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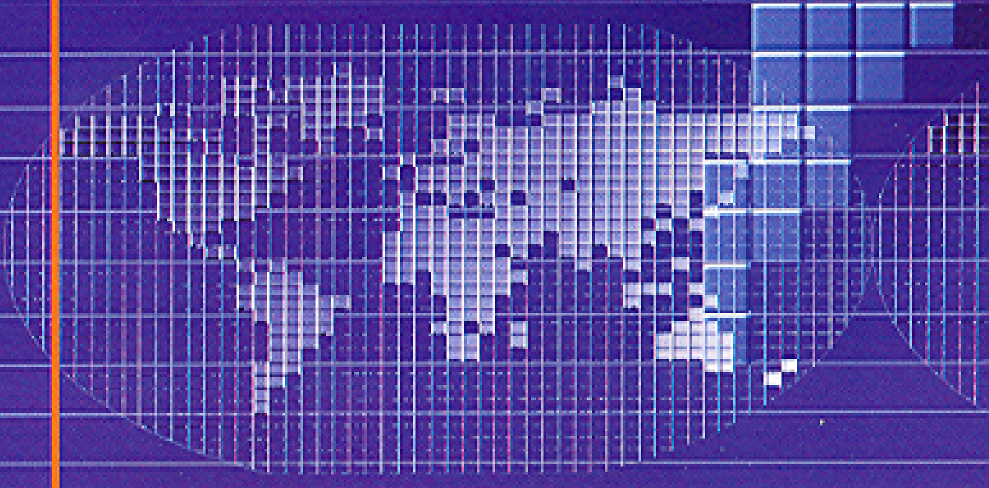

Aim and Scope

The *Journal of Applied Packaging Research* is an international forum for the dissemination of research papers, review articles, tutorials and news about innovative or emerging technologies for the packaging industry. The journal is targeted towards the broad packaging community including packaging scientists and engineers in industry or academic research and development, food scientists and technologists, materials scientists, mechanical engineers, industrial and systems engineers, toxicologists, analytical chemists, environmental scientists, regulatory officers, and other professionals who are concerned with advances in the development and applications of packaging.

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CONTENTS

Modified Atmosphere Packaging for Fresh-Cut Produce with Microperforated Films

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ABSTRACT: Application of modified atmosphere packaging (MAP) to fresh cut produce is challenging due to high respiration rate requirements. Perforations are being increasingly used when gas permeation rates of packaging films do not meet respiration requirements. Microperforations add value to film without significant increase in cost. Produce suppliers should validate MAP designs to verify necessity of perforations for fresh-cut produce.

The objective of this project was to verify MAP designs and justifications for microperforations for five commercially available fresh-cut products including rutabaga, sweet potato, yellow squash, a 50/50 blend of yellow squash and zucchini and turnip. Experiments involved determination of product respiration rates and packaging film oxygen transmission rates (OTR). Respiration rates were determined using an unsteady-state method in temperature controlled chambers at 1, 8 and 15°C. OTRs were determined at 15, 23 and 35°C using a commercial OTR analyzer. Target respiration rates were determined from functions representing derivatives of curves fitted to changes in headspace versus time. Changes in headspace oxygen were described by a hyperbolic decay curve, while production of CO_2 was described by a hyperbolic curve. Temperature sensitivities of respiration rates and OTR were estimated using the Arrhenius relationship. Results suggest that non-perforated films with OTRs of 3000, 6000, 1500, 1500 and 1500cc O_2/N_2.day would satisfy MAP requirements for rutabaga, sweet potato, yellow squash, a 50/50 blend of yellow squash and zucchini and turnip, respectively. Therefore, microperforations were probably justified for only fresh-cut sweet potato.

INTRODUCTION

CONSUMER demand for fresh and convenient foods has led to the growth of modified atmosphere packaging (MAP) as a technique to extend shelf life and reduce waste for a wide range of foods (Martinez et

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al., 2002). Fresh produce is particularly challenging to package because products contain living tissues that require adequate gas exchange to remain fresh. Produce respiration rate is one of the best measures that can be used to predict of shelf life. Generally, lower respiration rate translates into longer shelf life. Rate of respiration typically varies with oxygen concentration and inversely to carbon dioxide concentration. The goal of MAP is to design a package that provides an optimal level of oxygen and carbon dioxide transmission to match reduced respiration rate requirements of the produce.

RESPIRATION

Respiration in fruits and vegetables can be described by the following chemical reaction (Ryall and Pentzer, 1979; 1982):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy} \tag{1}$$

Attempts have been made to model respiration of fruits and vegetables with Michaelis Menten type kinetics with competitive inhibition of oxygen consumption by the production of carbon dioxide (Lee et al., 1991; Hagger et al., 1992).

Lowering the O_2 level around fresh fruits and vegetables reduces their respiration rate in proportion to the O_2 concentration, but a minimum of about 1–3% O_2 depending on the commodity, is required. Otherwise respiration will shift from aerobic to anaerobic. The glycolytic pathway replaces the Krebs cycle as the main source of energy for the plant tissues. Byproducts such as acetaldehyde and ethanol are formed which give off flavors and spoil the product (Kader, 1986). Injuring fruit and vegetable tissue by slicing generally increase the respiration rate 3 to 5 fold. The respiration rate also increases 2 to 3 fold as the product ages. (Laties, 1978).

PERMEATION

To maintain a desired atmosphere within a package, rates of gas permeation through the package must match respiration demands of products. This steady state relationship is described by Equation (1) (Robertson, 1993).

$$WR = \frac{\bar{P} A \Delta p}{L} \tag{2}$$

where W is the weight of produce, R is the respiration rate of produce (amount of gas/(weight of produce x time)), $\overline{P}$ is the gas permeation coefficient for the gas of interest through the particular plastic at a specified temperature (amount of gas x film thickness/(area of film x gas partial pressure difference on either side of the film x time), A is the area of the plastic package, Δp is partial pressure difference and L is film thickness.

Oxygen transmission rate (OTR) is often measured for particular films. OTR is related to permeability, $\overline{P}$, via Equation (2).

$$OTR = \frac{\overline{P}}{\Delta p \cdot L} \tag{3}$$

OTR is often measured using 100% oxygen as the test gas, which provides the maximum driving force for oxygen transmission (1 atm), and higher analytical resolution. OTR requirements may be predicted for air by combining Equations (1) and (2) by rearranging to form Equation (4).

$$\left(\frac{21}{100}\right) OTR = \frac{RW}{A(0.21 - p_{inside})} \tag{4}$$

where R is respiration rate of produce, W is the weight of the produce in the package, A is package area, and p_{inside} is the desired partial pressure of oxygen inside the package.

Determination of ideal storage conditions (temperature and gas compositions) for products requires extensive experimentation under controlled conditions. Often, ideal conditions vary considerably for any particular product and may be a function of produce size, geometry, cultivar, season, etc. Therefore, ideal conditions are better described as ideal ranges of conditions and therefore, package designs tend to be conservative. The following conditions for produce items related to those studied here were found in the literature.

