

PREDICTIONS OF SHELF-LIFE OF PACKAGED CEREAL BY AN ACCELERATED TEST TECHNIQUE AND A MATHEMATICAL MODEL

> Thests for the Degree of M. S. MICHIGAN STATE UNIVERSITY Vallop Manathunya 1976





This is to certify that the

thesis entitled

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has been accepted towards fulfillment of the requirements for

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## ABSTRACT

# PREDICTIONS OF SHELF-LIFE OF PACKAGED CEREAL BY AN ACCELERATED TEST TECHNIQUE AND A MATHEMATICAL MODEL

By

Vallop Manathunya

Ready-to-eat cereals may lose their consumer acceptance for a variety of causes, but one of the most important is the loss of crispness resulting from adsorption of moisture from the atmosphere. To prevent such moisture adsorption, cereals are customarily packed in packages which resist water vapor penetration. The amount of package protection which must be provided depends upon the time elapsing between manufacture and consumption. This elapsing time is widely named as shelf-life of the product. Shelf-life of a product can presumably be estimated by many methods. The most common method to the food industry is the accelerated test technique. However, shelf-life studies by this method may be expensive and time consuming, hence shelf-lives of some products are determined by having actual testing while shelf-lives of some of the "like" products may be estimated to have the same values without testing. Since this way of estimation may give incorrect results, a scientific and theoretical approach to the prediction of shelf-life is proposed in this thesis. A simple mathematical model aiding shelf-life prediction of cereals was developed having moisture content as the

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# A MATHEMATICAL MODEL

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# A THESIS

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Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

School of Packaging

DEDICATED TO MY PARENTS AND DEAREST SISTER FOR THEIR ENCOURAGEMENT AND UNQUESTIONING SUPPORT

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## INTRODUCTION

Basically, the functions of a package are to contain, to carry, to preserve, to communicate and to display. Protection of the product's qualities from the storage environment is the major concern in most cases. The rational selection of packaging materials to insure optimal protection requires knowledge of the functional properties of the packaging materials and the packaging requirements to the food. Cereals may lose their appeal for a variety of causes, but one of the most important is the loss of crispness resulting from adsorption of moisture from the environment. In addition, adsorption of water vapor also indirectly promotes chemical and/or biological changes to the cereals. Permeability of packaging materials to water vapor is the most important criterion for this research to follow when assessing the performance of cereal packages; the choice of packaging material will affect the shelf-lives of the cereals directly.

Shelf-life is a term generally used to denote the length of time a packaged product will remain useful and of acceptable and salable quality when it is subjected to various factors encountered in its channels of distribution. Shelf-life depends on a large number of factors, such as temperature, relative humidity, water vapor permeation rate of the package, package configuration, water vapor adsorption of the product, etc. For cereals packed in flexible

pouches, the rate of water vapor permeation and the adsorption isotherms of those cereals are the two particular factors responsible for the eventual unacceptability of the product. The adsorption isotherm of a cereal is best described as a plot of the amount of water adsorbed as a function of the equilibrium relative humidity surrounding the material. The amount of water is that which is held after equilibrium has been reached at a constant temperature.

Shelf-life of a food product can be determined in different ways. The most popular method, commonly used in the food industry, is the accelerated test technique.

Accelerated conditions have a great effect on the product stability, and properties of the packaging material compare to that of room conditions.  $\overline{/}$  Although water vapor adsorption at higher temperature is less than that at lower temperature and the rate of permeation at higher temperature is greater than that at lower temperature, according to the fact that the permeability constant which is dependent upon temperature increases exponentially with temperature, the reactions which determine shelf-life at one temperature can become significant at another temperature, and vice versa. For example, an enzymatic reaction becomes dominant at higher temperature rather than at lower temperature. The influence of high and low humidities on shelf-life may have similar effects, too. It is believed that accelerated testing at high temperature and humidity will be rather inconclusive, since room and accelerated conditions might not have similar effects. No attempt has been made in this research to determine what particular factors are responsible for

this inconclusive effect. It was a practical experiment to prove that the accelerated test which is used by the food industry to predict shelf-lives of different products is not suitable.

Although shelf-life prediction by an accelerated test technique is commonly used by the food industry, most of the time this technique is not applied to all the products. Generally, the food industry predicts shelf-lives of "like" products, such as different cereals, without having actual testing of all the "like" products. They usually base their judgments on past accelerated testing of a product to predict shelf-lives of other "like" products. Actual testing of all the "like" products is not commonly performed because to carry out even accelerated tests for all the products is very costly and takes a lot of time.

Three cereals were chosen for this research, two of which were sugar-coated. The ring-shaped, sugar-coated cereal was named cereal A. The regular flake-shaped, sugar-coated cereal was named cereal B. Cereal C was the name designated for the nonsugar-coated cereal. Three different cereals were chosen because they have different abilities of adsorbing water vapor. Because adsorption of water vapor affects the storage lives of the cereals, different storage lives can be expected. Polyethylene of two thicknesses (3 mil and 1-1/4 mil) and Saran (1 mil thickness) were used as packaging films, even though cereals in the market are not actually packaged in plastic pouches. The purpose of selecting such films was to show that different films have different effects on the storage lives of the products. Polyethylene of different thicknesses

will have different rates of water vapor permeation, depending upon the thickness. The thicker film will have a lower rate of permeation than the thinner one because the permeation rate is inversely proportional to the thickness. Saran, which has the lowest permeation to water vapor when compared to other films of the same thickness, can be expected to give the longest storage life from the standpoint of protection against water vapor.

A mathematical model was developed for the prediction of cereals' shelf-lives. The model includes the theoretical considerations that are important to the prediction of cereals' shelf-lives. Those are the rate of water vapor permeation through the packaging film, moisture in the headspace, and water vapor adsorption of the cereals. The model developed was so simple that it enables the rapid prediction of storage life and it is also possible to apply for package design and optimization.

#### **Objectives**

The objectives of this study are:

- (i) To prove that the accelerated test technique is not accurate for the prediction of cereals' shelf-lives.
- (ii) To show that a simple mathematical model can be used for the prediction of cereals' shelf-lives.

