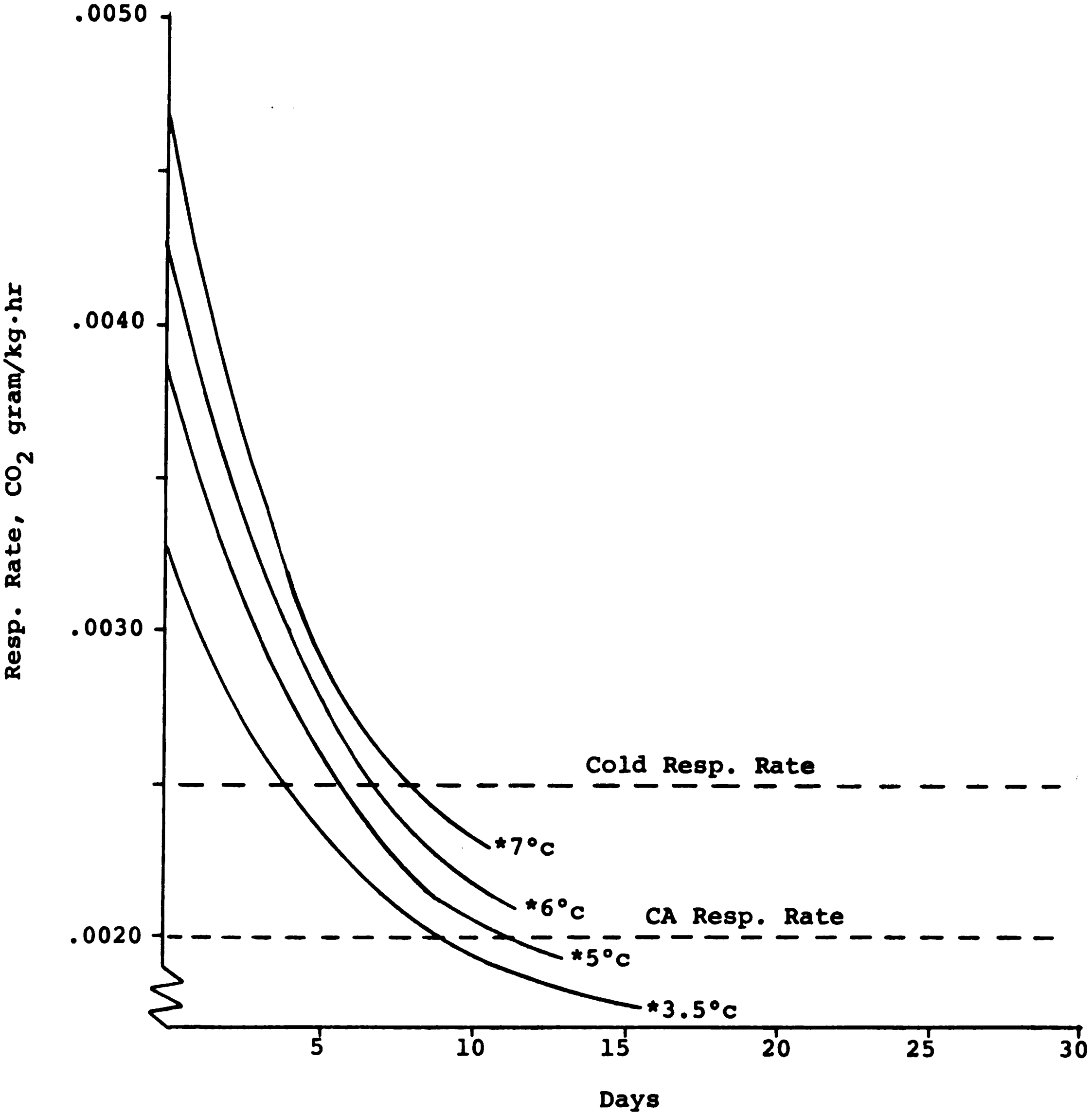
$\tilde{P}_{co_2} = 1.47 \times 10^{-3}$

Figure 13.--Results of One Mil Cellulose Acetate Simulations.



$\tilde{P}_{o2} = 1.75 \times 10^{-5}$
$\tilde{P}_{co_2} = 8.8 \times 10^{-5}$

Figure 14.--Results of One Mil Low Density Polyethylene Simulations.



* anaerobic conditions, simulation terminated

$\tilde{P}_{o2} = 8.57 \times 10^{-6}$

$\tilde{P}_{CO_2} = 2.97 \times 10^{-5}$

Figure 15.--Results of One Mil Polybutadiene Simulations.

These two respiration rate values were calculated from the FUNCTION RESP of the model in the appendix. The environmental values of cold storage and CA storage were substituted into the model.

The cold and CA respiration rates are important in the analysis of the data. These two respiration rates are reference points in analyzing the effectiveness of the packages. The package would be effective in extending storage life if the respiration rate is below the respiration rate of cold storage. The respiration rate is an index of storage potential.

Cellulose acetate (Figure 13) is not an effective package. It is not effective because the final respiration rate at the lowest temperature, 3.5°C, is .0032. This rate is greater than the cold storage respiration rate (.0025). The storage life provided by this package would be less than the storage life attained through cold storage conditions.

The low density polyethylene (Figure 14) provided a package option that will extend storage life. In an ambient temperature of 3.5°C, an effective respiration is achieved. The respiration rate is .0022. Within seven days, the respiration was below .0025. The respiration rate was still falling after thirty days, indicating that equilibrium conditions had not been reached.

The oxygen concentration at the end of the simulation was .0491. This partial pressure was almost .02 above the extinction point. In order to state with confidence that this package would extend storage life, an additional simulation was made. The duration of the simulation is 210 days, or 7 months.

The results of this simulation are presented in Figure 16. The equilibrium conditions are: 4.716% oxygen, 3.289% carbon dioxide, and a respiration rate of .00220 grams carbon dioxide/Kg x hr. It can now be stated that the low density polyethylene package at 3.5°C is effective.

The barrier properties of polybutadiene are too restrictive (Figure 15). Anaerobic conditions are established at all temperatures. Less than 3% oxygen was reached within 11 to 15 days.

Table 4 is a summary of the simulations. The values represent the conditions at the 30th day of the simulation, unless anaerobic conditions develop. In event of anaerobiosis, the values are taken from the day that anaerobic fermentation initiated.

Section 2: Thickness

Changing the thickness will alter the equilibrium of the package. Increasing the thickness is similar to using a less permeable material.

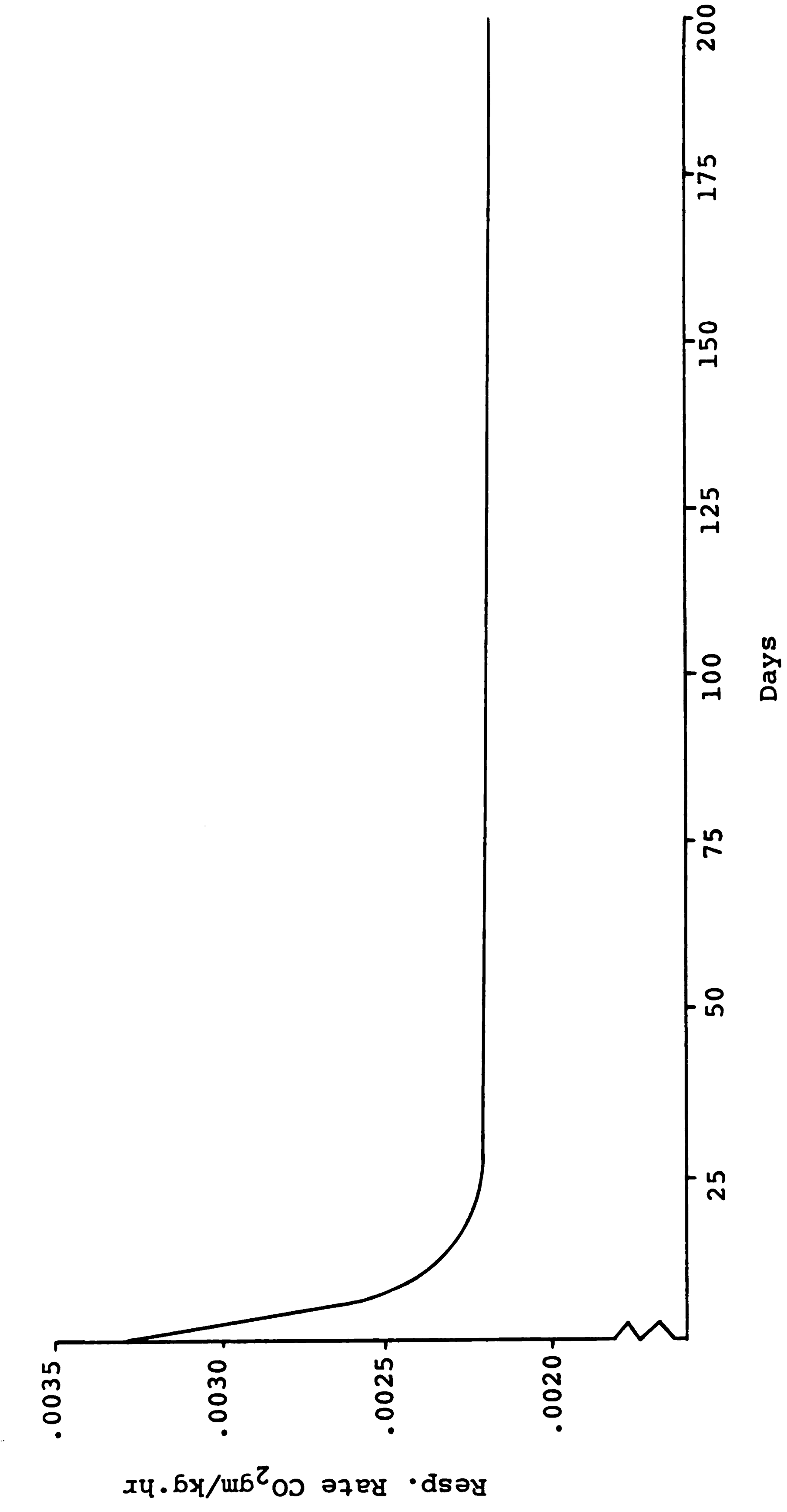


Figure 16.--Low density polyethylene, extended simulation at 3.5°C.