PERFORATED FILMS

Many attempts have been made to model the transmission rates of gases through perforated films. Emond et al. (1991) and Fonseca et al. (1996) made empirical models of diffusion of gases through perforated films. Fishman et al. (1996) modeled the transmission rate of gases after Ficks law of diffusion while Hirata et al used Grahams law of diffusion. Renault (1994) model the diffusion of gas through perforated films with

Maxwell Stefans law. In this experiment the OTR of perforated samples and non perforated samples were measured and the OTR of package was calculated by Equation (5).

$$\text{Total Bag OTR} = OTR_{film} \text{ x Film Area} + OTR_{perf} \times \text{Perf Area} \quad (5)$$

Rutabagas

Rutabagas should be stored in an atmosphere of approximately 5% CO_2 and > 5% O_2 between 1°C and 3°C for maximum shelf life (Gorny, 1997).

Sweet Potato

Sweet Potatoes should be stored in an atmosphere of approximately 6.5% CO_2 and >12% O_2 between 0°C and 4°C for maximum shelf life (http://usna.usda.gov/hb66/147freshcutvegetables.pdf).

Squash

Squash is highly perishable and should not be stored for more than 2 weeks. Optimal storage conditions are 5°C to 10°C at 95% RH (Hardenburg et al., 1986). Lower oxygen atmospheres are of no beneficial use for Squash (Leshuk and Saltveit, 1990; Mencarelli et al., 1983). Squash is susceptible to chilling injury at temperatures below 5°C. (Ryall and Lipton, 1979).

Zucchini

Sliced zucchini develops water soaked areas (chilling injury) at 0°C and brown discoloration between 5°C and 10°C, which increases with storage duration. Zucchini slices can be dipped in solutions of $CaCl_2$ alone or with NaOCl. Calcium treatments reduce development of decay and total microbial growth, and ascorbate loss. Optimal storage conditions for zucchini are 0.25% to 1% oxygen at 0°C to 5°C (Gorny, 1997).

Turnips

Turnips can be held 4 to 5 mo at 0°C (32°F) with 90 to 95% RH. An ideal atmosphere has not been determined for turnips 6 (http://usna.usda.gov/hb66/140turnip.pdf).

The objectives of this work were to verify performance of commercially produced MAP packages and assess necessity for cost-adding film perforations used produce certain fresh-cut product packages.

MATERIALS AND METHODS

Headspace Analysis

Bagged product samples were shipped to the University of Florida via overnight delivery in insulated packaging equipped with two freezer cold packs. Several shipments contained temperature recorders that showed product enroute approximately 18 hours with temperatures generally between 4 and 10°C (Figure 1).

Upon arrival at our laboratory, products were placed in a 1–3°C controlled environmental chamber for about 24 to 48 hours prior to use. A dab of silicone sealant was applied to each bag upon arrival in order to create a septum through which a needle was inserted to sample achieved headspace gas compositions of product samples. A headspace analyzer (Pack Check, Mocon, Inc., Minneapolis, MN) was used to determine oxygen and carbon dioxide concentrations in sample headspaces. Table 1 shows results of headspace measurements.

Product Respiration Rates

Product respiration rates were measured using an unsteady-state method [3]. Briefly, a given amount of product is placed in hermetically

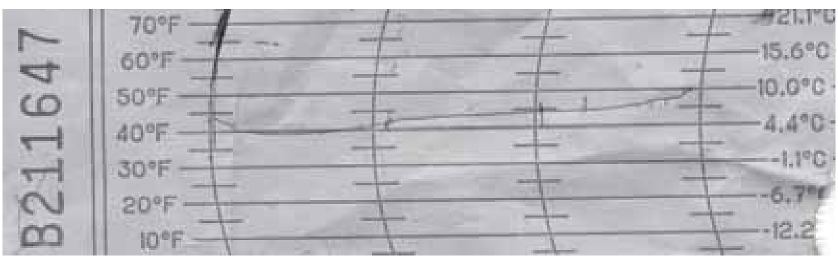

Figure 1. *Actual data logger results for sample shipment from commercial producer to University of Florida.*

Table 1. *Headspace data from bagged samples.*

Item	O_2 (%) Mean	O_2 (%) S.D.	CO_2 (%) Mean	CO_2 (%) S.D.	Density (g/cm^3)	Density S.D.
Rutabaga	8.30	3.16	10.81	2.22	1.00	0.001
Sweet Potato	11.17	5.88	9.41	5.34	0.95	0.015
Squash	15.51	1.20	7.51	1.22	0.88	0.008
Squash and Zucchini	13.45	1.38	8.71	1.19	0.90	0.040
Turnips	7.46	2.69	11.32	2.10	0.90	0.012

Means and standard deviations for headspace data are from 10 samples. Average density values and standard deviations calculated from 3 samples.

sealed jars and changes in headspace gas compositions are monitored over time. Empirical curves are fitted to gas versus time data and mathematical derivatives of these curves (instantaneous slopes), provide respiration rates as a function of gas composition.

One quart mason jars were used for unsteady-state respiration experiments. Holes were drilled (about 1/2 inch) into mason jar lids to accommodate a rubber septum. Prior to conducting respiration experiments, product densities were measured via water displacement in the jars (Table 1). Product densities were used to calculate head space gas volume from the difference between container volume and sample volume. Nine Samples of each product (ca. 125 g) were placed in each jar. For Squash and Zucchini samples, about half was squash and half was zucchini, by weight. Lids were placed firmly on jars and holes were sealed with rubber septa. Three samples of each product were placed in controlled environmental chambers set at 1, 8 and 15°C. Oxygen and carbon dioxide concentrations were measured periodically using the headspace analyzer (Pac-Check, Mocon, Inc., Minneapolis, MN). Samples stored at 15, 8 and 1°C were measured about every 2 hours, 4 hours, and 12 hours, respectively.

Oxygen Transmission Rate (OTR) Measurements

Some bags possessed multiple perforations (Sweet Potato, Squash, Squash and Zucchini and Collard Greens) other did not (Rutabaga and Turnips). Oxygen transmission rates for all samples were measured in duplicate at 15, 23 and 35°C.

Non-Perforated Film Areas

Two samples from the front panel of the package of each product were prepared by cutting a 100 cm^2 sample films using a standard cutting die and razor knife. Film sample were then mounted into the oxygen transmission rate analyzer (Oxtran 2/20, Mocon, Inc., Minneapolis, MN).

Perforated Samples

Perforated samples were prepared using a masking technique. Briefly, representative perforations were selected and foil masks were applied to the surrounding film. Masked samples incorporated a fixed film area containing one perforation. All masked sample areas were 5.07 cm^2 except for the Collard Green sample , which was 0.79 cm^2. Oxygen transmission rates for all masked samples were measured in duplicate at 15, 23 and 35°C using the Mocon Oxtran 2/20 (Mocon, Inc., Minneapolis, MN).

RESULTS AND DISCUSSION

Headspace

Sample headspace data proved to be highly variable, as seen by relatively large standard deviations in Table 1. However, data appear to be in desirable ranges.

Respiration

Changes in carbon dioxide and oxygen concentrations with time showed approximately linear or hyperbolic trends. Squash and Zucchini at 15°C, Rutabaga at 15°C and 8°C and Turnips at 15°C and 8°C showed nonlinear behavior. For oxygen, a hyperbolic decay function was used to fit data using non-linear regression [Equation (4)]:

$$y = y_0 + \frac{ab}{b + x} \qquad (6)$$

Where y is oxygen concentration, x is time and y_0, a, and b are coefficients. For carbon dioxide, a hyperbolic function was used to fit data using a non-linear regression [Equation (5)]:

$$y = y_0 + \frac{ax}{b + x} \tag{7}$$

where y is carbon dioxide concentration, x is time and y_0, a, and b are coefficients. Figure 2 shows changes in gas compositions for Rutabaga at 15°C. Measured data and fitted curves are shown in Figure 6 and fitted curve coefficients are provided in Table 2.