#### LITERATURE REVIEW

Prediction of shelf-life in a given food package combination and the related problem of prediction of packaging protection required for a given food to be stored for a specific time are of importance to the food industry. Shelf-life can be determined in different ways. The first, traditional method involves actually testing the product, held under normal conditions, for loss or gain of moisture, loss of flavors, odors or crispness, and all other factors considered in defining the salability of a product, until it is no longer salable. The major drawback of this method is the time involved before any results are obtained. To reduce the testing time, an accelerated test technique was introduced. This technique uses high testing temperature and humidity, compared to those of normal conditions. Easter (1953) described how to forecast shelf-life from an accelerated laboratory test. The accelerated test technique assumes the direct relationship of reactions which determine the shelf-life at normal and accelerated conditions. Actual testing of the product is done under normal and accelerated conditions until the product under accelerated conditions is deteriorated or unacceptable.

Traditional methods for selection of proper flexible packaging materials to insure high quality store for the desired market life of a food product are based essentially on experience and estimation. These methods involved selection of several films which

have given good results from previous tests, storage of the food in these films for a number of months, and then subjectively picking the best film from the group. This commonly led to overprotection in many cases and was a very costly procedure in terms of time and manpower expended. These types of studies have been used exclusively in the analysis of storage of foods.

A more scientific alternative approach to shelf-life prediction and/or packaging protection requirements is the development of a mathematical model to fit all the experimental data. Considering dehydrated foods, since cereals are dehydrated products, dehydrated foods deteriorate through several mechanisms depending on their composition and environment. These include lipid oxidation, nonenzymatic browning, enzymatic hydrolysis, degradation of proteins and other structural polymers leading to toughening, loss of crispness, and caking leading to insolubility (Mizhari et al., 1970; Quast et al., 1972; Quast and Karel, 1972; Heiss and Eichner, 1971a and 1971b; Sapers et al., 1974; Labuza et al., 1972; Rockland, 1969). In a package the food is separated from the external environment by the package film barrier. The major function of packaging is to reduce or eliminate the rate of transportation of water vapor or oxygen through the package barrier into the internal environment. This is because the rate of deterioration depends on the conditions of the internal environment in terms of the partial pressure of water vapor or oxygen. The analysis of the properties of food are necessary in order to make any prediction of storage. For example, an equation for the moisture content as a function of water vapor pressure or

oxygen pressure in the package is necessary, as well as an equation for the rate of transport of water vapor pressure or oxygen pressure in the package, and also an equation for the rate of transport of water vapor or oxygen across the package barrier as a function of the vapor pressure difference across the barrier.

Many studies have been done in the past in which storage life and/or packaging protection requirements have been calculated on the basis of certain properties of the food or package. Oswin (1946), Heiss and Eichner (1971b), Caurie (1970 and 1971), and Iglesias et al. (1975) developed some models for prediction of shelf-life on the basis of adsorption of water by the food to some critical level of moisture content. Labuza et al. (1972) reviewed some mathematical models which could be used to predict packaging requirements on the basis of film properties, and the basic physical/ chemical properties of several space rations. Similar types of models were developed by many experts, not only for dehydrated foods but for other foods as well. Quast et al. (1972) and Quast and Karel (1973) developed a mathematical model simulating shelf-life of potato chips. Quast and Karel (1972) developed a computer simulation of storage life of foods undergoing spoilage by two interacting mechanisms. Mizhari et al. (1970) and Karel et al. (1971) developed a computer model for dehydrated cabbage. Henig (1975) developed a mathematical model representing the changes in respiratory gas concentrations within fresh potato packs. However, according to the author's knowledge, no article has been found which describes the

comparison of the cereal shelf-life determination method of accelerated testing to that of prediction by a mathematical model.

The use of mathematical models is significantly better than a hit-or-miss type of study and allows much more confidence in choosing a package. The use of the models also takes much less time than packaging study methods previously used, being economical as well as a good tool.

# DEVELOPMENT OF A MATHEMATICAL MODEL FOR THE PREDICTION OF FOOD PRODUCT SHELF-LIFE

Permeation of gas and vapor through glass and metal is considered to be negligible, while paper has extremely high permeation to both gas and vapor. In contrast, all plastics are permeable to gas and vapor in some degree, depending upon the nature of the permeant, nature of the film, temperature, partial pressure difference, and so on. Because a number of excellent reviews exist on permeation (Lebovits, 1966; Major and Kammermeyer, 1962; Reeves and Kilgore, 1964; Rogers, 1964), this will be briefly described.

Permeation may be described as a gas or vapor dissolving into one side of a membrane under pressure or concentrated driving force, diffusing across the membrane under a concentration gradient and desorbing from the low-pressure side. The rate of water vapor permeation through the packaging material at a given time is inversely proportional to the thickness and directly proportional to the permability constant, package surface area and pressure difference (Gyeszli, 1971). This can be expressed as

$$\frac{dM}{dt} = \bar{P} \frac{A}{x} (P_0 - P_i)$$
(1)

where

M = amount of water vapor permeated across the film, gm, t = time, sec,

 $\overline{P}$  = permeability constant of the film,  $\frac{(g. H_2^{0})(cm)}{(sec)(cm^2)(\Delta atm)}$ A = surface area of the film,  $cm^2$ , x = film thickness, cm.

Assumptions were made when the equation was derived.

- Permeability constant is independent of the film's thickness and water vapor partial pressure difference between the two sides of the film.
- (ii) Thickness of the films was assumed constant; the films did not swell upon the exposure of high relative humidity or moisture content.
- (iii) When a film was determined to have any definite thickness, it was assumed that the film of the same roll has the same thickness, even though unevenness of the film's thickness can occur.
- (iv) Water vapor was performing as an ideal gas.

Due to the many assumptions applied to the equation, errors were expected when compared to the actual test data. It was considered that these assumptions are appropriate since the purpose of this research is to develop a model that is simple and practically useful and at the same time gives adequate prediction.

Generally, it is easier to measure the percent relative humidity than to measure the water vapor pressure. Relation between the water vapor pressure and the percent relative humidity is given by Equation (2).

$$P = \frac{P}{100} \cdot H$$
 (2)

where

P = water vapor pressure at a temperature, atm,
P<sub>s</sub> = saturated water vapor pressure at a temperature, atm,
H = percent relative humidity.

Assume that the temperature inside and outside the package is the same; the rate of permeation can be expressed by Equation (3),

$$\frac{dM}{dt} = \overline{P} \cdot \frac{A}{x} \cdot \frac{P_s}{100} (H_0 - H_i)$$
(3)

where

 $H_0$  = percent relative humidity outside the package,  $H_i$  = percent relative humidity inside the package.