TABLE 4.--Summary of Program Simulation.

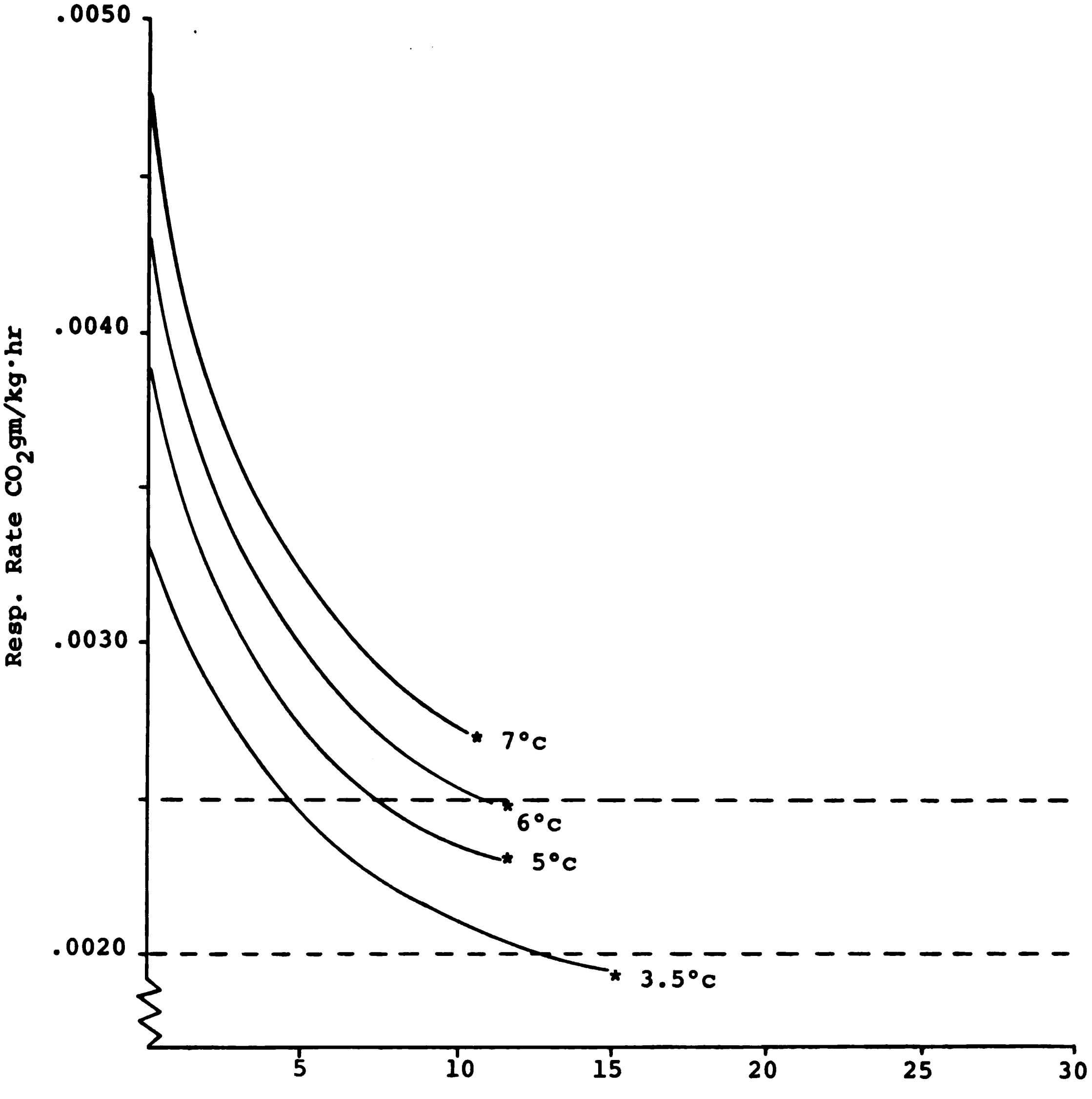
Film	Temp. °C	Final ppO_2	Final $ppCO_2$	Final RR
Cellulose Acetate	3.5	.1906	.0035	.003249
	5.0	.1882	.0038	.003790
	6.0	.1865	.0040	.004196
	7.0	.1848	.0043	.004641
Low Density P.E.	3.5	.0491	.0331	.002207
	5.0	.0417	.0347	.002528
	6.0	.0369	.0358	.002766
	7.0	.0322	.0369	.003023
Polybutadiene	3.5	.0281*	.0874	.001738
	5.0	.0244*	.0928	.001928
	6.0	.0278*	.0964	.002094
	7.0	.0259*	.0998	.002240

*Anaerobic Condition.

The thickness of the low density polyethylene in Section 1 was increased from one mil to two mils. The results of the 2 mil simulation was anaerobic conditions at all temperatures (Figure 17). Anaerobic conditions were reached in 10-15 days. The outcome for 2 mils is similar to the results of the least permeable material in Section 1, ploybutadiene.

Section 3: Pallet-sized Product-generated Atmosphere Package

The commercial impact of product-generated atmosphere packages is significant. The model is based on a five-pound retail package. The impact would be



*anaerobic conditions, simulation terminated.

Figure 17.--Two Mil Low Density Polyethylene.

maximized if the concept of product-generated atmosphere packages could be applied to storage containers. Most of Michigan apple growers store apples in pallet bins instead of the retail package.[52]

The apples are placed in pallet bins at time of harvest. The base of the bin is a standard pallet size (40 inches x 48 inches) and is 32 inches in height. The weight capacity is 1100 - 1200 pounds.

Once at the warehouse, the bin and apples are drenched with a fungicide and water solution. The bins are then moved to storage and rapidly cooled. The apples are then retail-packaged and shipped, according to sales demand.

This system is advantageous to immediate retail packaging on three counts. This first advantage is that an employment level can be regulated. Immediate retail packaging means that all the packaging efforts are concentrated during the harvest season.

The labor force already fluctuates on a seasonal basis. Immediately packaging the apples would amplify the fluctuations in employment. Harmonizing packaging with sales demand would have stabilizing effects on the growers' workforce.

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[52] Unpublished apple storage information, March 1976, Richard Patterson, School of Packaging, Michigan State University, East Lansing, Michigan.

A second advantage is that a bottleneck in the packaging operation can be avoided. In order to package the fruit as it is harvested, the operation would need an enormous capacity. The investment to accommodate a high capacity, short-duration packaging operation may be prohibitive for most growers. By the grower packaging as the demands require, a more moderate size operation can fulfill the packaging needs.

The final advantage is that better quality fruit will reach the retail market. It is inevitable that handling operations, such as sorting and packaging, bruise some of the fruit. Bruises are not visible immediately and lead to deterioration. If the fruit is packaged and then stored for several months, the bruises incurred from the packaging operation will initiate deterioration. By the time the fruit reaches the market, the bruised apples from the packaging operation will be inferior in quality.

Storing in pallet bins minimizes the handling prior to storage. This in turn will eliminate much of the rotting. Whatever damaged fruit there is at the time of packaging can be sorted out during the pre-packaging operation. This type of operation would enable greater numbers of high-quality fruit to reach the retail market.

A simulation was conducted with the pallet bin as the product-generated atmosphere package. The pallet bin would be more practical than a five-pound package in current storage operations.

Only low density polyethylene film was in the simulations. The change in package size to 40" x 48" x 32" necessitates changes in the package's parameters. These changes are:

1. Weight is based on 1200 pounds. This is 545,454 grams.
2. Package void space is 685,542 cm^3.
3. Film area is 61,111 cm^2.
4. Film thickness is 1.5 mil.[53]

Low density polyethylene was not successful in producing a beneficial atmosphere (Figure 18). The extinction point for oxygen was reached within 7 to 10 days, depending on the temperature.

The carbon dioxide accumulations are in excess of 12 percent at all four temperatures. This accounts for the extremely low respiration rates in the simulations. Such high partial pressures are not used in conjunction with low oxygen partial pressures. The physiological disorder, carbon dioxide injury, is a problem at the higher carbon dioxide concentrations.

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[53] D. H. Dewey, H. J. Raphael and J. W. Goff, "Polyethylene Covers for Apples Stored in Bushel Crates on Pallets," Quarterly Bulletin, Mich. Agri. Exp. Stn., (1959), 42(1):197.

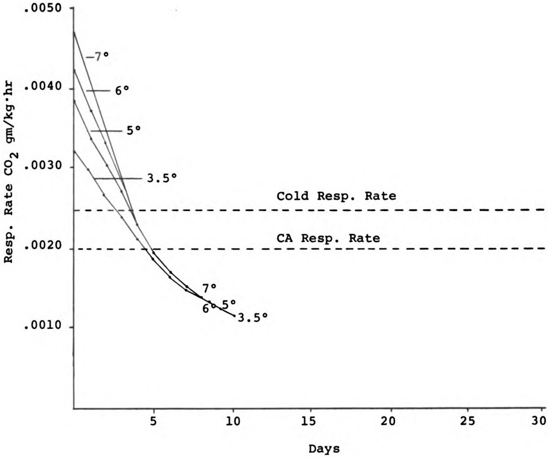

Figure 18.--Low Density Polyethylene 1.5 mil Pallet Bin.

In summary of this chapter, it is possible to produce a beneficial atmosphere within a package. Each package variable has a significant effect on the equilibrium and must be consolidated into the package system.

CHAPTER VII

ECONOMICS

In order to analyze the various storage costs of cold storage, CA storage and product-generated atmospheres storage packages on a monthly basis, it is necessary to determine the maximum storage life of each type of storage. Based on Figure 19, the cold storage of McIntosh is depleted after approximately four months and the last CA storage apples are predicted to be sold after about seven months. The monthly storage costs are based on four months and seven months, respectively, for cold storage and CA storage. The results in Chapter VI indicated that the optimum product-generated atmosphere package was one mil low-density polyethylene at 3.5°C. Based on the theoretical respiration rate (Figure 14) the maximum storage life from this package is assumed to be six months.