Some products could be reasonably approximated as linear for changes in oxygen and carbon dioxide with time. These data were fitted with Equation 6.

$$y = ax + b \tag{6}$$

where y is either oxygen or carbon dioxide concentration, x is time and a, and b are coefficients. Table 2 provides coefficients for all products at all temperatures for oxygen. Data fitted with Equation 6 are indicated with the term, Linear in the yo column of Table 2.

Rates of respiration for both oxygen and carbon dioxide were calculated from the derivatives of the non-linear regression functions. Cases where gas compositions changed linearly with time suggested that respiration rate was not a strong function of gas composition under the spe-

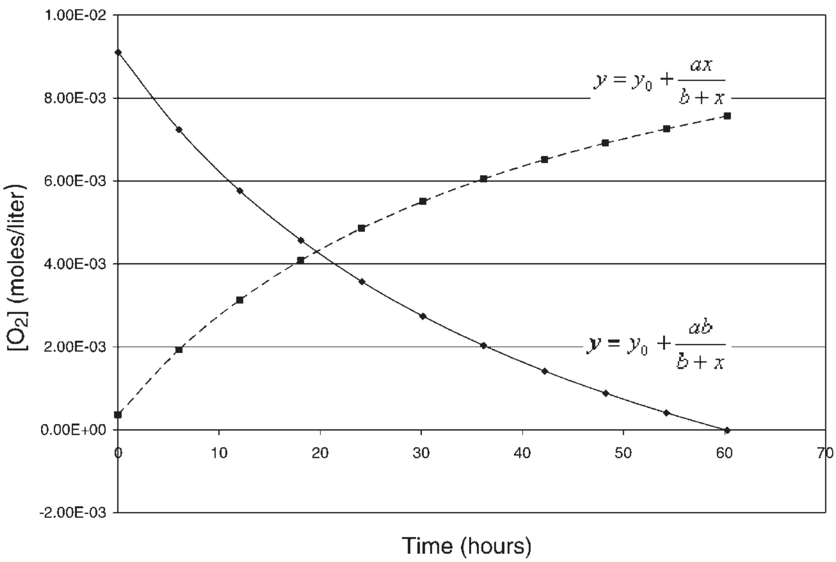

Figure 2. Unsteady state respiration data for Rutabaga at 15°C.

Table 2. *Oxygen respiration coefficients and estimated respiration rates at target oxygen concentrations in packages.*

	Temp (°C)	y_0 (mol.liter)	*a*	*b*	r^2	Desired O_2	Avg HS (cm^3)	Avg Wt (g)	O_2 (mol)	[O_2] (mol.l)	t (hrs)	R O_2 (mol/l/kg/day)
Rutabaga	15	–6.95E–03	1.60E–02	4.590E+01	0.9972	8.0%	785.04	125.41	2.6560E–03	3.3833E–03	25.38	1.156E–03
	8	–4.71E–03	1.42E–02	7.827E+01	0.9962	8.0%	784.97	125.48	2.7219E–03	3.4675E–03	57.57	4.799E–04
	1	–2.37E–02	3.26E–02	1.074E+03	0.9980	8.0%	785.11	125.34	2.7919E–03	3.5561E–03	211.10	1.692E–04
Sweet Potato	15	–1.41E–02	2.35E–02	3.676E+01	0.9942	12.0%	778.04	125.60	3.9485E–03	5.0749E–03	27.16	1.683E–03
	8	–1.88E–02	2.84E–02	8.656E+01	0.9966	12.0%	777.99	125.65	4.0466E–03	5.2013E–03	59.28	9.186E–04
	1	Linear	1.00E–04	9.600E–03	0.9939	12.0%	778.05	125.59	4.1502E–03	5.3341E–03	Constant	1.000E–04
Squash	15	–1.63E–02	2.55E–02	7.792E+01	0.9993	10.0%	767.13	125.46	3.2443E–03	4.2291E–03	59.86	8.343E–04
	8	Linear	1.00E–04	9.600E–03	0.9765	10.0%	767.53	125.11	3.3268E–03	4.3344E–03	Constant	1.000E–04
	1	Linear	6.00E–05	1.000E–02	0.9672	10.0%	767.37	125.25	3.4110E–03	4.4451E–03	Constant	6.000E–05
Squash and Zucchini	15	–3.42E–03	1.29E–02	2.951E+01	0.9986	10.0%	770.28	125.22	3.2576E–03	4.2291E–03	26.05	9.824E–04
	8	Linear	1.00E–04	9.600E–03	0.9917	10.0%	770.12	125.36	3.3380E–03	4.3344E–03	Constant	1.000E–04
	1	Linear	5.00E–05	1.000E–02	0.9666	10.0%	767.37	125.25	3.4110E–03	4.4451E–03	Constant	5.000E–05
Turnips	15	–9.15E–03	1.81E–02	7.997E+01	0.9914	7.5%	770.31	125.31	2.4433E–03	3.1718E–03	69.27	5.175E–04
	8	–5.73E–03	1.47E–02	1.628E+02	0.9954	7.5%	769.94	125.64	2.5029E–03	3.2508E–03	145.08	2.013E–04
	1	Linear	2.00E–05	8.000E–03	0.9682	7.5%	770.06	125.52	2.5673E–03	3.3338E–03	Constant	2.000E–05

Table 3. *OTR values for non-perforated film samples.*

Item	15°C (cc/m²/day)	23°C (cc/m²/day)	35°C (cc/m²/day)
Rutabaga	691	1,052	2,223
Sweet Potato	1,027	1,667	3,068
Squash	1,016	1,667	3,344
Squash and Zucchini	982	1,552	3,133
Turnips	763	1,241	2,317
Collard Greens	685	1,044	2,094

cific test conditions and these were considered to be a constant equal to the slope of the fitted curve. Rates of oxygen consumption were similar to carbon dioxide evolution, suggesting respiration quotients, RQ, of about unity for all products. Therefore, further calculations were based solely on oxygen consumption. Table 2 provides additional data used to estimate average rates of oxygen consumption at apparently desirable package oxygen levels for each product at each temperature.

Oxygen Transmission Rates

Average OTR values for non-perforated and perforated film sections are provided in Tables 3 and 4, respectively.