The amount of water vapor transported across the package film will spread out in the headspace of the package and equilibrate with the food. The water vapor is then adsorbed by the food. The amount of water adsorbed depends on the internal water vapor pressure or the equilibrium relative humidity inside the package. When the amount of water adsorbed is plotted against the equilibrium relative humidity, this is called the adsorption isotherm of the food. Labuza (1968) described the theoretical fundamentals of isotherm equations in the analysis of packaging kinetics. The simplest equation of all is the equation of straight line. Since the data of adsorption isotherms within the range of 10-50% RH on Figures 10 and ll can be fitted relatively well by straight lines, a straight line equation was then applied for this model. The straight line equation is expressed as,

$$m = a + bH$$

where

- m = water vapor adsorbed/dry solid, %,
- a = intercept of the straight line on Y-axis, % water vapor adsorbed,
- b = slope of the straight line,  $\frac{\% \text{ water vapor adsorbed}}{\% \text{ relative humidity}}$
- H = percent relative humidity.

If W is the amount of dry solid weight of the product, the amount of water vapor adsorbed  $(m_1)$  can be expressed as

$$m_1 = (a + bH_1) \frac{W}{100}$$
 (5)

Labuza et al. (1972) assumed that all of the water vapor transported across the package was solely adsorbed by the food material because the water vapor will rapidly equilibrate with the food. One must not ignore that there is water vapor distributed in the headspace, too, even though this is a very small amount. The amount of water vapor in the headspace is the number of water molecules. This can be determined by using the Ideal Gas Law,

$$n = \frac{P_{i}V}{RT}$$
(6)

where

n = number of water vapor molecules in the headspace, P = water vapor pressure inside the package, atm, i V = volume of the headspace gas, c.c., (4)

R = gas constant, = 
$$82.06 \frac{(c.c.)(atm)}{(°C)(moles)}$$
,  
T = absolute temperature, °K.

Since 1 mole of water vapor weighs 18 gm, and the water vapor pressure can be expressed in terms of relative humidity, Equation (6) can be expressed as

$$m_2 = 18 \cdot P_s \frac{H_i}{100} \cdot \frac{V}{RT}$$
(7)

where

m<sub>2</sub> = amount of water vapor in the headspace, gm,
P<sub>s</sub> = saturated water vapor at temperature inside the package, atm,
H<sub>i</sub> = percent relative humidity inside the package.

The total amount of water vapor (M) inside the package is the sum of the amount of water vapor adsorbed by the product and water vapor in the headspace. Or,

$$M = m_1 + m_2 \tag{8}$$

From Equations (5) and (7),

$$M = (a + bH_i) \frac{W}{100} + \left(18 \cdot \frac{P_s}{100} \cdot H_i \cdot \frac{V}{RT}\right)$$
(9)

The rate of water vapor permeation equals the changes in water vapor content inside the package with time, or,

Rate of 
$$= \frac{d}{dt}$$
 (total amount of H<sub>2</sub>O permeation  $= \frac{d}{dt}$  inside the package)

From Equations (3) and (9), we have,

$$\overline{P} \cdot \frac{A}{x} \cdot \frac{P_s}{100} (H_0 - H_i) = \frac{d}{dt} \left[ (a+bH_i) \frac{W}{100} + \left( 18 \cdot \frac{P_s}{100} \cdot H_i \cdot \frac{V}{RT} \right) \right]$$
(10)

In Equation (10), relative humidity inside the package is the only factor that varies with time; the others remain constant, so,

$$\overline{P} \cdot \frac{A}{x} \cdot \frac{P_s}{100} (H_0 - H_i) = \left(18 \cdot \frac{P_s}{100} \cdot \frac{V}{RT} + \frac{bW}{100}\right) \frac{dH_i}{dt}$$

0r

$$\frac{\mathrm{dH}_{\mathbf{i}}}{\mathrm{dt}} = \frac{\overline{P} \cdot \frac{A}{x} \cdot \frac{P_{\mathbf{s}}}{100}}{\left(18 \cdot \frac{P_{\mathbf{s}}}{100} \cdot \frac{V}{RT} + \frac{bW}{100}\right)} (H_0 - H_{\mathbf{i}})$$

Let

$$J = \frac{\overline{P} \cdot \frac{A}{x} \cdot \frac{P}{100}}{\left(18 \cdot \frac{P}{100} \cdot \frac{V}{RT} + \frac{bW}{100}\right)}$$

So

$$\frac{dH_{i}}{dt} = J (H_{0} - H_{i})$$

$$\frac{dH_{i}}{H_{0} - H_{i}} = J dt$$

Integrate H, from 0 to t sec,

$$\int_{0}^{t} \frac{dH_{i}}{H_{0} - H_{i}} = \int_{0}^{t} J dt$$

$$\frac{H_{0} - H_{i}}{H_{0} - H_{i}(t)} = e^{Jt}$$
(11)

or

$$t = \frac{1}{J} \ln \left( \frac{H_0 - H_1}{H_0 - H_1(t)} \right)$$
(12)

where

- H<sub>0</sub> = percent relative humidity outside the package,
  H<sub>1</sub> = initial percent relative humidity inside the package,
  = percent relative humidity inside the package
- - t = time for the relative humidity inside the package to reach the value of H i(t), sec,
  - J = constant.

Equation (12) can be used to find the time to reach a given moisture content which can be expressed in percent relative humidity as well from the adsorption isotherm of that food. Once the critical moisture content or critical relative humidity of the package product is established shelf-life of the product can then be determined. Inversely, if the shelf-life and critical moisture content of the product are established, this equation can be used to select the appropriate packaging material as well. By inserting the established values in the equation, J-value can be determined. Once the J-value is known, the permeability constant can be determined. Then one can find out if there is any packaging material that possesses the same permeability constant as determined. The packaging material that possessed the same permeability constant as determined should be selected as the packaging material for the product. By using this technique, the packaged product will have a shelf-life as established without being overprotected.

#### EXPERIMENTAL

## Preparation of Cereal Package Samples

Cereal samples weighing from 20 to 30 gm were packed in three films having the same size of  $14-1/2 \times 17$  cm pouches and heat sealed. Thirty samples of each product in each film were prepared.

#### Determination of Initial Moisture Content

Initial moisture content of the three cereals was determined by using the Cenco Moisture Balance. Approximately 5 g of cereal sample were exposed to infrared radiation which provides temperatures of varying degrees. Cereal A was exposed to infrared radiation at  $300^{\circ}$ F while cereals B and C were exposed at 240°F for 11, 10, and 12 min, respectively. The percentage of moisture content was determined by reading of the loss of weight of the sample due to the loss of moisture content. Moisture content was expressed in the unit of  $\frac{g.\moisture}{100\ g.\ dry\ solid}$ . Results are in Table 5.