Implementation of the product-generated atmosphere package would affect five cost areas of storage: building and equipment, labor, management, storage supplies/repairs, and energy.

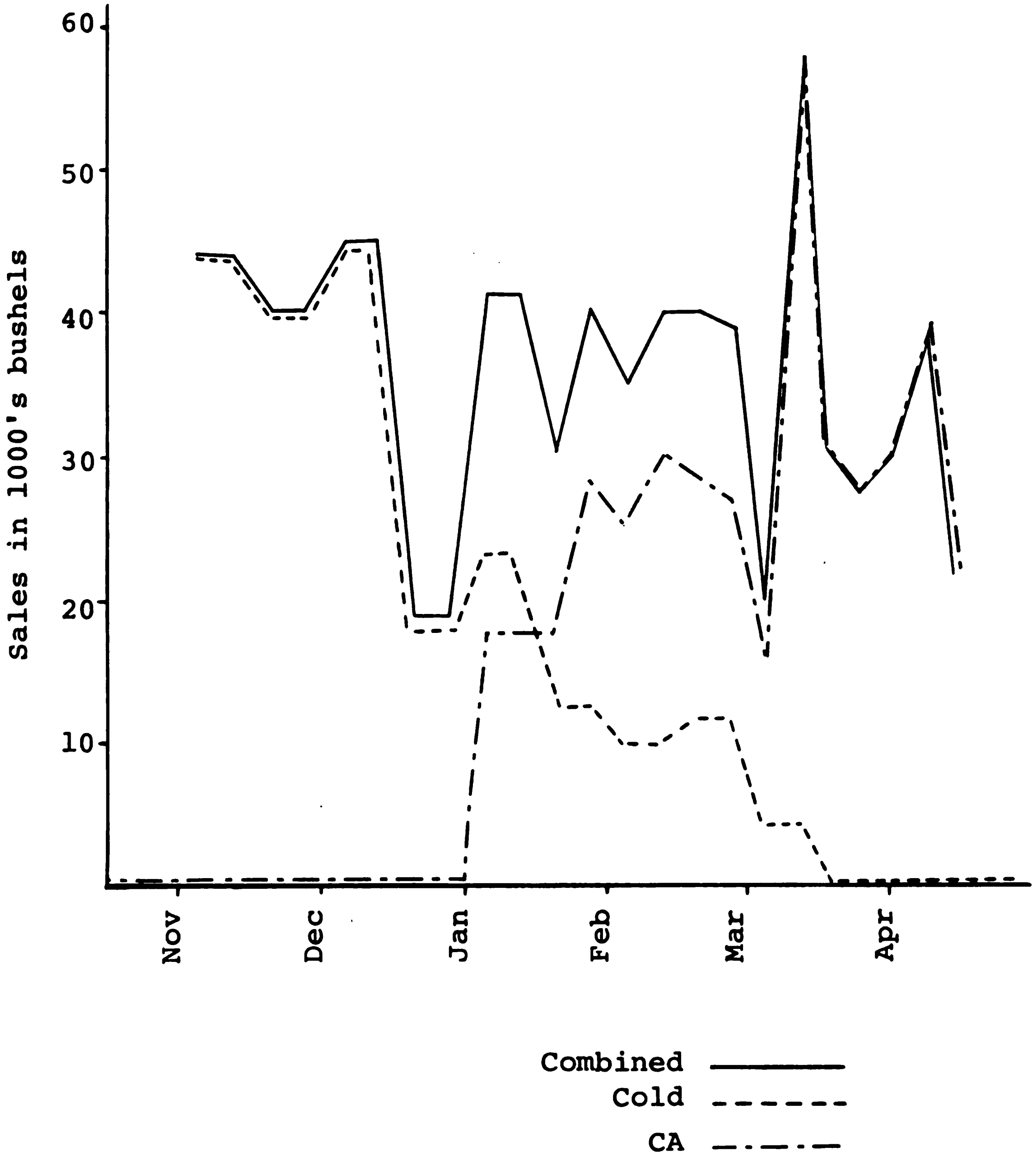

Figure 19.--Michigan 1976 McIntosh Sales Cold, CA and Combined.

Packaging material costs are not effected. The current retail package and the product-generated atmosphere package both utilize one mil low density polyethylene. Therefore, packaging material costs have not been included in this cost analysis.

The average size cold storage warehouse in Michigan accommodates 72,000 bushels of apples and the average capacity for CA storage warehouses is 80,000 bushels.[54] The cost analysis is based on the average size cold and CA storage warehouses.

All cost figures are based on unpublished work by Brown and Pierson.[55] The costs in this work are expressed in a per storage season basis. To reduce the costs to costs per month, the cold storage seasonal costs were divided by four and the CA storage costs were divided by seven. The description of the various cost areas is based on work done by Mathia[56] unless otherwise referenced.

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[54] Unpublished apple packing cost information, December, 1975. N Brown, County Building, Grand Haven, Michigan and T. Pierson, Dept. of Agri. Econ., MSU, East Lansing, Michigan, pp. 7-10.

[55] Ibid., pp. 9-10.

[56] G. A. Mathia, "Cost of Storing North Carolina Apples," Economics Information Report No. 5, N.C. State University (1967), pp. 8-19.

Section 1: Building and Equipment

Building and equipment costs command the total investment costs. The difference in investment costs between cold and CA storage is significant. Buildings and equipment have an expected life of 25 years.[57]

The storage process for cold storage is a simple procedure that requires only the monitoring and control of temperature. Building and equipment costs are $13.00 per square foot. Interest and depreciation amounts to $.136/bushel/year. Interest and depreciation accrue throughout the year, even though the buildings may be empty much of the time. The income from the storage season must be used to meet interest and depreciation expenses. Therefore, the yearly interest and depreciation expense must be offset by profits from the storage season. This expense will amount to $.0340/bushel/month.

CA storage and equipment is more sophisticated than that found in cold storage. It is necessary that the structure has airtight storage rooms and equipment to measure and maintain the gas components, as well as the storage temperature. The building and equipment costs are based on a cost of $21.00 per square foot. Interest and depreciation amounts to $.291/bushel/year (storage season). This will be a monthly expense of $.0416.

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[57] *Ibid.*, p. 9.

Product-generated storage packages would utilize cold storage facilities. Building and equipment costs are the same for storage packages as for cold storage. The cost for the storage season is \$.136/bushel/6 months, or \$.0227/bushel/month.

Section 2: Labor

Labor costs are essentially the same in cold storage and CA storage. Both storage methods require placing fruit into storage,[58] removing fruit from storage and daily monitoring storage conditions and appraising fruit quality.

The average wage is essentially the same in either storage method. The average hourly wage for labor in cold storage is \$3.35/hr and for CA it is \$3.39/hr. Labor time per bushel is nine seconds for cold storage (4-mongh storage period) and eighteen seconds for CA storage (7-month storage period).

Labor costs for cold storage is \$.01/bushel/4 months, or \$.0025/bushel/month. The seasonal labor cost of CA storage is \$.018/bushel/7 months. The monthly cost is the same as cold storage, \$.0025/bushel/month.

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[58] J. C. Thompson, "Apple Storage Costs in New York State," Agricultural Experimental Station, Res. 87 (1962), p. 23.

This monthly labor cost, $.0025, is used for product-generated atmosphere packages. The seasonal cost would be $.015/bushel/6 months.

Section 3: Management

The hourly costs for management for both storage methods is $6.69/hr. The time spent per bushel in cold storage (4 months) was three seconds or $.006/bushel/4 months, or $.0015/bushel/month. Management costs for CA storage (seven months) was somewhat higher. Management was costed at 8 seconds per bushel. This is $.016/bushel/7 months, or $.0023/bushel/month.

It is not clear what the difference between $.0015 and $.0023 is attributed to. It is assumed here that the management costs for the product-generated storage package will be the higher of the two, or $.0023/bushel/month. This would be a seasonal cost of $.138/bushel/6 months.

Section 4: Storage Supplies and Repairs

Other than supplying refrigerant, few supplies and repairs are needed for cold storage. However, CA storage requires the purchase of carbon dioxide scrubbers, such as caustic soda, which is a significant expense. Additional expenses, although minor, would be caulking compound and charcoal.

Repairs are also more costly for CA storage than cold storage. Before each season, the storage rooms are inspected, renovated and repaired to maintain air-tightness. During the storage period there is a continual effort to prevent gas leaks and maintain the equipment used in monitoring the storage atmosphere.[59]

Therefore, the costs in this category are $.055/bushel/7 months of CA and $.011/bushel/4 months for cold storage. The month costs per bushel for CA and cold storage are $.0079 and $.0028, respectively.

Product-generated atmosphere packages would utilize the same facilities as cold storage. Monthly costs for storage supplies and repairs should not be affected ($.0028/bushel/month). Since the storage season lasts six months or 50 percent longer, seasonal supply and repair costs will reflect the extra use. The seasonal cold storage cost for supplies and repairs will be increased 50 percent to represent these costs for product-generated atmosphere packages. The seasonal cost per bushel is $.0165.

Section 5: Energy

Energy is the main component of operating costs. Energy used to operate refrigeration and CA equipment

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[59] Ibid., pp. 28-29.

is the primary energy expense. Energy requirements for lights and miscellaneous items are insignificant.

On a month to month basis, energy expenses are erratic. The first month of storage has the greatest energy requirement because of the need to rapidly cool the apples. The following months also fluctuate because of changes in seasonal temperatures. In this analysis, the energy costs are a per-month average for the storage season.

The energy expenses for cold storage is $.06/bushel/4 months, or $.015/bushel/month, and, for CA storage, is $.13/bushel/month, or $.0186. CA storage maintains a temperature of 3.5°C for McIntosh as opposed to +.5°C in cold storage. The energy required for refrigeration during the first four months of CA storage would be less than the energy needed for four months of cold storage. However, this lower energy requirement is offset by the power needed to refrigerate during the succeeding months, which will be warmer, and the operation of carbon dioxide scrubbers and other CA equipment.