Non-perforated samples displayed classical Arrhenius type temperature sensitivity (Figure 3). Therefore, the Arrhenius equation may be used to predict OTR values for films at particular temperatures of interest. The Arrhenius equation is described by Equation (7).

$$\ln(OTR) = \ln(k_0) - \frac{E_a}{RT} \tag{7}$$

where k_0 is a constant, E_a is activation energy (joules/mole), R is the ideal gas law constant (8.314 joules/mole/Kelvin) and T is absolute tempera-

Table 4. *OTR values for perforated film samples.*

Item	15°C (cc/m²/day)	23°C (cc/m²/day)	35°C (cc/m²/day)
Sweet Potato	3,100	2,900	4,400
Squash	920	1,200	2,500
Squash and Zucchini	5,900	5,000	6,900
Collard Greens	680	1,000	2,100

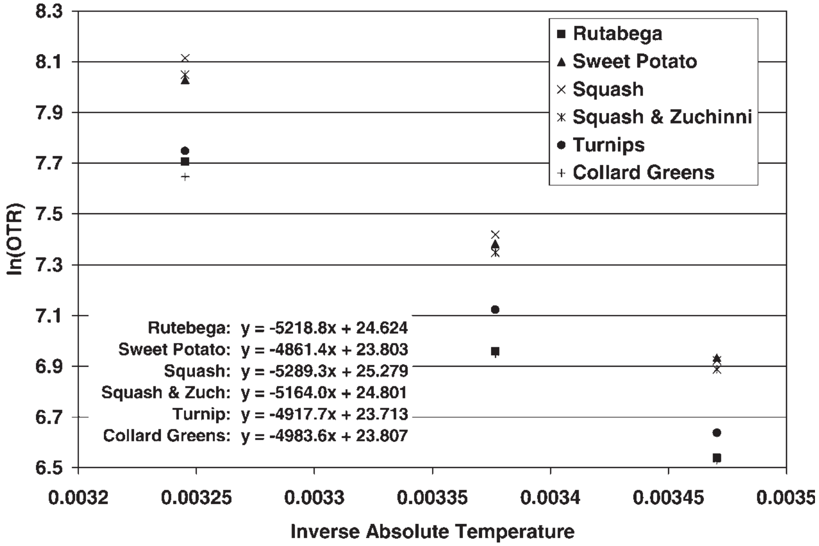

Figure 3. *OTR Arrhenius plot for non-perforated film samples.*

ture (Kelvin). Linear regressions of data in Table 6 provide Arrhenius parameters shown in Table 5.

OTR values for perforated samples did not show consistent sensitivity to temperature, therefore, average OTR values from experiments at 15, 23 and 35°C were used for further analysis. It should be noted that OTR data for perforations in Squash and Zucchini didnt compare well to those determined for Squash, but samples appeared fairly similar. For this reason, OTR data for perforated Squash samples were used for computations for both Squash and Squash and Zucchini.

Table 5. *OTR values at target temperatures along with Arrhenius parameters for film samples.*

		Non-Perforated Film			Perforated Film	
Item	Design T (°C)	E_a (joule/mol)	ln(k_0)	OTR @ T (cc/m^2/day)	OTR @ T (cc/m^2/day)	Mask Area (cm^2)
Rutabaga	3	43,389	24.624	306.61		
Sweet Potato	3	40,418	23.803	492.16	3,470	5.07
Squash	5	43,975	25.279	524.79	1,540	5.07
Squash and Zucchini	5	42,933	24.801	510.54	5,930	5.07
Turnips	3	40,886	23.713	366.84		
Collard Greens	3	41,434	23.807	317.44	1,260	5.07

Table 6. *Total OTR values calculated for each product bag.*

Item	Holes (per bag)	Total Area (cm^2/bag)	Perf Area (cm^2/sample)	Film Area (cm^2/bag)	Perf OTR (cc/day/bag)	Film OTR (cc/day/bag)	Measured Total OTR (cc/day/bag)	Calculated OTR (cc/day/bag)
Rutabaga	0	817	0	817	0	25	**25**	**65**
Sweet Potato	11	850	56	794	213	39	**252**	**154**
Squash	8	760	41	720	50	38	**88**	**25**
Squash and Zuchinni	8	793	41	753	192	38	**230**	**23**
Turnips	1	791	0	791	0	29	**29**	**24**
Collrd Greens	13	1,910	66	1,844	108	59	**167**	**—**

Table 5 provides Arrhenius parameters for film samples as well as average OTR values for perforated samples.

Overall OTR values for product bags were estimated by combining OTR contributions from non-perforated and perforated film as described by Equation (8).

Table 6 provides bag areas, OTR contributions from film (non-perforated) areas and perforated areas as well as total measured OTR for each sample bag. The final column of Table 6 provides calculated OTR requirements (Calculated OTR) based on combined results of this work including physical characteristics of each product, bag surface area, estimated bag headspace volume, respiration requirements, desired oxygen levels, desired storage conditions, etc..

Measured and Calculated OTR values match quite well, considering levels of natural variation inherent in such samples. These data suggest that packages currently in use are well designed for the application. Data also suggest that perforations may not be required for Squash and Squash and Zucchini products. Therefore, shelf life comparison studies for Squash and Squash and Zucchini products with and without perforations are warranted.

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Using the *C-e* Pairs to Develop Conventional Cushion Curves and Cushioning Specifications

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ABSTRACT: Cushion curves are commonly used to design protective packaging, but their use is primarily limited to the selection of cushion thickness and load bearing area. Generating the curves also requires significant time and testing resources. This paper reviewed the theoretical basis of the conventional cushion curves and explores the relationship between cushion curves and a parent curve, which is based on the *C-e* curve (Cushion factor (*C*)- Impact absorption capacity (*e*) curve). The notion of using *C-e* pairs to generate cushion curves with any desired cushion thickness/drop height is introduced, based on a single master cushion curve with a limited number of measured *G*-values and Static Stresses. We recommend that instead of generating a set of cushion curves, only a master cushion curve representing different real world scenarios should be provided to packaging designers. This simple method is different that the methods based on energy-stress methods in its simple and practical way in developing a master cushion curve. In addition, the paper recommends the use of the *C-e* parent curve as a replacement for conventional cushion curves for designing protective packaging.

INTRODUCTION

USING cushion curves to design shock protection for sensitive products is a common practice. A shock cushion curve describes the correlation of the deceleration transmitted to an object falling on a cushion material and the static loadings on the cushion. There are two alternative methods of empirical development of cushion curves: the guided platen method (GPM) described in ASTM D-1596[1] used by most material suppliers such as BASF, and the enclosed test block (ETB) method described in ASTM D-4168 [2,3] for Form-in-Place (FIP) materials that is

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used exclusively by Sealed Air for published curves. These two methods return different results with differences well within the range of interest for critical designs. GPM is very controlled and repeatable, whereas ETB is more predictive of actual performance. In GPM, The cushion curves are derived using a cushion tester that drops a platen of specified weight from a known drop height onto a rectangular cube of cushioning of predetermined material, load bearing area and thickness. In ETB, the test block and weights are placed into the cavity of the test cushion in a corrugated container, the completed package is then subjected to drops or controlled shocks. The deceleration occurring on the platen or test block at impact is monitored and recorded by an accelerometer. A *G*-value (acceleration in g's) is used to model the maximum deceleration level. Five drops from a particular drop height are performed on a sample at a given static stress loading. The average of the deceleration readings from the last four of these drops is the *G*-value for the given static stress (σ = Weight/bearing area). This G-σ value represents a point that is plotted on the cushion curve. By adding weight to the platen, the static stress on the cushion material can be increased. Through a series of tests at various static loadings, data is generated and presented in the form of cushion curves.

Cushion curves provided by resin suppliers such as BASF proved to be a very efficient tool in 70's and 80's, when rulers and calculators were the basic tools of engineering design. The engineer can locate the critical acceleration level on vertical axis of the cushion curves and then draw a horizontal line across the cushion curves through this point. Any portion of the curve which falls below the critical acceleration line indicates the static loading range where the cushion should transmit less than the critical acceleration. The curve crossed indicated the appropriate cushion thickness to be chosen.