# Determination of Moisture Gained and Total Moisture Content of the Samples

Half of the prepared samples were hung in a walk-in controllable chamber. Temperature and humidity of the chamber were set at 100°F and 70% RH. This was designated as the accelerated testing conditions. The other half of the samples were hung in a chamber having a temperature of 76.5°F and 50% RH by average. This was

assigned as the room testing conditions. The samples were hung in such a manner that they would not touch each other or the chamber walls. This was to insure that each package had full exposure to the testing conditions. (See Figure 12.)

Measurement of weight gained was made periodically. Weight gain of samples was the average of fifteen samples and expressed in the unit of  $\frac{g. \text{ moisture}}{100 \text{ g. dry solid}}$ . Total amount of moisture at different periods was the sum of the initial moisture content and the averaged weight gain of those periods. Results are in Tables 6-8.

The total moisture content of the samples and the time were plotted. The plots of moisture content and time of the same cereal packed in the same film but stored in the two testing conditions were made on the same figure so that the time ratio of the two conditions can be determined (see Figures 1-9).

The time ratio was determined by drawing a straight line from the axis of moisture content parallel to the axis of time passing the curves of accelerated and room conditions. The straight line drawn must pass the curves of accelerated and room conditions. At the points where the straight line passes the curves, the time of accelerated and room conditions was read. By dividing the time at room condition by the time at accelerated conditions, the time ratio can be obtained. Results are in Table 9.

#### Determination of Permeability Constant

Dow Chemical Company which was the film supplier provided the water vapor transmission rates of the three films. Water vapor transmission rates were determined by using standard method ASTM E96-66,

for both room and accelerated conditions. These rates were converted to permeability constant, having the unit of  $\frac{g.(H_2O)(cm)}{(sec)(cm^2)(\Delta atm)}$ , by assuming that the partial pressure of water vapor inside the test dish is 0 atm. The assumption was based on the fact that adsorption of moisture by the desiccant at partial condition is much greater than the diffusion of moisture through the barrier. Results are in Table 2.

#### Determination of Volume of Headspace Gas

The method used resembles that of Griffin (1972). The cereal package was weighed suspended in water at atmospheric pressure. Then it was transferred and sunk in a vacuum desiccator carrying water. The pressure in the desiccator was then reduced until the gases in the package expanded sufficiently to create a condition of neutral buoyancy. The volume of the gas was then calculated from the difference in pressure (atmospheric vs. neutral buoyancy) and the weight of the package suspended in water at atmospheric pressure. Result is in Table 3.

Some errors can be expected from this method, because the volume of headspace gas was determined when the packages were in full expansion, while the package for actual storage test did not expand. Although the error can be relatively high, this will have little effect on the result of the calculation, because most of the water vapor in the package will be adsorbed rapidly by the cereal compared to the very small amount of water vapor left in the headspace gas of the package. This can be seen in the sample of calculation, Example 1. Moisture content of the headspace is 0.000046 gram, while the amount of moisture adsorbed by the cereal is 0.0167 gram. Headspace moisture content accounts for less than 1% of the moisture adsorbed by the cereal. In addition, this method is the only practical method available to the author's knowledge.

#### Determination of Adsorption Isotherms

The adsorption isotherm of each product was determined by using saturated aqueous solutions of salts in contact with an excess of the definite solids phase. Samples of cereals weighing approximately 7 g were placed in an enclosed container over a saturated aqueous solution of a salt maintained at a definite % RH and temperature. Saturated aqueous solutions were prepared to obtain different % relative humidities. (See Table 4.) When equilibrium was reached, the moisture content of the samples was determined using Cenco Moisture Balance. To obtain the adsorption isotherms the moisture contents were plotted against the corresponding % relative humidities.

Adsorption isotherms of the three cereals were determined for both temperatures: 100°F and 76.5°F. Results are in Table 4. The plots of adsorption isotherms of the cereals are in Figures 10 and 11.

	Accelerated Condition	Room Condition
Temperature (°F)	100	76.5
Relative Humidity (%)	70	50
Saturated vapor pressure (atm.)	) 0.065	0.031

DATA

Table 1. -- Data of test conditions.

Table 2.--Data of permeability constant.

Test Conditions	Packaging Films	Permeability constant $((\alpha + 0)(cm))$
		$\overline{P}$ , $\left(\frac{(g, n_2)}{2}\right)$
		$\left((\Delta \text{ atm})(\text{sec})(\text{cm}^2)\right)$
Accelerated	PE (3 mil)	$4.87 \times 10^{-10}$
	PE (14 mil)	$5.24 \times 10^{-10}$
	Saran	$9.53 \times 10^{-11}$
Room	PE (3 mil)	$1.41 \times 10^{-10}$
	PE (1½ mil)	$1.41 \times 10^{-10}$
	Saran	$2.35 \times 10^{-11}$

Table 3. -- Volume of headspace gas and package surface area.

The	average	value of	f headspace	gas was	200	c.c.
The	average	package	surface are	ea was	493.084	cm. <sup>2</sup>

			Mois	ture Cont	ent
Test Condition	Chemical	% RH	$\left(\frac{g}{100}\right)$	. moistur g.dry so	<u>e</u> 11d)
			A	Cereals B	С
100°F	LiCl <sup>(1)</sup>	11.1	2.04	1.21	2.56
	кс <sub>2</sub> н <sub>3</sub> 0 <sub>2</sub> <sup>(1)</sup>	20.4	2.61	1.83	3.52
	$MgCl_2^{(1)}$	31.9	3.09	2.46	4.11
	Cr0 <sub>3</sub> <sup>(1)</sup>	40.2	3.31	2.97	5.04
	κNO <sub>2</sub> <sup>(2)</sup>	45.9	3.90	3.30	5.54
	Na2 <sup>Cr20</sup> 7 <sup>(2)</sup>	50.0	4.00	3.84	6.10
	NaNO2 <sup>(2)</sup>	61.8	6.04	5.93	
76.5°F	ZnCl <sub>2</sub> (2)	10.0	2.25	1.52	2.56
	LiCl <sup>(2)</sup>	15.0	2.30	1.68	2.75
	кс <sub>2</sub> н <sub>3</sub> 0 <sub>2</sub> <sup>(2)</sup>	20.0	2.67	2.25	2.99
	CaCl <sub>2</sub> (2)	32.3	3.09	2.67	3.90
	Cr0 <sub>3</sub> <sup>(2)</sup>	35.0	3.47	2.97	5.04
	κNO <sub>2</sub> <sup>(2)</sup>	48.6	4.07	3.57	5.26
	Na <sub>2</sub> Cr <sub>2</sub> 0 <sub>7</sub> (2)	54.1	4.38	3.83	6.61
	NaNO <sub>2</sub> (2)	64.8	7.18	6.61	9.53

Table 4.--Data of adsorption isotherms.