The optimum temperature of the atmosphere for a product-generated storage package is 3.5°C. To achieve this temperature inside the package, a lower storage temperature will be needed. It has been shown that at the same storage temperature, crates with polyethylene liners have an internal temperature that is 1°C greater than unlined crates. These were unsealed liners.[60] When air flow is restricted, a lower temperature is necessary to maintain the temperature of the air around the apple.

If a sealed package were used, it is conceivable that the storage temperature needed to establish a 3.5°C internal temperature may be close to the cold storage temperature of 0-1°C.

When comparing the energy expense of product-generated storage packages to CA storage, the added refrigeration cost for the storage packages is partially offset by several factors. Refrigeration for the product-generated storage packages does not include the seventh month, May, which is the warmest storage month. Also, the storage packages would not utilize a carbon dioxide scrubber or most of the other CA equipment, all of which require energy to operate.

From this discussion, it is assumed that the energy requirements for CA and product-generated storage packages are approximately the same, $.0186/bushel/month. The seasonal energy costs would be $.1116/bushel/6 months.

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[60] D. H. Dewey, H. J. Raphael, and J. W. Goff, "Polyethylene Covers for Apples Stored in Bushel Crates on Pallets," p. 206.

Section 6: Summary

The storage costs for the three methods are summarized below. Costs are presented on a monthly and a seasonal basis.

Table 5 summarizes costs of storage methods on a monthly basis. Product-generated storage packages have the smallest monthly cost per bushel, even though management and energy costs are greater than cold storage. CA costs are almost 2½ cents greater than product-generated atmosphere packages on a monthly basis.

TABLE 5.--Storage Economics on a Monthly Basis.

Dollars/Bushel/Month	Cold	C.A.	P.G. (Product-generated)
Building & Equipment	.0340	.0416	.0227
Labor	.0025	.0025	.0025
Management	.0015	.0023	.0023
Supplies & Repairs	.0028	.0079	.0028
Energy	.0150	.0186	.0186
TOTAL	$.0558	$.0729	$.0489

Table 6 summarizes the seasonal costs of the storage methods. The total costs show that product-generated storage packages will provide a storage period that is two months longer than cold storage for a cost of \$.07/bushel. The additional month provided by CA storage would almost cost an extra \$.22/bushel.

TABLE 6.--Storage Economics on a Seasonal Basis.

Dollars/Bushel	Cold	C.A.	P.G. (Product-generated)
Building & Equipment	.1360	.2910	.1360
Labor	.0100	.0180	.0150
Management	.0060	.0160	.0138
Supplies & Repairs	.0110	.0550	.0165
Energy	.0600	.1300	.1116
TOTAL	\$.2230	\$.5100	\$.2929

CHAPTER VIII

CONCLUSION

The product-generated atmosphere is a unique concept from a packaging perspective. Presently, packaging is used to protect or maintain the internal conditions of the package. Producing conditions that extend storage life would be a new function for the package.

Product-generated atmosphere package is not a proven method in the storage of fruits and vegetables. The results of this study do indicate that product-generated atmosphere package is a feasible storage method. It is feasible not only in terms of storage, but also in terms of economics. Further work is recommended to establish product-generated atmosphere packages as a viable storage method.

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APPENDIX

APPENDIX

Section 1: Assumptions

The assumptions made in the computer simulation are listed below:

1. Apple metabolism adjusts instantaneously to any change in the atmosphere.
2. Solubility of oxygen and carbon dioxide in apple sap at a given temperature is equivalent to water solubility constants.
3. Temperature effect on metabolism is additive to the oxygen-carbon dioxide effect.
4. Temperature does not affect the R.Q.
5. No physiological disorders in the package.
6. Internal package humidity and apple transpiration are not factors.

Section 2: Values for Program Parameters

This section quantifies the parameters of equations (1) and (2), with the exception of "RR(p_{O_2},p_{CO_2},T)." The computer program symbols are in parentheses.

Three films were used in the simulation. They were chosen on a basis of relative permeability rates.

1. Cellulose Acetate

a. $\tilde{P}_{O_2}$ (PERO2Z)=2.44x10^{-4} $\frac{\text{cm}^3 \text{ x standard temp. \& press x cm thickness}}{\text{cm}^2 \text{ x hour x atmosphere}}$

b. activation energy for oxygen (EPO2) = 4200 kcal/mole

c. $\tilde{P}_{CO_2}$ (PERCO2Z) = 1.47 x 10^{-3} $\frac{\text{cm}^3 \text{ x STP x cm}}{\text{cm}^2 \text{ x hour x atm}}$

c. activation energy for carbon dioxide (EPCO2) = 5200 kcal/mole

2. Low density polyethylene

a. (PERO2Z) = 1.75 x 10^{-5}

b. (EPO2) = 10000

c. (PERCO2Z) = 8.8 x 10^{-5}

d. (EPCO2) = 9000

3. Polybutadiene
    a. (PERO2Z) = 8.57×10^{-6}
    b. (EPO2) = 5000
    c. (PERCO2Z) = 2.97×10^{-5}
    d. (EPCO2) = 4300

W_A(WA) = 2273 grams

Retail package sizes for apples are typically 3, 4 and 5 pound packages.[61] A five pound package was chosen for this simulation.

V(V) = 3606 cm^3

The value for the headspace volume of package system is the sum of the headspace void in the package and the intercellular spaces in the apples. The package is assumed to be of cylindrical shape with a diameter of 6 inches (15.24 cm) and a height of 12 inches (30.48 cm). The density of McIntosh is .814 gm/cm^3 and the apple has about 30 percent intercellular space.[62]

The commercial ratio of product volume to package volume is 0.5 for apples.[63] The ratio for this package is 2792/5560 or 0.5.

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[61] M. A. Hanna and N. N. Mohsenin, "Pack Handling of Apples," J. of Agri. Eng. Research (1972), 17(2):164.

[62] A. V. Troyan; L. I. Mel'nichuk and S. S. Kedesh, "Determining the Intercellular Volume of Succulent Fruit," Pishshevaga Tekhnologiya (1972), 3:183.

[63] R. G. Tomkins, p. 237.

R(RGAS) = 82.06

This is a gas constant.

t(DELT) = 4

Time increment is 4 hours. The duration of the simulation (TMAX) is 720 hours or 30 days. CA storage may require 2-3 weeks to attain desired storage conditions (39). It is believed that equilibrium or anaerobic conditions would be reached within 30 days.

$p_o = 1$

It is assumed that pressure is constant at one atmosphere (standard pressure). The value is then "1" and "p_o" is not a variable in this simulation.

T_o(TA) = 273°K

It is assumed that gasses in the internal and external atmosphere are at standard tempersture, which is 0°C or 273°K.

A(AREA) = 1824.1 cm^2

Surface area of cylinder.

x(XM) = 1.0 mil

Thickness of film in mils. One mil is the common thickness of film used in retail apple packages.

(XC) = 2.54×10^{-3} cm/mil

Conversion factor to convert mils to centimeters.

$p_{O_2}^{e}$(PO2E) = .21

Partial pressure of oxygen in air is 0.21.

$p_{CO_2}^{e}$ (PCO2E)

Partial pressure of carbon dioxide in air is 0.0003

$p_{O_2}^{i}$ (PO2) = .2007

Average internal partial pressure of oxygen for package. (PO2) is based on the volume and partial pressure of the headspace and the intercellular spaces in the apple. The partial pressure of oxygen in intercellular spaces is 0.17.

$p_{CO_2}^{i}$ (PCO2) = 0.0095

Average partial pressure of carbon dioxide inside the package. The partial pressure of carbon dioxide in intercellular spaces is 0.04.

T(TEMP(NQQ) and TC) = 3.5°, 5°, 6° and 7°C

The program model is designed to simulate the product-generated atmosphere package at four specific temperatures. The lowest temperature, 3.5°C was chosen on the basis that this is the storage temperature of CA stored McIntosh apples.

Storage life is inversely proportional to temperature.[64] Small changes in temperature have a significant negative

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[64] *Ibid.*, p. 241.

effect on storage potential. Increasing the storage temperature above 7°C may cancel out any benefit derived from the package.

T_A(TA) = TC + 273°

TC + 273° converts degrees Celcius to degrees Absolute.

S_{O_2}(T) (SO2) = SOLO2(TC) $\frac{\text{gm } O_2}{\text{Kg} \cdot \text{hr}}$

SOLO2(TC) is a function within the program simulation. This function has solubility factors for several temperatures between 0°C and 20°C. This covers the possible range of storage temperatures. SOLO2(TC) interpolates the solubility for a given temperature based on data stored in the function.

There was no data available on oxygen solubility in apple sap. It was necessary to make an assumption. It was assumed that apple sap has the same solubility constants as water.

$C_{CO_2}(T)$ (SCO2) = SOLCO2(TC) $\frac{\text{gm } CO_2}{\text{Kg} \cdot \text{hr}}$

SOLCO2(TC) is also a function within the program simulation. It interpolates the solubility of carbon dioxide in water (apple sap).

$\tilde{P}_{O_2(T)}$ (PERO2) = PERO2Z x e^x x [-EPO2/1.987 x (1/TA - 1/273)]

The permeability rate varies according to temperature. (PERO2) reflects the permeability rate at specific temperatures (TA).

$\tilde{P}_{CO_2(T)}$ (PERCO2) = PERCO2Z x e^x x [-EPOC2/1.987 x (1/TA - 1/273)]

PERCO2 reflects the permeability rate a specific temperature (TA).

Section 3: Program Prototype

The model consists of a main program and three functions.

APPLER, the main program (Figure 20) is concerned with the simulation of the diffusion of oxygen and carbon dioxide through the package. The internal concentration of these gases continue to change until the package system is at a steady state.

A check is made for the extinction point of oxygen. A partial pressure below this point indicates anaerobiosis and a steady-state condition that will not be reached. The system terminates at this point.

The functions SOLO2 and SOLCO2 (Figure 21) determine the volume of oxygen and carbon dioxide dissolved in the apple sap (water).

The function RESP (Figure 22) computes the respiration rate as influenced by environmental conditions.