LIMITATION OF THE CONVENTIONAL CUSHION CURVES AND RELEVANT RESEARCH

There are three main limitations to the use of cushion curves. First, generating a full range of the cushion curves with eight cushion thicknesses and a range of drop heights (as shown in Figure 1), would require more than 10,000 samples drops. It is a very time consuming and labor intensive process. Although the ETB method appears to be closer to actual cushion performance, the longer time involved in preparing the

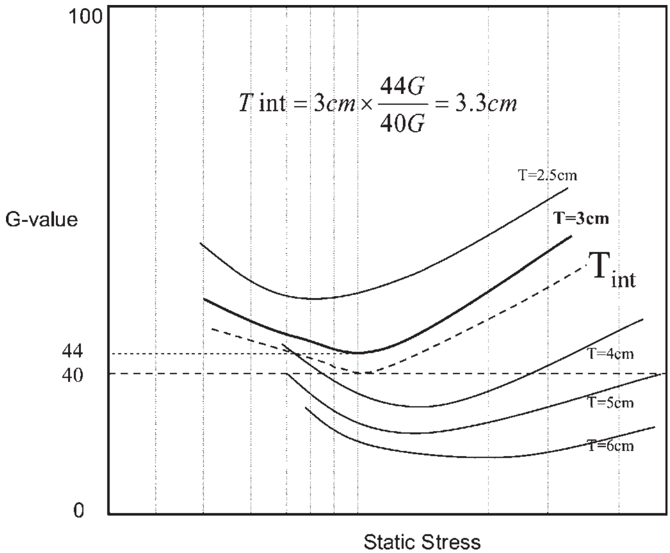

Figure 1. *Intersection line between two cushion curves, the vertical axis indicates the acceleration level in* G *and horizontal axis indicates static stress in kg/cm^2 (from [3]).*

samples, compared to GPM, limits its application to cushion systems other than FIP.

Second, companies producing high-volume products are using a reverse design approach, in order to optimize the 20/40 foot container volumes. Engineers start with the internal size of a 20/40 foot container and "work backwards" on the layout and overall dimensions of the shipping container (L × W × H). The external dimensions of the product, the cushion thickness, and the void between the cushioned product and the shipping container are pre-determined parameters. In this scenario, the ratio of thickness/drop height will be different from that presented in the cushion curves. The designer is often unable to utilize the cushion curve with the desired thickness. One of the methods the engineer commonly employs to overcome this problem, is to use the intersection line method to calculate the cushion thickness between the two cushion curves (see Figure 1) [4].

Third, the cushion curves available now are basically of two types, the first drop curve and the averaged 2nd–5th drop curve. For polyurethane (PU), polyethylene (PE) and polypropylene (PP) materials, the averaged value should be pretty close to individual drops, but for molded pulp and expanded polystyrene (EPS), the acceleration level between the 2nd drop and 5th drop can be significantly different. For any material the levels for drop 2 and 5 can differ with higher loadings.

A simplified technique has been introduced to produce a full set of cushion curves using a dynamic stress-energy method to reduce the time and resources needed to generate the curves [5, 6]. This method requires one of the usual cushion curves for an arbitrary drop height and cushion thickness to deduce the dynamic stress-energy curve for the material. The trend line is required to approximate the stress-energy curve in order to generate all other cushion curves [7]. There is a possibility that the trend line used for approximating the dynamic-stress does not reflect the real cushion characteristics. For example, the exponential curve is only adequate for closed-cell cushions. The dynamic stress-energy curve of crushable materials, such as corrugated board, is difficult to approximate with one single function.

Instead of producing the Stress-Energy curve for duplicating the cushion curves, a simpler way is introduced in this paper. This method produces all cushion curves directly from one master cushion curve, thus, the possible inaccuracy caused by approximation of the stress-energy method using trend lines is eliminated. The method applies also to all cushioning, including both energy absorbing material and crushable cushioning.

THE *C-e* CURVE AND CONVENTIONAL CUSHION CURVES

When a cubic cushion sample is placed on the cushion tester, and a flat-faced platen is used to impact the cushion, the process can be described in the following formulas, based on energy conversion theory [8, 9]:

$$C = G \times \left(\frac{t}{h}\right) \tag{1}$$

$$e = \sigma \times \left(\frac{h}{t}\right) \tag{2}$$

Where, C is the dynamic cushion factor of the cushion material. Different materials with different densities will have different C-values. C also indicates how many times larger the real cushion thickness should be than the theoretical cushion thickness. G is G-value measured during the impact.

The symbol *e*, is the impact absorption capacity, which describes the relationship of the impact energy versus cushion volume, i.e. $mgh/At = \sigma(h/t)$ where *m* is the mass of the product, *A* is the load bearing area, *g* is gravitational constant, *h* is drop height, *t* is the cushion thickness and σ is the static stress.

The *C-e* curve can be developed based on the formulas above. The *C-e* curve is in fact a very simple curve representing considerable information, including *G*-value, static stress, cushion thickness, drop height and other cushion properties. By incorporating *G*-values into the formula, the *C* will be calculated. The *C-e* curve will give the cushion thickness and bearing area when the horizontal line, indicating the *C*-value, is drawn across the *C-e* curve. The *C-e* curve consists of densely packed data, especially at the lower static loading levels, such that a small shift in loading can have a significant effect on the resulting deceleration. The curves demonstrate less variation on deceleration levels at higher static loads. Therefore, the *C-e* curve needs to be further modified. Combining formulas (1) and (2) yields $G = (C \cdots e)/\sigma$, i.e., the conventional cushion curves are derived. The C-e curve can be defined as the *C-e* parent curve which consolidates all cushion curve information in one single curve.

The relationship between the *C-e* parent curve and conventional cushion curves can be illustrated in the Figure 2. Each cushion curve in a set of curves consists of a set of *C-e* pairs $((C1, e1), (C2, e2), \ldots), (C_{opt}, e_{opt}), \ldots (C_n, e_n)$. The *C-e* pairs in one cushion, calculated through formulas (1) and (2), appear in every one of the other cushion curves. By linking the points in the curves with the same *C-e* pairs, curves *C*1-*e*1, . . . C_{opt}-e_{opt} are formed. These curves are called adjacent cushion curves [11].