(1) Wink and Sears 1950.

(2) International Critical Tables.

Test Condition	Como a 1	Initial Moisture Content	Intercept	Slope
lest Condition	Cereal	g. moisture 100 g. dry solid	a	b
Accelerated	А	3.44	1.49	0.051
	В	2.69	0.44	0.066
	С	1.85	1.67	0.083
Room	A	3.44	1.66	0.049
	В	2.69	0.995	0.054
	С	1.85	1.71	0.071

Table 5.--Data of initial moisture content, adsorption isotherms, intercept and slope.

Table 6	Increase of moistur	e content	of cereal A in accele	rated and	room testing conditio	.su
			ROOM CONDITION			
ΡE	(3 mil)	ΡE	(1½ mil)	Sa	Iran	
TIME (days)	moisture content (g. moisture) 100 g. dry solid)	TIME (days)	moisture content (g. moisture 100 g. dry solid)	TIME (days)	moisture content (g. moisture) 100 g. dry solid)	
0	3.437	0	3.437	0	3.437	
16.00	3.868	8.20	3.991	16.00	3.714	
22.32	3.940	15.00	4.412	22.30	3.766	
28.05	3.981	23.32	4.454	28.07	3.796	
35.20	4.033			35.02	3.848	
			ACCELERATED CONDITIO	z		
0	3.437	0	3.437	0	3.437	
0.72	3.653	0.72	4.001	0.72	3.560	
1.00	3.786	1.00	4.207	1.00	3.622	
1.72	4.043	1.72	4.772	1.72	3.807	
2.01	4.104	2.01	4.926	2.01	3.848	

			ROOM CONDITION		
ΡE	(3 mil)	ΡE	: (1½ mil)	Se	ıran
TIME (days) 0	moisture content <u>g. moisture</u> 100 g. dry solid 2.688	TIME (days) 0	moisture content <u>g. moisture</u> <u>100 g. dry solid</u> 2.688	TIME (days) 0	moisture content <u>g. moisture</u> <u>100 g. dry solid</u> 2.688
14.00	3.165	6.29	3.277	14.80	3.033
20.31	3.326	13.00	3.534	21.80	3.284
26.05	3.386	22.04	3.685	26.85	3.314
33.23	3.477			34.03	3.445
			ACCELERATED CONDITIO	N	
0	2.688	0	2.688	0	2.688
0.71	2.943	0.71	3.157	0.71	2.820
1.00	3.024	1.00	3.350	1.00	2.882
1.71	3.310	1.71	3.840	1.71	3.024
2.00	3.371	2.00	3.982	2.00	3.075

Table 7.--Increase of moisture content of cereal B in accelerated and room testing conditions.

			ROOM CONDITION		
PE	(3 mil)		PE (1½ mil)		Saran
TIME (days)	moisture content (g. moisture 100 g. dry solid	TIME (days)	moisture content g. moisture 100 g. dry solid	TIME (days)	moisture content (g. moisture 100 g. dry solid
0	1.847	0	1.847	0	1.847
13.96	2.597	6.16	2.708	13.95	2.283
20.90	2.789	12.96	3.508	20.93	2.414
26.01	2.890	21.94	3.802	26.00	2.526
33.13	3.032	32.13	3.992	33.13	2.617
			ACCELERATED CONDITIC	N	
0	1.847	0	1.847	0	1.847
0.75	2.191	0.75	2.556	0.75	2.090
1.03	2.323	1.03	2.819	1.03	2.191
1.74	2.678	1.74	3.539	1.74	2.424
2.03	2.830	2.03	3.772	2.03	2.516

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Cereal	Film	Moisture Content %	Time of acc. condition (days)	Time of room condition (days)	Ratio $\begin{pmatrix} t_{room} \\ t_{acc.} \end{pmatrix}$
A	PE (3 mil)	3.75	0.9	10.5	11.67
	PE (1½ mil)	3.75	0.45	4.0	8.89
	Saran	3.75	1.60	18.4	11.5
	PE (3 mil)	3.50	0.3	1.9	6.33
	PE (1½ mil)	3.50	0.1	0.6	6.0
	Saran	3.50	0.2	1.8	9.0
В	PE (3 mil)	3.25	1.6	17	10.63
	PE (1½ mil)	3.25	0.85	6	7.06
	Saran	3.25	2.8	22.2	7.93
	PE (3 mil)	3.00	0.80	8	10.0
	PE (1½ mil)	3.00	0.50	2.90	5.8
	Saran	3.00	1.5	11.7	7.8
С	PE (3 mil)	2.50	1.4	11.2	8.0
	PE (1½ mil)	2.50	0.6	4.0	6.67
	Saran	2.50	2	24.8	12.4
	PE (3 mil)	2.25	0.9	6.2	6.89
	PE (1½ mil)	2.25	0.3	2.5	8.33
	Saran	2.25	1.3	14	10.77

Table 9. -- Time ratio of room and accelerated conditions.