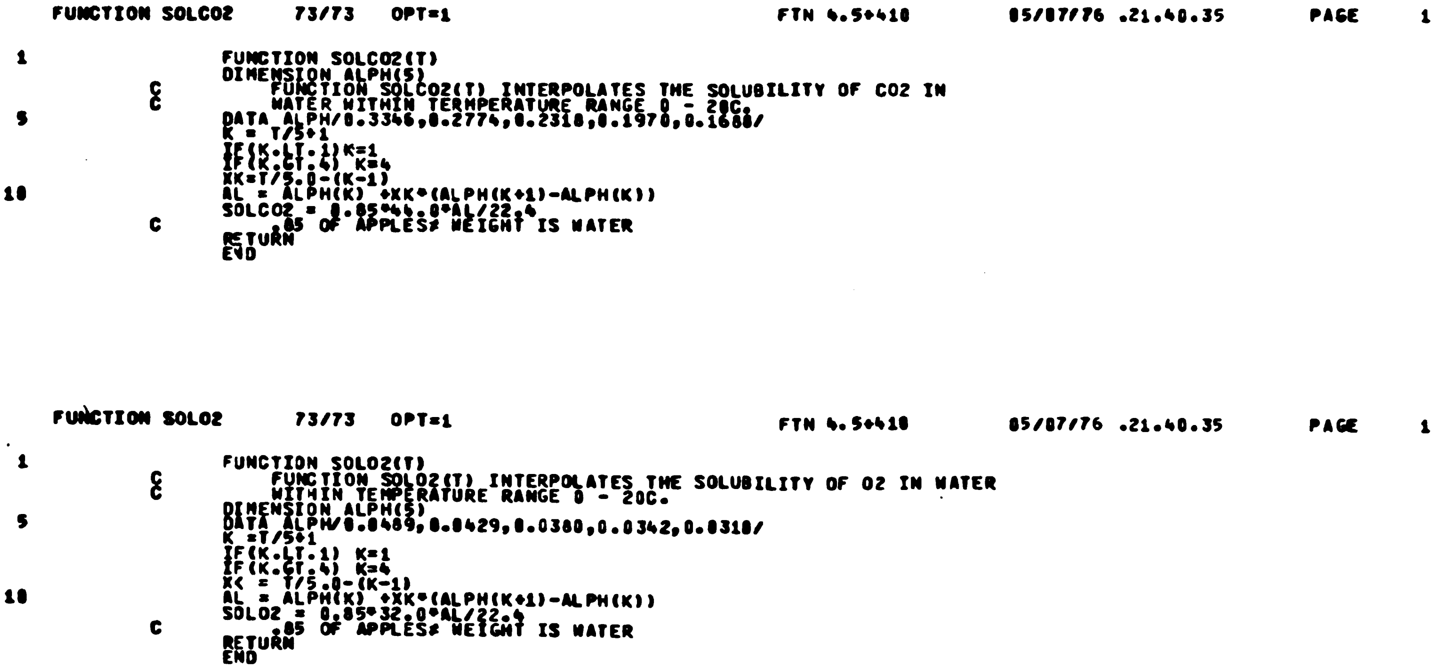
The program consists of four 720 hour (30 day) simulations. Temperature is the only variable changed in the four simulations. The time increment is 4 hours. Conditions are printed out every six increments or every 24 hours.

```
PROGRAM APPLER      73/73    OPT=1                     FTN 4.5+410        05/07/76 .21.40.35        PAGE     1

      PROGRAM APPLER(INPUT,OUTPUT=65)
      DIMENSION TEMPC(4)
      DATA TEMPC/3.5,5.0,6.0,7.0/
      WA=2273.0
      V=3606.
      AREA=1824.1
      RGAS=82.06
      XM=1.0
      XC=XM*2.54E-03
      PO2E = 0.21
      PCO2E= .0003
      PERO2Z =1.72E-05
      PERCO2Z = 6.0E-05
      EPO2 = 10000.
      EPCO2 = 9000.
C
C         WA IS WEIGHT OF APPLES IS GRAMS EQUAL TO 5 LBS.
C         V IS THE COMBINED VOLUME OF HEADSPACE AND INTERCELLULAR SPACES
C         IN APPLES IN CUBIC CENTIMETERS.
C         RGAS IS A AS CONSTANT.
C         AREA IS THE SURFACE AREA (CM SQUARED) OF BAG WITH DIMENSIONS
C         6 INCHES BY 12 INCHES.
C         XM IS THICKNESS EXPRESSED IN MILS.
C         XC IS XM CONVERTED TO CENTIMETERS.
C         PO2E AND PCO2E ARE EXTERNAL CONCENTRATIONS OF O2 AND CO2.
C         PERO2Z AND PERCO2Z ARE THE RESPECTIVE PERMEABILITY CONSTANTS
C         FOR OXYGEN AND CARBON DIOXIDE AT ZERO DEGREES.
C         EPO2 IS KCAL/MOLE - - - ACTIVATION ENERGY FOR OXYGEN
C         PERMEABILITY.  EPCO2 IS ACTIVATION ENERGY FOR CARBON DIOXIDE.
C
C
      TMAX = 720.0
C         DURATION OF SIMULATION IS 720 HOURS OR 30 DAYS.
      DELT=4.
C         TIME INCREMENT IS FOUR HOURS.
      MQQ=0
      PRINT 205,AREA,V,WA,PO2E,PCO2E
  205 FORMAT(*H*,40X,*BAG MATERIAL IS LOW DENSITY POLYETHYLENE*,//,40X,*
     31.  BAG AREA IS*,F8.1,* SQUARE CENTIMETERS*,//,40X,*2.  VOLUME IS*
     4,F8.1,*  CUBIC CENTIMETERS*,//,40X,*3.  WEIGHT OF APPLES IN GRAMS
     5IS*,F8.1,//,40X,*4.  THE EXTERNAL PARTIAL OF OXYGEN IS*,F6.3,//,40
     6X,*5.  CARBON DIOXIDE EXTERNAL PARTIAL PRESSURE IS*F7.4)
      NQQ=0
  160 NQQ=NQQ+1
      TC = TEMPC(NQQ)
      TA = TC+273.0
C         TC IS STEADY-STATE TEMPERATURES IN DEGREES C.
C         TA IS TC CONVERTED TO DEGREES K.
      SO2=SOLO2(TC)
      SCO2 = SOLCO2(TC)
C         SO2 AND SCO2 ARE THE SOLUBILITIES OF O2 AND CO2 AT TEMP. TC.
      PERO2= PERO2Z*EXP(-EPO2/1.987*(1.0/TA-1.0/273.0))
      PERCO2 = PERCO2Z*EXP(-EPCO2/1.987*(1.0/TA-1.0/273))
C         PERO2 AND PERCO2 ARE PERMEABILITY CONSTANTS AT TA.
  100 PRINT 215
  215 FORMAT(////////,20X,*O2 PERMEABILITY*,4X,*CO2 PERMEABILITY*,6X,*M
     6ILS*,6X,*T-CELSIUS*,5X,*T-ABSOLUTE*,6X,*SOL-O2*,6X,*SOL-CO2*,//)
      PRINT 220,PERO2,PERCO2,XM,TC,TA,SO2,SCO2
  220 FORMAT(15X,2E20.10,F10.1,F13.1,F15.1,F13.4,F12.4,//)
      QO2=SO2*WA/1000.+32.*V/(RGAS*TA)
      QCO2=SCO2*WA/1000.+44.*V/(RGAS*TA)
C         1000 CONVERTS GRAMS TO KILOGRAMS
C        QO2 IS CAPACITY FOR O2 IN PACKAGE - - - GRAMS/ATMOSPHERE.
C         QCO2 IS CAPACITY FOR CO2 IN PACKAGE - - - GRAMS/ATMOSPHERE.
      DPO2 = PERO2*(32.0/22400.0)*AREA/XC
      DPCO2 = PERCO2*(44.0/22400.0)*AREA/XC
C         DPO2 IS THE TRANSMISSION RATE OF O2 IN GRAMS/HR-ATMOSPHERE.
C         DPCO2 IS THE TRANSMISSION RATE OF CO2 IN GRAMS/HR-ATMOSPHERE.
      PO2=.2007
      PCO2=.0095
C          CONCENTRATIONS OF O2 AND CO2 AVAILABLE INSIDE PACKAGE
C         (INITIAL), THIS INCLUDES THE GAS IN INTERCELLULAR SPACES AS
C         WELL AS HEADSPACE.
      PRINT 210
  210 FORMAT(*H*,16X,*TIME*,13X,*OXYGEN*,10X,*CARBON DIOXIDE*,6X,*RESPIR
     8ATION*,/,30X,*CONCENTRATION*,6X,*CONCENTRATION*,11X,*RATE*,//)
      TIME = 0.0
```

Figure 20-1.--Program Appler.

```
PROGRAM APPLER     73/73    OPT=1                           FTN 4.5+410        05/07/76 .21.40.35        PAGE     2

        120 RR=RESP(PO2,PCO2,TC,TIME)
            R = RR*WA/1000.
      C           R IS THE RESPIRATION RATE (GRAM CO2/KG-HR)
            QA=DPO2*(PO2E-PO2)-R*.727
      C           QA IS THE NET LOSS IN GRAMS OF O2 WITHIN PACKAGE (O2 PERMEATED
      C           IN MINUS O2 LOSS DUE TO RESPIRATION).
            QB=DPCO2*(PCO2E-PCO2)+R
      C           QB IS NET CO2 GAIN IN GRAMS (CO2 EXPIRED MINUS CO2 PERMEATED
      C           OUT).
            PO2=PO2+(QA/QO2)*DELT
            PCO2=PCO2+(QB/QCO2)*DELT
      C            PO2 AND PCO2 ARE THE NEW INTERNAL O2 AND CO2 CONCENTRATIONS.
            IF(PO2.GT.PO2E) GO TO 100
            IF(PCO2.LT.0.0) GO TO 100
            IF(PO2.LT.0.0) GO TO 100
            IF(PCO2.GT.PO2E) GO TO 100
      C           CHECK FOR BLOW-UP CONDITIONS.
            TIME = TIME+DELT
            MOQ=MOQ+1
            IF(MOQ.LT.6) GO TO 120
            DAY=TIME/24.
            PRINT 200,DAY,PO2,PCO2,RR
            MOQ=0
            IF(PO2.GT.0.03) GO TO 110
      C           CHECK FOR ANAEROBIC CONDITIONS
            PRINT 240
        240 FORMAT(//,30X,*ANAEROBIC CONDITIONS EXIST . . . TERMINATE.*)
            TIME=TMAX
      C           THIS STATEMENT WILL TERMINATE SIMULATION
        110 IF(TIME.LT.TMAX) GO TO 120
        100 IF(NQQ.LT.4) GO TO 160
      C
      C           AS LONG AS TIME IS LESS THAT 720 HOURS THE PROGRAM WILL
      C           CONTINUE TO LOOP BACK TO REFERENCE 120 AND SIMULATE CHANGING
      C           RESPIRATION RATE AND INTERNAL ATMOSPHERIC CONDITIONS.  ONCE
      C           TMAX IS EQUALLED THE ACTION IS LOOPED BACK TO REFERENCE 160
      C            FOR A DIFFERENT TEMPERATURE.  SPECIFIC SOLUBILITIES AND
      C           PERMEABILITY CONSTANTS ARE RECALCULATED BASED ON TEMPERATURE
      C            CHANGE.
      C
        200 FORMAT(10X,F10.0,3F20.0)
            END
```