Of the *C-e* pairs, the C_{opt}-e_{opt} is regarded as the optimal point value

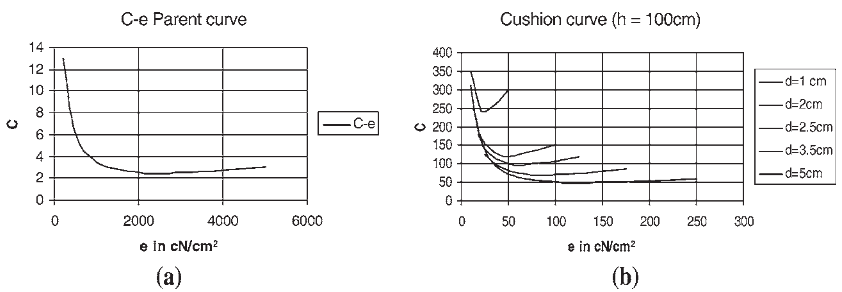

Figure 2. C-e *parent curve and the simplified conventional cushion curves [10].*

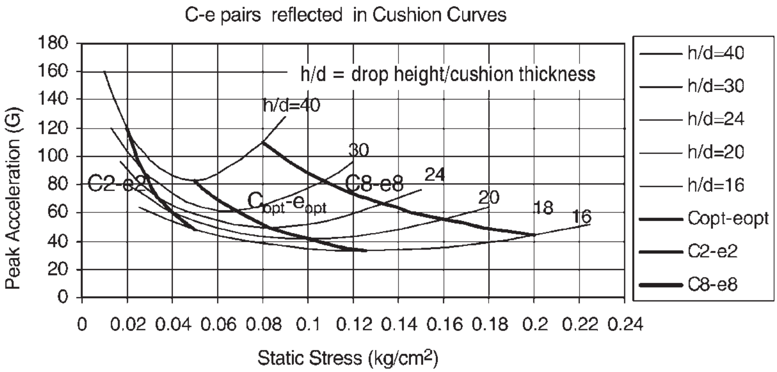

Figure 3. *Cushion curve and* C-e *pairs.*

when it comes time to design the cushioning. The point C_{opt} -e_{opt} curve in the parent *C*-*e* curve represents a curve that links all the optimal points (lowest point of each curve) (Figure 3). Every cushioning material with a given density has only one pair value, C_{opt} and e_{opt}.

Theoretically, the C_{opt}-e_{opt} point is the basis of the cushion dimension. In an actual design, a safety factor may be required in order to meet the necessary protection level. From Figure 3, it is noted that slightly increasing the material thickness results in widened optimum load bearing areas in cushion curves. If the fragility *G*-value and drop height fall outside of the optimum area of the *C*-*e* curve, changing densities or materials is necessary.

DEVELOPING CUSHION CURVES WITH *C-e* PAIRS

Having analyzed the relationship between the *C*-*e* curve and the other curves, every cushion curve has the same *C*-*e* pairs regardless of the ratio of drop height/cushion thickness. To produce a set of cushion curves, only one master cushion curve is required. Based on data from the master cushion curve, *G* and σ values will be used into formulas (1) and (2) for calculating *C*1 and *e*1. The rest of cushion curves can be derived by calculating the static stress and *G*-value according to the *C*1 and *e*1 values.

To find the pair value (*C*1, *e*1) for a particular material, start by choosing a drop height and cushion thickness. According to ASTM D 1596 or ASTM D 4168, add the lightest weight to the platen and drop it on the cushion sample. Record the deceleration level from the 1st to 5th drops and average the deceleration of the 2nd to 5th drops with respect to G (1,1), the G-value at the first static loading of cushion curve 1. It usually requires at least five samples to average the $G(1,1)$ value. Next, use $G(1,1)$ and $\sigma(1,1)$ ($\sigma(1,1)$ = weight/bearing area) in the formula $C(1,1) = G(1,1)*d/h$ and $e(1,1) = \sigma(1,1)*h/d$, and a pair value $C(1,1)$, $e(1,1)$ is calculated. By adding weights to the platen, additional static loadings $\sigma(1,2)$, $\sigma(1,3)$, . . . are derived. If a minimum of 7 static loadings are required, then in order to plot a master cushion curve, 6 other impact tests under $\sigma(1,2)$, . . . $\sigma(1,7)$ are to be repeated to calculate $G(1,2)$, $G(1,3)$, . . . $G(1,7)$. According to these 7 paired values, 7 $C1$-$e1$ pairs can be calculated from the formulas (1) and (2).

The following example shows how a simple spreadsheet from Excel can be set up to generate the 8 cushion curves based on only one measured master cushion curve (the sample was made from Dynopor, EPS, density 23 kg/cm³). First, 9 static stress loadings in kg/cm² were chosen and defined in the $\sigma(1)$ column as 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, and 0.09 for the given $h/d = 40$. Then, impact tests were conducted using a cushion tester for these 9 static loadings. The 9 tested G-values of 160, 120, 98, 86, 83, 87, 97, 110 and 128 were measured and recorded as the $G(1)$ array in the spreadsheet. Based on the $\sigma(1)$array and $G(1)$array, $C1$ and $e1$ values were computed as (4,0.4), (3,0.8), . . . (3.2, 3.6). These values are highlighted in the spreadsheet below.

A	B	C	D	E	F	G	H	I	J	K	L	M	N
h/d=40				h/d=35		h/d=30		h/d=26		h/d=24		h/d=22	
Measured value		C-e value		Calculated σ-G value from C-e value									
σ(1)	G(1)	e	C	σ(2)	G(2)	σ(3)	G(3)	σ(4)	G(4)	σ(5)	G(5)	σ(6)	G(6)
0.01	160	0.4	4	0.011429	140	0.013333	120	0.015385	104	0.016667	96	0.018182	88
0.02	120	0.8	3	0.022857	105	0.026667	90	0.030769	78	0.033333	72	0.036364	66
0.03	98	1.2	2.45	0.034286	85.75	0.04	73.5	0.046154	63.7	0.05	58.8	0.054545	53.9
0.04	86	1.6	2.15	0.045714	75.25	0.053333	64.5	0.061538	55.9	0.066667	51.6	0.072727	47.3
0.05	83	2	2.075	0.057143	72.625	0.066667	62.25	0.076923	53.95	0.083333	49.8	0.090909	45.65
0.06	87	2.4	2.175	0.068571	76.125	0.08	65.25	0.092308	56.55	0.1	52.2	0.109091	47.85
0.07	97	2.8	2.425	0.08	84.875	0.093333	72.75	0.107692	63.05	0.116667	58.2	0.127273	53.35
0.08	110	3.2	2.75	0.091429	96.25	0.106667	82.5	0.123077	71.5	0.133333	66	0.145455	60.5
0.09	128	3.6	3.2	0.102857	112	0.12	96	0.138462	83.2	0.15	76.8	0.163636	70.4

h/d=20		h/d=18		h/d=16	
Calculated σ-G value from C-e value					
σ(7)	G(7)	σ(8)	G(8)	σ(9)	G(9)
0.02	80	0.022222	72	0.025	64
0.04	60	0.044444	54	0.05	48
0.06	49	0.066667	44.1	0.075	39.2
0.08	43	0.088889	38.7	0.1	34.4
0.1	41.5	0.111111	37.35	0.125	33.2
0.12	43.5	0.133333	39.15	0.15	34.8
0.14	48.5	0.155556	43.65	0.175	38.8
0.16	55	0.177778	49.5	0.2	44
0.18	64	0.2	57.6	0.225	51.2

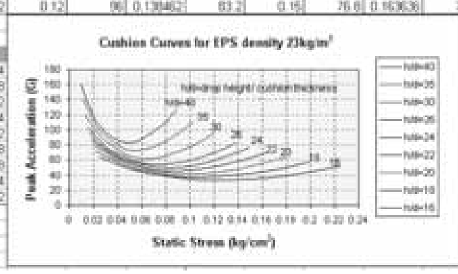

Figure 4. *Experimental data used to plot cushion curves.*

A set of *C*-*e* pairs has been produced that can be used to generate the rest of the cushion curves for *h*/*d* = 35, 30, 26, 24, 22, 20, 18 and 16. In the spreadsheet, σ(2), and *G*(2) are the calculated results, generated along with the *C*-*e* curves. The σ(2), σ(3), . . . σ(9), and *G*(2), *G*(3), . . . *G*(9) values are not necessarily integers, because these values are calculated from formulas 1 and 2, since the spreadsheet produces the curve, exactly as required. Similarly, adding σ(2) – *G*(2), σ(3) – *G*(3), . . . σ(11) – *G*(11), 11 cushion curves are generated in a very short time.