Table 1	0Percents calculat	ige difference of ed results.	moisture co	ontent from actual e	xperimental results	and model
Cereal	Film	Test Condition	Time (days)	Mex. ( <u>g. moisture</u> 100 g. dry solid	Mcalc. ( <u>g. moisture</u> (100 g. dry solid)	% diff. % -M_calc. x100 M_ex
A	PE (3 mil)	accelerated	0.72	3.653	3.583	1.92
			1.00	3.786	3.633	4.03
			1.72	4.043	3.764	6.91
			2.00	4.104	3.814	7.06
		room	16.00	3.868	3.578	7.48
			22.32	3.940	3.625	7.98
			28.05	3.981	3.664	7.96
			35.20	4.033	3.709	8.05
В	Pe (1½ mil)	accelerated	0.72	4.001	3.814	4.67
			1.00	4.207	3.934	6.48
			1.72	4.772	4.197	12.04
			2.00	4.926	4.285	13.01
		roon	8.20	3.991	3.644	8.70
			15.00	4.412	3.766	14.64
			23.32	4.454	3.873	13.05

ALUAL	דה לכסוורדוותפת	1				
А	Saran	accelerated	0.72	3.560	3.525	1.0
			1.00	3.622	3.558	1.72
			1.72	3.807	3.640	4.39
			2.00	3.848	3.671	4.60
		room	16.00	3.714	3.531	4.93
			22.30	3.766	3.564	3.57
			28,07	3.796	3.592	5.37
			35.20	3.848	3.625	5.79
B	PE (3 m11)	accelerated	0.71	2.943	2.860	2.83
			1.00	3.024	2.925	3.28
			1.71	3.310	3.079	6.97
			2.00	3.371	3.139	6.87
		room	14.00	3.165	2.898	8.43
			20.31	3.362	2.978	11.41
			26.05	3.386	3.044	10.10
			33.23	3.477	3.118	10.32

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Table 10 (continued)

	-1.81	-1.32	1.99	2.67	8.91	9.28	7.76	1.52	2.44	4.24	4.75	7.17	12.60
	3.214	3.394	3.764	3.890	2.985	3.206	3.399	2.777	2.812	2.896	2.929	2.815	2.870
	.157	.350	.840	.980	.277	.534	.685	.820	.882	.024	.075	.033	.284
	ŝ	ſ	£	ς	£	£	e	5	3	ĉ	ſ	ę	£
	0.71	1.00	1.71	2.00	6.29	13.00	22.40	0.71	1.00	1.71	2.00	14.80	21.80
	elerated				E			elerated				Ħ	
(1	acc				1001			acci				1001	
contruned	(1½ mil)							ran					
	PE							Sa					
TOPT	æ							В					

Table 10 (continued)

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12.26 14.15

2.908 2.958

3.314 3.445

26.85 34.03

U	PE (3 mil)	accelerated	0.75	2.191	2.240	-2.25
			1.03	2.320	2.382	-2.68
			1.74	2.678	2.805	-4.75
			2.03	2.830	2.851	-0.75
		room	13.96	2.597	2.443	5.91
			20.90	2.789	2.703	3.38
			26.01	2.890	2.876	0.49
			33.13	3.032	3.098	-2.19
C	PE (1½ mil)	accelerated	0.75	2.556	2.962	-15.80
			1.03	2.819	3.193	-13.26
			1.74	3.539	3.929	-11.03
			2.03	3.772	4.191	-11.12
		room	6.16	2.708	2.195	18.93
			12.96	3.508	2.533	27.80
			21.94	3.802	2.923	23.13
			32.13	3.994	3.298	17.43

Table 10 (continued)

Saran	accelerated	0.75	2, 090	2.079	0.52	l
		1.03	2.191	2.171	0.93	
		1.74	2.424	2.377	1.92	
		2.03	2.516	2.459	2.25	
	room	13.95	2.283	2.188	4.18	
		20.93	2.414	2.343	2.94	
		26.00	2.526	2.450	2.99	
		33.13	2.617	2.595	0.82	

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Table 10 (continued)

Note M \_ moisture content from actual experimental test ex.

M<sub>calc.</sub> - moisture content from model calculation.

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Figure 1.--Moisture content vs. time of cereal A in PE (3 mil).



Figure 2.--Moisture content vs. time of cereal A in PE ( $1\frac{1}{2}$  mil).



Figure 3.--Moisture content vs. time of cereal A in Saran.



Figure 4.--Moisture content vs. time of cereal B in PE (3 mil).



Figure 5.--Moisture content vs. time of cereal B in PE (1<sup>1</sup>/<sub>2</sub> mil).



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Figure 12. -- Samples in humidity chamber.

#### SAMPLE OF CALCULATION

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Cereal A packed in PE (3 mil) will be used for the following illustrations.

## Example 1. Determination of Moisture Content by Using the Model to Compare the Result With That of the Experimental Test

The experimental moisture content of cereal A packed in PE (3 mil) stored under room conditions for 16.00 days is 3.868

<u>g. moisture</u> 100 g. dry solid , from Table 6. To see if the model gives adequate predictions, the model is used to determine the moisture content at such conditions.

$$t = \frac{1}{J} \ln \left( \frac{H_0 - H_1}{H_0 - H_1(t)} \right)$$
(12)

or

$$\frac{H_0 - H_1}{H_0 - H_1(t)} = e^{Jt}$$
(13)

where

- $H_0 =$ outside relative humidity at room condition --50%, from Table 1,

m = a + bH

where

- m = initial moisture content of cereal A = 3.44  $\frac{g. \text{ moisture}}{100 \text{ g. dry solid}}$ , from Table 5,
- a = adsorption isotherm intercept of cereal A = 1.66, from Table 5,
- b = adsorption isotherm slope of cereal A = 0.049, from Table 6.

So

$$H_{i} = \frac{3.44 - 1.66}{0.049} = 36.3\%$$
  

$$t = \text{time of store} = 16.00 \text{ days} = 1,382,400 \text{ sec,}$$
  

$$J = \text{constant,}$$
  

$$= \frac{\overline{P} \cdot \frac{A}{x} \cdot \frac{P_{s}}{100}}{\left(18 \cdot \frac{P_{s}}{100} \cdot \frac{V}{RT} + \frac{bW}{100}\right)}$$

where

$$\overline{P} = \text{permeability constant of PE (3 mil) at 76.5°F} = 1.41 \times 10^{-10} \frac{(g.H_2^{0})(cm)}{(sec)(cm^2)(\Delta \text{ atm})}, \text{ from Table 2,}$$

$$A = \text{package surface area} = 493.084 \text{ cm}^2, \text{ from Table 3,}$$

$$x = \text{thickness of the film} = 3 \text{ mil} = 0.00762 \text{ cm,}$$

$$P_x = \text{saturated water vapor pressure at } 100°F = 0.031 \text{ atm,}$$

$$V = \text{headspace volume of the package} = 200 \text{ e.c., from Table 3,}$$

$$R = \text{gas constant} = 82.06 \frac{\text{c.c. atm}}{^\circ \text{C mole}}$$

$$T = \text{absolute temperature of } 76.5°F = 297.4°K,$$

$$W = \text{dry weight of cereal A} = 34.034 \text{ g.}$$

$$J = \frac{(1.41 \times 10^{-10}) \left(\frac{493.084}{0.00762}\right) \left(\frac{0.031}{100}\right)}{\left(\frac{18 \ (0.031) \ (200)}{(100) \ (82.06) \ (297.4)}\right) + \frac{(0.049) \ (34.034)}{100}}$$
$$= \frac{2.83 \times 10^{-9}}{-----} = 1.69 \times 10^{-7}$$