Figure 20-2.--Program Appler.



```
FUNCTION SOLCO2      73/73    OPT=1                          FTN 4.5+418        05/07/76 .21.40.35       PAGE     1

              FUNCTION SOLCO2(T)
              DIMENSION ALPH(5)
C                  FUNCTION SOLCO2(T) INTERPOLATES THE SOLUBILITY OF CO2 IN
C                  WATER WITHIN TERMPERATURE RANGE 0 - 20C.
              DATA ALPH/0.3346,0.2774,0.2318,0.1970,0.1688/
              K = T/5+1
              IF(K.LT.1)K=1
              IF(K.GT.4) K=4
              XK=T/5.0-(K-1)
              AL = ALPH(K) +XK*(ALPH(K+1)-ALPH(K))
              SOLCO2 = 0.85*44.0*AL/22.4
C                .85 OF APPLES≠ WEIGHT IS WATER
              RETURN
              END
```

```
FUNCTION SOLO2       73/73    OPT=1                          FTN 4.5+418        05/07/76 .21.40.35       PAGE     1

              FUNCTION SOLO2(T)
C                  FUNCTION SOLO2(T) INTERPOLATES THE SOLUBILITY OF O2 IN WATER
C                  WITHIN TEMPERATURE RANGE 0 - 20C.
              DIMENSION ALPH(5)
              DATA ALPH/0.0489,0.0429,0.0380,0.0342,0.0318/
              K =T/5+1
              IF(K.LT.1) K=1
              IF(K.GT.4) K=4
              X< = T/5.0-(K-1)
              AL = ALPH(K) +XK*(ALPH(K+1)-ALPH(K))
              SOLO2 = 0.85*32.0*AL/22.4
C                .85 OF APPLES≠ WEIGHT IS WATER
              RETURN
              END
```

Figure 21.--Functions SOLCO2 and SOLO2.

```
FUNCTION RESP       73/73    OPT=1                    FTN 4.5+410       05/07/76 .21.40.35       PAGE    1

      FJNCTIJN RESP(PO2,PCO2,T,TIME)
C         THIS FUNCTION CALCULATES THE RESPIRATION RATE IN GRAMS CO2/KG-
C         HR BASED ON THE PARTIAL PRESSURES OF OXYGEN AND CARBON DIOXIDE
C         INSIDE THE PACKAGE AND THE AMBIENT TEMPERATURE.
C         R IS THE EFFECT OF OXYGEN ON RESPIRATION
C         THE CARBON DIOXIDE EFFECT IS REPRESENTED BY VARIABLE XK.
C         FIRST XK EQUATION CALCULATES CO2 EFFECT FOR CONCENTRATIONS .00
C         TO .08 AND THE SECOND EQUATION IS VOR CONCENTRARIONS BETWEEN
C         .08 AND .16.
      R=6.+22.2*PO2
  100 XK=1.0-2.25*PCO2
      IF(PCO2.LE.0.08)GO TO 120
      XK=.82-6.6*(PCO2-0.08)
  120 R =R*XK
      TAN=T+273.0
      TA = TAN
      XT=EXP(-8101.*(1./TA-1./293.))
  140 RESP=R*1.375*XT/751.4
C         THE FACTOR 1.375 CONVERTS OXYGEN UPTAKE TO CARBON DIOXIDE
C         OUTPUT, I.E., 44/32.
C         THE 751.4 CONVERTS CC AT 293-K TO GRAMS.
      IF(TIME.GT.0.0)GO TO 150
      PRINT 300,TIME,PO2,PCO2,RESP
  300 FORMAT(10X,F10.0,3F20.8)
  150 RETURN
      END
```

Figure 22.--Function RESP.

Section 4: Data from Simulations and Proof of Program

This section presents the data from the simulation. Values are printed out for the following:

1. Material name
2. Bag area
3. Headspace volume
4. Weight of apples
5. External partial pressure of oxygen
6. External partial pressure of carbon dioxide
7. Oxygen permeability
8. Carbon dioxide permeability
9. Mils thickness
10. Temperature, degrees Celcius
11. Temperature, degrees absolute
12. Solubility constant of oxygen
13. Solubility constant of carbon dioxide
14. Time, in days
15. Internal oxygen concentration
16. Internal carbon dioxide concentration
17. Respiration Rate.

Figure 23, 24 and 25 show the results of the simulations for cellulose acetate, low density polyethylene and polybutadiene, respectively. Figure 26 verifies the program by reducing the time increment from four hours to two hours. This simulation is for low density polyethylene at 7°C.

```
BAG MATERIAL IS CELLULOSE ACETATE
1.  BAG AREA IS  1824.1 SQUARE CENTIMETERS
2.  VOLUME IS  3606.0  CUBIC CENTIMETERS
3.  WEIGHT OF APPLES IN GRAMS IS  2273.0
4.  THE EXTERNAL PARTIAL OF OXYGEN IS  .210
5.  CARBON DIOXIDE EXTERNAL PARTIAL PRESSURE IS  .0003



 O2 PERMEABILITY    CO2 PERMEABILITY      MILS      T-CELSIUS    T-ABSOLUTE      SCL-O2      SCL-CO2



 .2891250422E-13    .1659648251E-12       1.0          3.5         276.5         .0543       .4918

TIME          OXYGEN             CARBON DIOXIDE       RESPIRATION
           CONCENTRATION         CONCENTRATION           RATE

  0.         .20070000             .00950000           .00326645
  1.         .19285757             .00347110           .00326673
  2.         .19107613             .00345776           .00325264
  3.         .19067451             .00345478           .00324945
  4.         .19058399             .00345411           .00324873
  5.         .19056358             .00345396           .00324857
  6.         .19055809             .00345392           .00324854
  7.         .19055794             .00345392           .00324853
  8.         .19055771             .00345392           .00324853
  9.         .19055766             .00345391           .00324852
 10.         .19055765             .00345391           .00324852
 11.         .19055764             .00345391           .00324852
 12.         .19055764             .00345391           .00324852
 13.         .19055764             .00345391           .00324852
 14.         .19055764             .00345391           .00324852
 15.         .19055764             .00345391           .00324852
 16.         .19055764             .00345391           .00324852
 17.         .19055764             .00345391           .00324852
 18.         .19055764             .00345391           .00324852
 19.         .19055764             .00345391           .00324852
 20.         .19055764             .00345391           .00324852
 21.         .19055764             .00345391           .00324852
 22.         .19055764             .00345391           .00324852
 23.         .19055764             .00345391           .00324852
 24.         .19055764             .00345391           .00324852
 25.         .19055764             .00345391           .00324852
 26.         .19055764             .00345391           .00324852
 27.         .19055764             .00345391           .00324852
 28.         .19055764             .00345391           .00324852
 29.         .19055764             .00345391           .00324852
 30.         .19055764             .00345391           .00324852
```

Figure 23-1.--Results of the Simulation for Cellulose Acetate.

```
 O2 PERMEABILITY    CO2 PERMEABILITY       MILS      T-CELSIUS    T-ABSOLUTE      SOL-O2       SOL-CO2

 .2804580746E-03    .1746506248E-02        1.0          5.0         278.0          .0521        .4632

TIME           OXYGEN              CARBON DIOXIDE        RESPIRATION
            CONCENTRATION          CONCENTRATION            RATE

  0.          .20070000              .00950000            .00383186
  1.          .19080905              .00381952            .00381520
  2.          .18876000              .00380155            .00379583
  3.          .18833818              .00379808            .00379185
  4.          .18825134              .00379736            .00379103
  5.          .18823346              .00379722            .00379086
  6.          .18822978              .00379719            .00379083
  7.          .18822912              .00379718            .00379082
  8.          .18822887              .00379718            .00379082
  9.          .18822884              .00379718            .00379082
 10.          .18822883              .00379718            .00379082
 11.          .18822883              .00379718            .00379082
 12.          .18822883              .00379718            .00379082
 13.          .18822883              .00379718            .00379082
 14.          .18822883              .00379718            .00379082
 15.          .18822883              .00379718            .00379082
 16.          .18822883              .00379718            .00379082
 17.          .18822883              .00379718            .00379082
 18.          .18822883              .00379718            .00379082
 19.          .18822883              .00379718            .00379082
 20.          .18822883              .00379718            .00379082
 21.          .18822883              .00379718            .00379082
 22.          .18822883              .00379718            .00379082
 23.          .18822883              .00379718            .00379082
 24.          .18822883              .00379718            .00379082
 25.          .18822883              .00379718            .00379082
 26.          .18822883              .00379718            .00379082
 27.          .18822883              .00379718            .00379082
 28.          .18822883              .00379718            .00379082
 29.          .18822883              .00379718            .00379082
 30.          .18822883              .00379718            .00379082
```