COMPARISON BETWEEN EXPERIMENTALLY DERIVED DATA AND *C-e* PAIRS CALCULATED DATA

In order to verify the above method, cushion curve data from Sealed Air was chosen to compare the experimental data and *C*-*e* pairs calculated data. The Sealed Air testing was performed as per ASTM D4168 using Shock Machine Simulation of Free Fall Drop (ASTM D5487) with essentially 2 ms duration step velocity input pulses. The drop heights were 12″, 18″, 24″ and 30″ and the cushion thicknesses used were 2″, 3″ and 4″ [12].

The transmitted shock data that averaged drops 2–5 at 3″ thickness

Table 1. *Comparison between experimentally derived data and* C-e *calculated data.*

G-value derived from testing conducted by Sealed Air							**Calculated *G*-Value using *C-e* pairs**
Drop #	**1**	**2**	**3**	**4**	**5**	**Avg drops 2–5**	
Static Stress psi		Thickness 2″, drop height 12″					
0.4	22	26	27	28	29	28	25.5
		Thickness 3″, drop height 12″					
0.2	32	32	30	30	30	31	28.25
0.4	18	20	21	22	22	21	20
		Thickness 3″, drop height 18″					
0.4	20	24	26	30	32	28	25.5
		Thickness 2″, drop height 24″					
0.2	48	52	52	52	52	52	51
		Thickness 4″, drop height 24″					
0.4	20	24	28	32	34	30	25.5
		Thickness 3″, drop height 30″					
0.4	29	37	44	52	58	48	50

and the 24″ drop height was randomly selected for the master cushion data. The calculated static stresses are not necessarily the same as the design of the experiment. The following table shows a comparison between the experimentally derived *G*-value and the calculated *G*-value with the same static stress.

The calculated results match the experimental data well.

USING THE *C-e* PARENT CURVE TO DESIGN CUSHIONING

In addition to the two aforementioned limitations, a disadvantage in designing cushion dimensions by hand with the assistance of conventional cushion curves is that it is not clear what the static loading should be to keep *G* less than the required level. There are so many choices, in terms of static loading on the cushions, a trial and error approach is often the last resort.

With advanced computer tools, the primary reason to simplify the *C-e* curve with respect to cushion curves utilized in the ‘70s and ‘80s becomes unnecessary. Using a simple Excel spreadsheet, the *C-e* curve can be expressed as a continuous function. For example, the experimental *C-e* curve plotted in Figure 4 (*C, e* value) can be approximated as a function $C = 0.5941e^2 - 2.59418e + 4.7655$ (Figure 5). The curve, *C-e* experiment, represented the plotted curve based on nine sets of *C-e* data in the figure. Curve Poly. (*C-e experiment*) is the approximated *C-e* curve from the *C-e* experiment curve. This approximated mathematical equation makes computer aided cushion design viable without using a ruler. And

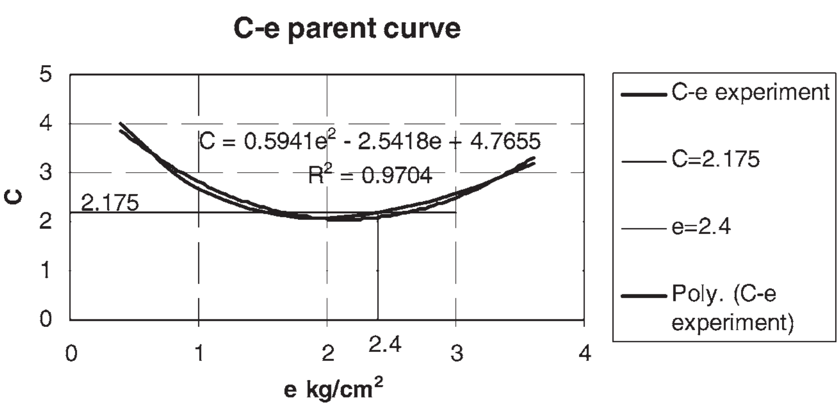

Figure 5. C-e *pairs are regressed to a C(e)continual function.*

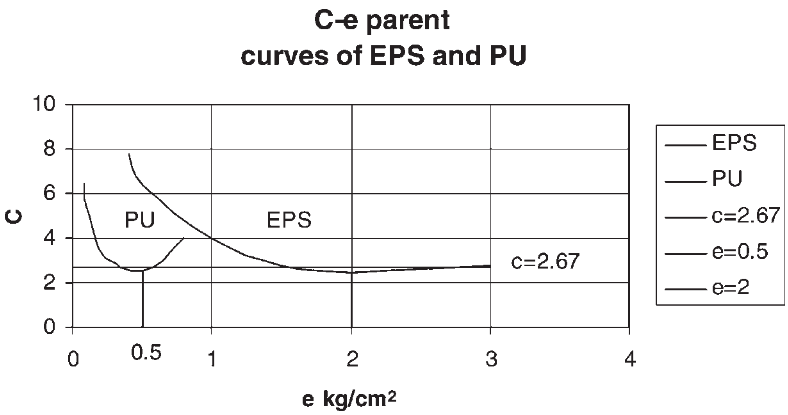

Figure 6. *Curves for EPS and PU.*

the most important consideration is that any desired cushion dimension can be derived from the calculation.

The other advantages of using *C*-*e* curves to design cushion dimensions is that the designer is able to choose the right cushioning material and density to meet the requirements of cushion thickness, *G*-value, weight and drop height by consolidating parent *C*-*e* curves of different materials into one curve set. Consider, for example, the design of a cushion for a 5 kg product with a fragility of 80 *G*s, an anticipated drop height of 60 cm and a cushion thickness is 2 cm. In the first step, the C-value is calculated, $C = 80 \cdot 2/60 = 2.67$. Draw a horizontal line indicating the *C*-value in Figure 6, which defines two parent *C*-*e* curves of polyurethane (PU) and expanded polystyrene (EPS). The most desired cushion material will be the material with its lowest point of the U-shaped curve. In this example, both PU and EPS are adequate materials, with $e = 0.5$ and $e = 2$. EPS is chosen as the cushion material because less material would be required (the larger the e, the less load bearing cushion area needed). In addition, the relative flat EPS *C*-*e* curve gives a wide range of static stress load options for keeping the *G*-value less than 80 *G*s.

CONCLUSION AND DISCUSSION

Although there are different ways to simplify the cushion development process, the theoretical background is necessarily the same. Using *C*-*e* pairs is an accurate and quick way to develop curves, based on the Excel spreadsheet data shown above.

Starting with the master curve, all the data developed is subject to the same positive and negative factors that affect the master curve. In other words, the generated curves are no better than the original master curve and will take on the characteristics of the master curve. It is therefore important to make sure that the master curve covers all aspects of the real world design. By taking advantage of the quick method, for example, a set of 5 master cushion curves for the 1st, 2nd . . . and 5th drops, can provide the packaging designer with all the information to develop just the needed cushion curves, with respect to specific applications.