Substitute all the known values in Equation (12),

0.000046 + 0.0167

So

$$\frac{50 - 36.3}{50 - H_{i(t)}} = e^{(1.69 \times 10^{-7})(1,382,400)}$$
$$H_{i(t)} = 39.15$$

Then the moisture content can be calculated from the relative humidity by Equation (4),

$$m = a + bH$$
  
= 1.66 + (0.049)(39.15) = 3.578

So, the calculated moisture content is  $3.578 \frac{\text{g. moisture}}{100 \text{ g. dry solid}}$ . The difference between experimental result and the prediction is  $\frac{3.868 - 3.578}{3.868} = 0.0748 \text{ or } 7.48\%$ . The result can be seen in Table 10.

## Example 2. Prediction of Cereal's Shelf-Life

Considering cereal A packed in PE (3 mil) again, if cereal A has the critical moisture content of about 4.000 g./100 g. dry solid,

the shelf-life of cereal A can be determined by the following solution.

Determine the critical relative humidity by using Equation (4)

$$m = a + bH$$

$$H = \frac{4.00 - 1.66}{0.049} = 47.76$$

Determine shelf-life (t) by using Equation (12)

$$t = \frac{1}{J} \ln \left( \frac{H_0 - H_i}{H_0 - H_i(t)} \right)$$

where

 $H_0 =$ outside relative humidity of the package, assume 50%;

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H<sub>i</sub> = initial relative humidity of cereal A which can be determined if the initial moisture content is known by using Equation (4); for the purpose of illustration the initial moisture content of 3.44 was drawn from Table 5 in which it gives H<sub>i</sub> of 36.3%;

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$$J = constant = 1.69 \times 10^{-7}$$
.

So

t = 
$$\frac{1}{1.69 \times 10^{-7}}$$
 ln  $\left(\frac{50 - 36.3}{50 - 47.76}\right)$  = 4.14 months.

#### DISCUSSION AND CONCLUSION

Traditionally, the food industry used accelerated tests for determining shelf-lives of food products. Shelf-life of a food product is determined by multiplying the duration that causes deterioration to the product at accelerated condition by the time ratio of room to accelerated conditions. For example, if the duration that causes deterioration to a product at accelerated conditions is 20 days and the time ratio of room to accelerated conditions is 15 (note that these selected numbers were picked just for the purpose of illustration--they do not belong to any particular test product), then shelf-life of the product is 20 times 15 which is 300 days. Accelerated tests allow the prediction without having to wait for the result as long as 300 days. However, in this case the test has to be performed for not less than 20 days, until the product will be deteriorated at accelerated conditions. Testing in a laboratory for 20 days may cost a lot of money and this requires controlled experimental units which usually are expensive. Due to the fact that shelf-life studies by accelerated tests are expensive and time consuming or the refusal to note some scientific facts, the food industry occasionally assumes the use of the same time ratio for other "like" products in predicting their shelf-lives. Considering this same example, when the time ratio of a product was determined

to be 15, they may assume that the time ratios of other "like" products are 15, too.

This is not correct, as we see in Table 9 where all the time ratios of all three cereals packed in different packaging films are shown. One can see that the time ratios of the three cereals packed in the same film do not have the same value. The time ratio of cereal A packed in PE (3 mil) is 11.67, while those of cereals B and C both in PE (3 mil) are 10.63 and 8.0, respectively. If the duration that causes deterioration at accelerated conditions to the three cereals is 20 days, shelf-lives of cereals A, B and C will be  $20 \times 11.67 = 233.4$  days,  $20 \times 10.63 = 212.6$  days, and  $20 \times 8.0 = 160$ days, respectively. We can see that shelf-lives of the three cereals are different and the differences are 0%, 8.9% and 31.4% from 233.4 days. Notice that the actual durations that cause deterioration at accelerated conditions to the three cereals were not determined because there was no intention of finding their actual shelf-lives, but to prove the objective of this research.

In addition, the time ratios at different points on the curves in Figures 1-9 are not the same. In Table 9, the time ratios of cereal A packed in PE (3 mil) at the points where moisture contents are 3.75% and 3.5% are 11.67 and 6.33, respectively. The time ratios of the same cereal packed in different films are different, too. The time ratios of cereal A packed in PE (3 mil), PE (1-1/4 mil) and Saran are 11.67, 8.89 and 11.5, respectively. So it is rather inappropriate to assume that the time ratios are the same

because the error of this assumption can be as high as 30.0% or higher.

Different cereals packed in the same film and the same cereal packed in different films will have, more or less, different shelf-lives. If the accelerated test is to be used for determination of their shelf-lives, actual testing should be done to all of them, because shelf-life depends on various factors. In the case of cereals which were packed in packaging films, shelf-life depends on the water vapor adsorptions of the cereals and the water vapor permation rates through the packaging films. Since the water vapor adsorptions of different cereals and water vapor permation rates through different films are not the same, it is inaccurate to assume that their shelf-lives are of the same values without any actual tests. However, to perform actual tests of all these products and packages is relatively expensive in terms of money, time and manpower expended. Therefore, other alternatives which enable prediction of shelf-life with less time and expense should be applied. That other alternative is the use of a mathematical model.

The mathematical model developed for this research is specifically for cereal products which have moisture content as the determining criterion. The model includes most important considerations expressed in terms of equations which make it a simple and potentially useful tool.

The mathematical model gives adequate predictions. A comparison of the model-predicted values and the actual experimental results appear in Table 10. (See Figures 1-9 for graph comparisons.)

The experimental results of the three cereals agree fairly well with the predictions. The percentage difference is in the range of 10-20% difference. The difference between experimental and predicted results is due to many reasons:

(i) Testing conditions, either the temperatures or relative humidities, were not constant as stated; the conditions fluctuated slightly from time to time. The conditions stated were the average values of periodical measurements of the testing conditions.

(ii) The model assumes the use of straight line adsorption isotherms between relative humidities of 10-50%.

(iii) The model developed under many assumptions as stated before.