Figure 23-2.--Results of the Simulation for Cellulose Acetate.

```
O2 PERMEABILITY    CO2 PERMEABILITY      MILS      T-CELSIUS      T-ABSOLUTE      SOL-O2      SOL-CO2

.2842062478E-03    .1866543776E-02        1.0         6.0            279.0        .0509       .4479

TIME          OXYGEN            CARBON DIOXIDE       RESPIRATION
           CONCENTRATION        CONCENTRATION           RATE

 0.          .20870000           .00950000            .00425812
 1.          .19929290           .00407063            .00422565
 2.          .18707730           .00404766            .00420210
 3.          .18664938           .00404388            .00419757
 4.          .18656673           .00404315            .00419670
 5.          .18655077           .00404301            .00419653
 6.          .18654769           .00404298            .00419649
 7.          .18654709           .00404298            .00419649
 8.          .18654693           .00404298            .00419649
 9.          .18654695           .00404298            .00419649
10.          .18654695           .00404298            .00419649
11.          .18654695           .00404298            .00419649
12.          .18654695           .00404298            .00419649
13.          .18654695           .00404298            .00419649
14.          .18654695           .00404298            .00419649
15.          .18654695           .00404298            .00419649
16.          .18654695           .00404298            .00419649
17.          .18654695           .00404298            .00419649
18.          .18654695           .00404298            .00419649
19.          .18654695           .00404298            .00419649
20.          .18654695           .00404298            .00419649
21.          .18654695           .00404298            .00419649
22.          .18654695           .00404298            .00419649
23.          .18654695           .00404298            .00419649
24.          .18654695           .00404298            .00419649
25.          .18654695           .00404298            .00419649
26.          .18654695           .00404298            .00419649
27.          .18654695           .00404298            .00419649
28.          .18654695           .00404298            .00419649
29.          .18654695           .00404298            .00419649
30.          .18654695           .00404298            .00419649
```

Figure 23-3.--Results of the Simulation for Cellulose Acetate.

```
O2 PERMEABILITY     CO2 PERMEABILITY      MILS     T-CELSIUS     T-ABSOLUTE     SOL-O2     SOL-CO2

.2961153146E-03     .1468087973E-02       1.0         7.0           280.0        .0497      .4327

TIME          OXYGEN            CARBON DIOXIDE       RESPIRATION
           CONCENTRATION        CONCENTRATION           RATE

  0.         .27070000            .00950000           .00472823
  1.         .18764794            .00433937           .00467548
  2.         .18527827            .00430793           .00464708
  3.         .18485612            .00430387           .00464200
  4.         .18477277            .00430314           .00464109
  5.         .18475879            .00430301           .00464092
  6.         .18475627            .00430298           .00464089
  7.         .18475581            .00430298           .00464088
  8.         .18475573            .00430298           .00464088
  9.         .18475571            .00430298           .00464088
 10.         .18475571            .00430298           .00464088
 11.         .18475571            .00430298           .00464088
 12.         .18475571            .00430298           .00464088
 13.         .18475571            .00430298           .00464088
 14.         .18475571            .00430298           .00464088
 15.         .18475571            .00430298           .00464088
 16.         .18475571            .00430298           .00464088
 17.         .18475571            .00430298           .00464088
 18.         .18475571            .00430298           .00464088
 19.         .18475571            .00430298           .00464088
 20.         .18475571            .00430298           .00464088
 21.         .18475571            .00430298           .00464088
 22.         .18475571            .00430298           .00464088
 23.         .18475571            .00430298           .00464088
 24.         .18475571            .00430298           .00464088
 25.         .18475571            .00430298           .00464088
 26.         .18475571            .00430298           .00464088
 27.         .18475571            .00430298           .00464088
 28.         .18475571            .00430298           .00464088
 29.         .18475571            .00430298           .00464088
 30.         .18475571            .00430298           .00464088
```

Figure 23-4.--Results of the Simulation for Cellulose Acetate.

```
                    BAG MATERIAL IS LOW DENSITY POLYETHYLENE

                    1.  BAG AREA IS  1824.1 SQUARE CENTIMETERS

                    2.  VOLUME IS  3606.0  CUBIC CENTIMETERS

                    3.  WEIGHT OF APPLES IN GRAMS IS  2273.0

                    4.  THE EXTERNAL PARTIAL OF OXYGEN IS  .210

                    5.  CARBON DIOXIDE EXTERNAL PARTIAL PRESSURE IS  .0003


 O2 PERMEABILITY    CO2 PERMEABILITY    MILS    T-CELSIUS    T-ABSOLUTE    SOL.O2    SOL.CO2

 .2172061587E-04    .1085655387E-03     1.0       3.5          276.5         .0593     .4928

TIME         OXYGEN            CARBON DIOXIDE      RESPIRATION
          CONCENTRATION        CONCENTRATION          RATE

 0.        .20070000           .00950000          .00326645
 1.        .17857972           .02361201          .00306205
 2.        .16011646           .03130211          .00288880
 3.        .14450863           .03531602          .00276443
 4.        .13120293           .03724049          .00267882
 5.        .11979669           .03799367          .00259755
 6.        .10998321           .03810632          .00253843
 7.        .10152009           .03788401          .00248963
 8.        .09421036           .03750127          .00244871
 9.        .08789059           .03705629          .00241401
10.        .08242328           .03660293          .00238437
11.        .07769156           .03616945          .00235891
12.        .07359546           .03576936          .00233698
13.        .07004908           .03540791          .00231805
14.        .06697839           .03508574          .00230169
15.        .06431947           .03480114          .00228752
16.        .06211706           .03455121          .00227526
17.        .06032335           .03433262          .00226465
18.        .05829698           .03414197          .00225545
19.        .05680211           .03397601          .00224749
20.        .05550772           .03383175          .00224059
21.        .05438693           .03370648          .00223461
22.        .05341649           .03359776          .00222943
23.        .05257623           .03350347          .00222495
24.        .05184871           .03342172          .00222107
25.        .05121888           .03335086          .00221770
26.        .05067341           .03328946          .00221479
27.        .05020121           .03323626          .00221227
28.        .04979238           .03319018          .00221008
29.        .04943841           .03315026          .00220819
30.        .04913196           .03311568          .00220655
```

Figure 24-1.--Results of the Simulation for Low Density Polyethylene.

```
 O2 PERMEABILITY   CO2 PERMEABILITY     MILS     T-CELSIUS    T-ABSOLUTE    SOL.O2    SOL.CO2

 .2396205029E-04   .1185983502E-03      1.0        5.0          278.0       .0521     .4682

TIME       OXYGEN          CARBON DIOXIDE    RESPIRATION
        CONCENTRATION      CONCENTRATION        RATE

  0.      .20070000          .00950000        .00383186
  1.      .17481648          .02607383        .00355065
  2.      .15373798          .03440354        .00332277
  3.      .13628986          .03833488        .00316501
  4.      .12169742          .03994399        .00304922
  5.      .10941472          .04035342        .00296020
  6.      .09903498          .04016871        .00288937
  7.      .09024192          .03971413        .00283165
  8.      .08278186          .03916068        .00278386
  9.      .07644702          .03859596        .00274388
 10.      .07106479          .03806243        .00271021
 11.      .06649058          .03757834        .00268174
 12.      .06240222          .03714925        .00265761
 13.      .05929677          .03677431        .00263712
 14.      .05648669          .03644960        .00261971
 15.      .05409772          .03617005        .00260490
 16.      .05206678          .03593029        .00259231
 17.      .05034025          .03572520        .00258161
 18.      .04887253          .03555007        .00257250
 19.      .04762485          .03540071        .00256476
 20.      .04656425          .03527343        .00255817
 21.      .04566269          .03516504        .00255257
 22.      .04489635          .03507277        .00254781
 23.      .04424495          .03499426        .00254376
 24.      .04369127          .03492746        .00254031
 25.      .04322064          .03487065        .00253739
 26.      .04282062          .03482233        .00253490
 27.      .04248061          .03478124        .00253278
 28.      .04219162          .03474630        .00253098
 29.      .04194599          .03471659        .00252945
 30.      .04173721          .03469134        .00252815
```

Figure 24-2.--Results of the Simulation for Low Density Polyethylene.

```
O2 PERMEABILITY    CO2 PERMEABILITY     MILS     T-CELSIUS     T-ABSOLUTE     SOL.O2     SOL.CO2

.25568421130E-04   .2257304415E+03      2.0        6.0           279.0        .0589      .4479

TIME        OXYGEN           CARBON DIOXIDE      RESPIRATION
         CONCENTRATION       CONCENTRATION          RATE

  0.       .20970000          .00950000          .00425812
  1.       .17201472          .02787038          .00391164
  2.       .14987149          .03656726          .00363981
  3.       .13036538          .04036143          .00345631
  4.       .11493523          .04170441          .00332387
  5.       .10211813          .04185786          .00322324
  6.       .09142729          .04146873          .00314393
  7.       .08248809          .04086506          .00307989
  8.       .07580284          .04020932          .00302738
  9.       .06872991          .03957825          .00298389
 10.       .06347053          .03900463          .00294767
 11.       .05905984          .03849908          .00291741
 12.       .05536047          .03806145          .00289206
 13.       .05225754          .03768674          .00287081
 14.       .04965487          .03736810          .00285299
 15.       .04747185          .03709832          .00283803
 16.       .04564086          .03687087          .00282548
 17.       .04410517          .03667807          .00281495
 18.       .04281720          .03651719          .00280611
 19.       .04173701          .03638143          .00279869
 20.       .04083112          .03626737          .00279247
 21.       .04007141          .03617158          .00278725
 22.       .03943431          .03609116          .00278287
 23.       .03890003          .03602366          .00277920
 24.       .03845200          .03596702          .00277611
 25.       .03807629          .03591950          .00277353
 26.       .03776123          .03587963          .00277136
 27.       .03749704          .03584618          .00276954
 28.       .03727558          .03581812          .00276802
 29.       .03708972          .03579459          .00276674
 30.       .03693395          .03577486          .00276567
```

Figure 24-3.--Results of the Simulation for Low Density Polyethylene.

```
O2 PERMEABILITY   CO2 PERMEABILITY   MILS   T-CELSIUS   T-ABSOLUTE   SOL-O2   SOL-CO2

.2726981749E-04   .1332358442E+03    1.0      7.0        280.0       .0497    .4327

TIME        OXYGEN        CARBON DIOXIDE    RESPIRATION
         CONCENTRATION    CONCENTRATION        RATE


 0.        .20070000        .03950000        .00472823
 1.        .16895854        .02980512        .00430256
 2.        .14405851        .03880612        .00397996
 3.        .12408166        .04238894        .00376781
 4.        .10784356        .04342079        .00361724
 5.        .09454492        .04330045        .00350416
 6.        .08360697        .04270628        .00341591
 7.        .07458897        .04196173        .00334535
 8.        .06714396        .04121542        .00328810
 9.        .06099312        .04053032        .00324123
10.        .05590968        .03992811        .00320268
11.        .05170743        .03941119        .00317088
12.        .04823357        .03897358        .00314461
13.        .04536177        .03860620        .00312289
14.        .04298773        .03829937        .00310493
15.        .04102523        .03804397        .00309007
16.        .03940301        .03783182        .00307778
17.        .03806211        .03765586        .00306761
18.        .03695378        .03751005        .00305921
19.        .03603771        .03738931        .00305225
20.        .03528058        .03728938        .00304650
21.        .03465481        .03720670        .00304175
22.        .03413764        .03713836        .00303782
23.        .03371022        .03708174        .00303457
24.        .03335698        .03703497        .00303189
25.        .03306505        .03699630        .00302967
26.        .03282379        .03696433        .00302783
27.        .03262440        .03693790        .00302632
28.        .03245963        .03691606        .00302506
29.        .03232346        .03689800        .00302403
30.        .03221093        .03688308        .00302317
```

Figure 24-4.--Results of the Simulation for Low Density Polyethylene.

```
BAG MATERIAL IS POLYBUTADIENE
1.  BAG AREA IS  1824.1 SQUARE CENTIMETERS
2.  VOLUME IS  3606.0  CUBIC CENTIMETERS
3.  WEIGHT OF APPLES IN GRAMS IS  2273.0
4.  THE EXTERNAL PARTIAL OF OXYGEN IS  .210
5.  CARBON DIOXIDE EXTERNAL PARTIAL PRESSURE IS  .0003


O2 PERMEABILITY    CO2 PERMEABILITY     MILS     T-CELSIUS    T-ABSOLUTE    SOL-O2    SOL-CO2


.9630584942E-05    .3283478941E-04      1.0        3.5          276.5        .0543     .4918

TIME         OXYGEN          CARBON DIOXIDE     RESPIRATION
          CONCENTRATION      CONCENTRATION         RATE

 0.         .20470004          .04950000         .00326645
 1.         .17762239          .02527531         .00303126
 2.         .15745736          .04302123         .00290238
 3.         .13970032          .05457947         .00261827
 4.         .12395553          .06360569         .00246846
 5.         .10991248          .07061543         .00234527
 6.         .09732252          .07601533         .00224294
 7.         .08598454          .08013223         .00215716
 8.         .07585558          .08311581         .00205543
 9.         .06686446          .08513327         .00197350
10.         .05880231          .08644061         .00190337
11.         .05151412          .08722815         .00185996
12.         .04487889          .08763540         .00181996
13.         .03880454          .08776531         .00178749
14.         .03321815          .08769443         .00176073
15.         .02806142          .08747975         .00173833

         ANAEROBIC CONDITIONS EXIST . . . TERMINATE.
```

Figure 25-1.--Results of the Simulation for Polybutadiene.

```
 O2 PERMEABILITY    CO2 PERMEABILITY     MILS     T-CELSIUS    T-ABSOLUTE    SOL-O2    SOL-CO2

 .1011529577E-04    .3425110022E-04      1.0        5.0          278.0       .0521     .4632

TIME          OXYGEN           CARBON DIOXIDE      RESPIRATION
           CONCENTRATION       CONCENTRATION           RATE

 0.          .20070000           .00950000          .00383186
 1.          .17363046           .03172277          .00350728
 2.          .15041039           .04872238          .00319994
 3.          .13028752           .06169717          .00295926
 4.          .11269337           .07155545          .00276802
 5.          .09719573           .07899037          .00261402
 6.          .08361308           .08439785          .00244114
 7.          .07191604           .08850572          .00229470
 8.          .06169028           .09033993          .00213710
 9.          .05262994           .09177267          .00210648
10.          .04451439           .09256911          .00204490
11.          .03718128           .09291599          .00199692
12.          .03050334           .09294721          .00195882
13.          .02440395           .09275852          .00192796

           ANAEROBIC CONDITIONS EXIST . . . TERMINATE.



 O2 PERMEABILITY    CO2 PERMEABILITY     MILS     T-CELSIUS    T-ABSOLUTE    SOL-O2    SOL-CO2

 .1044884943E-04    .3522020080E-04      1.0        5.0          279.0       .0509     .4479

TIME          OXYGEN           CARBON DIOXIDE      RESPIRATION
           CONCENTRATION       CONCENTRATION           RATE



 0.          .20070000           .00950000          .00425812
 1.          .17064735           .03428881          .00395722
 2.          .14521057           .05283975          .00348519
 3.          .12343007           .06081611          .00319944
 4.          .10458243           .07713712          .00297622
 5.          .08826134           .08471557          .00274522
 6.          .07450230           .08967547          .00253553
 7.          .06270833           .09283316          .00238727
 8.          .05241666           .09475551          .00228001
 9.          .04330006           .09592771          .00220062
10.          .03514923           .09631455          .00214053
11.          .02778103           .09639959          .00209398

           ANAEROBIC CONDITIONS EXIST . . . TERMINATE.
```

Figure 25-2.--Results of the Simulation for Polybutadiene.

```
 O2 PERMEABILITY   CO2 PERMEABILITY     MILS      T-CELSIUS     T-ABSOLUTE      SOL-O2      SOL-CO2

 .1079090115E-04    .3620950406E-04      1.0         7.0           280.0          .0497       .4327

TIME           OXYGEN            CARBON DIOXIDE       RESPIRATION
            CONCENTRATION        CONCENTRATION          RATE

 0.           .20670000           .00950000           .00472823
 1.           .16738348           .03710469           .00423428
 2.           .13960844           .05738995           .00378584
 3.           .11611167           .07226374           .00344854
 4.           .09602302           .08307130           .00316376
 5.           .07937233           .09022675           .00284570
 6.           .06548026           .09470256           .00263107
 7.           .05360453           .09740390           .00248217
 8.           .04325462           .09892119           .00237609
 9.           .03409718           .09964577           .00229851
10.           .02589959           .09934023           .00224023

              ANAEROBIC CONDITIONS EXIST . . . TERMINATE.
```

Figure 25-3.--Results of the Simulation for Polybutadiene.

```
   O2 PERMEABILITY     CO2 PERMEABILITY       MILS       T-CELSIUS       T-ABSOLUTE        SOL,O2          SOL,CO2

  .2726981749E-04     .1332358442E+03         1.0          7.0            280.0            .0497            .4387

 TIME              OXYGEN                CARBON DIOXIDE          RESPIRATION
               CONCENTRATION             CONCENTRATION              RATE

  0.              .20070000               .00950000               .00472823
  1.              .18397962               .02129523               .00449554
  1.              .16924305               .02934720               .00427034
  2.              .15615828               .03477358               .00410450
  2.              .14447208               .03836063               .00398680
  3.              .13309061               .04066252               .00385417
  3.              .12455545               .04207030               .00370832
  4.              .11604041               .04286005               .00366082
  4.              .10834020               .04322665               .00361252
  5.              .10136639               .04330752               .00355314
  5.              .09504286               .04319938               .00350101
  6.              .08930395               .04297007               .00345488
  6.              .08409209               .04266693               .00341380
  7.              .07935648               .04232281               .00337703
  7.              .07505194               .04196021               .00334399
  8.              .07113818               .04159440               .00331420
  8.              .06757875               .04123544               .00328729
  9.              .06434126               .04088981               .00326293
  9.              .06139618               .04056143               .00324084
 10.              .05871688               .04025249               .00322080
 11.              .05627922               .03996392               .00320260
 11.              .05406133               .03969508               .00318606
 11.              .05204334               .03944794               .00317102
 12.              .05020719               .03921934               .00315734
 12.              .04853649               .03900913               .00314490
 13.              .04701633               .03881621               .00313358
 13.              .04563313               .03863943               .00312328
 14.              .04437457               .03847766               .00311391
 14.              .04322943               .03832977               .00310538
 15.              .04218748               .03819468               .00309761
 15.              .04123944               .03807137               .00309055
 16.              .04037685               .03795886               .00308411
 16.              .03959201               .03785627               .00307826
 17.              .03887793               .03776274               .00307293
 17.              .03822822               .03767750               .00306808
 18.              .03763709               .03759985               .00306367
 18.              .03709927               .03752911               .00305966
 19.              .03660994               .03746468               .00305600
 19.              .03616475               .03740601               .00305268
 20.              .03575978               .03735259               .00304965
 20.              .03539119               .03730395               .00304690
 21.              .03505591               .03725968               .00304439
 21.              .03475088               .03721937               .00304211
 22.              .03447337               .03718269               .00304003
 22.              .03422089               .03714930               .00303815
 23.              .03399118               .03711892               .00303643
 23.              .03378221               .03709126               .00303487
 24.              .03359208               .03706610               .00303344
 24.              .03341911               .03704319               .00303215
 25.              .03326174               .03702235               .00303097
 25.              .03311858               .03700339               .00302990
 26.              .03298833               .03698613               .00302893
 26.              .03286983               .03697043               .00302804
 27.              .03276203               .03695614               .00302723
 27.              .03266396               .03694315               .00302650
 28.              .03257473               .03693132               .00302583
 28.              .03249356               .03692056               .00302522
 29.              .03241971               .03691076               .00302467
 29.              .03235252               .03690185               .00302417
 30.              .03229148               .03689375               .00302371
 30.              .03223579               .03688637               .00302329
```

Figure 26.--Results of the Simulation for Low Density Polyethylene at 7°C.