(iv) The unevenness of the films' thicknesses.

Prediction of cereal A's shelf-life packed in PE (3 mil) is shown in the Sample of Calculation, Example 2. One should not be surprised to find that shelf-life of the cereal is short, because this is not true. In fact, cereal A has a longer shelf-life than that shown in Example 2. Cereal A was predicted to have a life of 4.14 months because its initial moisture content was relatively high  $(3.44 \frac{g. moisture}{100 g. dry solid})$ . Normally, the initial moisture contents of most cereals when freshly produced are around  $2 \frac{g. moisture}{100 g. dry solid}$ . The initial moisture content of cereal A was high because after the cereal was brought from the manufacturer's storage, it was kept before its initial moisture was determined, for more than a week. During that time the cereal container was opened many times to the atmosphere. However, this is not critical, because it was not the intention of this research to determine the definite shelf-life of any cereals, but to show that the model can be used for the prediction. If the initial moisture content of cereal A is 1.7  $\frac{\text{g. moisture}}{100 \text{ g. dry solid}}$ , its shelf-life can be as high as 12.6 months assuming that its critical moisture content is 4.100  $\frac{\text{g. moisture}}{100 \text{ g. dry solid}}$ .

Prediction of shelf-life using a mathematical model can be done within a relatively short time and is less expensive when compared to other traditional methods. It is also possible to apply the mathematical model to package design and optimization in selecting the suitable and inexpensive packaging material which insures high quality and long life. This can be done if permeability constants of packaging materials having different prices were known.

#### SUMMARY

The accelerated test technique is an expensive method in terms of money, time and manpower expended. It has been shown that the technique is not appropriate for the prediction of shelf-life when it assumes the use of the same time ratio for all "like" products. A mathematical model was developed specifically for cereals which have moisture content as the determining criterion. It includes the theoretical considerations and gives adequate predictions. Prediction by the model can be done in a relatively short time and costs less, and it is also possible to apply for package design and optimization.

The model is suggested to be applicable to other food products which have moisture content as the determining criterion. In the case where straight line equations cannot be well fitted to the adsorption isotherms, or in the case when the temperature is not constant, other equations should be developed. This might require a computerized technique to aid the prediction.

REFERENCES

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#### REFERENCES

- ASTM E 96-66. Standard methods of test for water vapor transmission of materials in sheet form, 1968.
- Caurie, M., 1970. A new model equation for predicting safe storage moisture levels for optimum stability of dehydrated foods. J. Food Tech. 5(3): 301-7.
- Caurie, M., 1971. A single layer moisture absorption theory as a basis for the stability and availability of moisture in dehydrated foods. J. Food Tech. 6(2): 193-201.
- Easter, R. A., 1953. Forecasting shelf-life. Mod. Pkg. 26(6): 128-30, 174, 176, 178, 181.
- Felt, C.E., Buechele, A. C., Borchardt, L. F. and Koehn, R. C., 1945. Determining shelf-life of packaged cereals. Cereal Chem. 22(3): 261-71.
- Griffin, R. C., 1972. Testing. Package Development. Sept./Oct., pp. 16-19.
- Gyeszli, I., 1971. Gas and vapor permeability of the double wall compared to single wall plastic packages. M.S. thesis, Michigan State University.
- Heiss, R. and Eichner, E., 1971a. Moisture content and shelf-life I. Food Man. 46(5): 53-6, 65.
- Heiss, R. and Eichner, E., 1971b. Moisture content and shelf-life II. Food Man. (46(6): 37-8, 41-2.
- Henig, Y. S., 1975. Computer analysis of the variables affecting respiration and quality of produce packaged in polymeric films. J. Food Sci. 40(5): 1033-35.
- Iglerias, H. A., Chirife, J. and Lombardi, J. L., 1975. An equation correlating equilibrium moisture content in foods. J. Food Tech. 10(3): 289-97.

International Critical Tables, Vol. 1, pp. 67-8, 1926.

Karel, M., Mizhari, S. and Labuza, T. P., 1971. Computer prediction of food storage. Mod. Pkg. 44(8): 54-8.

- Labuza, T. P., Mizhari, S. and Karel, M., 1972. Mathematical model for optimization of flexible film packaging of foods for storage. Trans. of the ASAE 15(1): 150-55.
- Labuza, T. P., McNally, L., Gallagher, D., Hawkers, J. and Hurtado, F., 1972. Stability of intermediate foods. 1. Lipid Oxidation. J. Food Sci. 37(1): 154-59.
- Lebovils, A., 1966. Permeability of polymers to gases, vapors and lipids. Mod. Plas. 43(3): 139-42, 144, 146, 150, 194, 196, 198, 200, 202, 205-6, 208, 210, 213.
- Major, C. J. and Kammermeyer, K., 1962. Gas permeability of plastics. Mod. Plas. 39(7): 135, 138, 140, 142, 145-6, 179-80.
- Mizhari, S., Labuza, T. P. and Karel, M., 1970. Computer aided predictions of extent of browning in dehydrated cabbage. J. Food Sci. 35(6): 799-803.
- Quast, D. G. and Karel, M. 1972. Computer simulation of storage life of foods undergoing spilage by two interacting mechanisms. J. Food Sci. 37(5): 679-83.
- Quast, D. G., Karel, M. and Rand, W. M., 1972. Development of a mathematical model for oxidation of potato chips as a function of oxygen pressure, extent of oxidation and equilibrium relative humidity. J. Food Sci. 37(5): 673-78.
- Quast, D. G. and Karel, M., 1973. Simulating shelf-life. Mod. Pkg. 46(3): 50, 52-4, 56.
- Reeves, R. L. and Kilgore, W. E., 1964. Water vapor transmission through sacks and sack papers. TAPPI 47(7): 408-12.
- Rockland, L. B., 1969. Water activity and storage stability. Food Tech. 28(10): 1241-48.
- Rogers, C. E., 1964. "Permeability and chemical resistance," in <u>Engineering Design for Plastics</u>, edited by E. Bear, Reinhold Publishing Corporation, New York.
- Sapers, G. M., Panasink, O. and Talley, F. B., 1974. Flavor quality and stability of potato flakes. Effects of drying conditions, moisture content and packaging. J. Food Sci. 39(3): 555-58.
- Wink, W. A. and Sears, G. R., 1950. Instrumentation studies LVII. Equilibrium relative humidities above saturated salt solutions at various temperatures. TAPPI 33(9): 96A-99A.

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