A master cushion curve should consider the following factors:

a. Directional effect. Cushions differ in performance in compression and shear orientations and in edge and corner configuration.
b. Effect of rib and base depth or placement of the rib on the inside or outside surface. These factors will influence performance.
c. The *G*-value varies between the 2nd drop and 5th drop at a given static stress level. Does one use a weighted average or normal distribution?
d. Is the *G*-value based on shock response spectrum or on peak acceleration?
e. The variables of the static stress. Static stress can be applied in two ways: the surface area of the dummy weight is larger than surface area of the cushion, or the surface area of the dummy weight is smaller than the surface area of the cushion. It can be shown that cushion performance will vary.

The realities of developing protective packaging for an increasingly global economy put a new focus on efficiency and predictability. The balance of package volume and protective ability, combined with package cost, places a premium on good development process. The technique described in this paper is one way to increase the effectiveness of the development process.

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Development of Wholesale Packaging to Prevent Post-Harvest Damage to Rose Apples

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ABSTRACT: The purpose of this research was to determine post-harvest damage to rose apples due to transportation hazards and to comparatively evaluate the performance of the current and proposed wholesale packaging for the fruit. The methodology comprised of sampling and conducting damage analysis of rose apples of two varieties (Thongsamsri and Toonklao) distributed using commercial packaging to various retailers and wholesalers selected at random around the Bangkok metropolitan areas. Three kinds of current wholesale packaging were packed with newly harvested, damage-free, and uniform sized Thongsamsri rose apples and tested using a vibration simulator. The same testing was performed for the two types of proposed wholesale packaging. Performance of both types of packaging was evaluated in terms of damage parameters. Results showed that the post-harvest damage was mainly in the form of bruising and abrasion. The average fruit damage and the average damage percentage of abrasion were higher than that of bruising at both the wholesaler and retailer levels. The average fruit damage and the average damage percentages at the retailer were greater than that at the wholesaler for both varieties. Majority of the damage seen in the current packaging was a combination of bruising and abrasion. The proposed packaging uses diagonally horizontal fruit orientation which imparts a minimum bruising with negligible abrasion.

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1.0 INTRODUCTION

THE rose apple (*Eugenia javanica Lamk*) is indigenous to the East Indies and Malaya and is cultivated and naturalized in many parts of India, Southeast Asia and the Pacific Islands. This exotic fruit is very popular in Thailand. Its plantation in Thailand covers an area of 9,634 hectares, producing rose apple fruit with a market value of 31.5 million US Dollars [1]. Rose apple is a rich source of vitamins and minerals with the most popular variety being Thongsamsri [2].

In its post harvest journey from farm-to-fork, this fruit is subjected to a multitude of dynamic and static forces such as impacts, vibration and compression which reduce its value due to damage [3, 4]. Mechanical damage is the major cause of post-harvest losses [5]. Post-harvest damage of the mangosteen fruit in Thailand, in terms of rough surface and internal defects has been observed to be as high as 40.5% and the mechanical damage to sweet tamarind pods in typical retail packaging has been observed between 33.2% and 48.4% [6].

There have been several other studies related to the damage caused to fresh produce and fruits by distribution hazard elements. Beradinelli et al. reported that as many as 36% of Italian pears risk being damaged during transportation by trucks [7]. Singh and Marcondes have concluded that by switching from a truck with a leaf spring suspension to that with an air-ride suspension, vast improvement in the ride quality as well as damage reduction can be achieved [8]. However, the smoother suspension system does not totally eliminate vibration damage. A past study recommends that proper design and use of the protective packaging materials are important factors to reduce physical damage during distribution [9]. Although several studies on performance testing and evaluation of packaging for tropical fruits like mango, papaya, mangosteen, rambutan, and sweet tamarind have been conducted in the past, no such study has included rose apples [10,11,12,13, and 14].

This research was targeted to:

- Determine the post-harvest damage to rose apples due to transportation hazards
- Comparatively evaluate the performance of the current and proposed wholesale packaging for the fruit

2.0 MATERIALS AND METHODS

2.1 Determination of Post-Harvest Damage

Post harvest damage to two varieties of rose apples, Toonklao and Thongsamsri, was observed for transport destinations for retail and wholesale markets. For the retail destinations, three mobile retailers (pick-up trucks), three open markets and two popular supermarkets were targeted. All the retailers were selected at random around the Bangkok metropolitan area. For the wholesale sites, three fruit markets in Bangkok (Tai, Mahanak and Si-moomueng) were randomly selected.

Rose apples were manually harvested, packed and transported by trucks to all the destinations. For the retail market, rose apples are usually packed in 10-count plastic foam trays with stretch film on top and are sold without any cushioning by simply packing them in plastic bags for consumers. For the wholesale market, 13 kilograms of the fruit is generally packed in a double walled regular slotted corrugated box measuring 37 cm × 27.5 cm × 31 cm. The fruit in the box is not individually cushioned and packed in four layers with plastic bags sandwiched between the layers. 30 individual rose apples were randomly selected out of each source, retail and wholesale, for damage analysis.

2.2 Testing of the Current Wholesale Packaging

The current wholesale packaging tested consisted of the following (Figure 1):

- 10 kilogram capacity corrugated containers available in two sizes: 30.5 cm × 38.5 cm × 18.5 cm (corrugated box I) and 24.5 cm × 43.5 cm × 26 cm (corrugated box II)

Figure 1. *Current Wholesale Packaging.*

- 15 kilogram capacity frustum-like plastic baskets with 39.5 cm mouth diameter, 29 cm base diameter and 26 cm height
- 10 kilogram capacity expanded polystyrene (EPS) containers measuring 30.5 cm × 42.5 cm × 28 cm

The Thongsamsri rose apples packed in these containers were newly harvested, unblemished and approximately of the same size (100 gm/fruit). The procedure for packing the fruit in the current packages was as follows:

1. Bare rose apples were packed in four layers in an orderly fashion in the corrugated boxes with shredded paper (37 gm/layer) as cushioning between the fruit layers, container bottom and in the head space.
2. The bare fruit was placed in three layers in an orderly fashion in the plastic basket lined with two pieces of newspaper and sixteen 15 cm × 20 cm plastic bags uniformly placed to line the container bottom as cushion.
3. The fruit with 3 mm thick foam net was packed in an orderly fashion in a plastic bag lined with newspapers and shredded paper. The plastic bag was then vacuumed, sealed and placed in the EPS container that had a few holes at the bottom for drainage. Ice was put on the top of the vacuumed bag under the lid of the box.

Each package was selected at random to be tested using a vibration simulator (Chaiyapong et al., 2006) at the resonance frequency of 4 Hz for one hour according to the ASTM standard D999 method A2 [11,15]. Five replications were made for each package type tested. After testing, the fruit in each package was left for six hours to let the damage become visually apparent. The fruit was inspected for mechanical damage with respect to the fruit section as shown in Figure 2. Section “A” corresponds to the part of the fruit closest to the stem, section “B” is the middle part of the fruit and section “C” corresponds to the remainder of the fruit. Each section is about 2.5 cm apart.

The average damage per fruit (D_x) and the average damage percentage per package (D_y) were calculated using the following relationships:

$$\text{Average fruit damage } (D_x,\ \%) = \frac{\Sigma[(\text{Total damaged area of a fruit section / Fruit surface area}) \times 100]}{\text{Total fruit in package}}$$

or

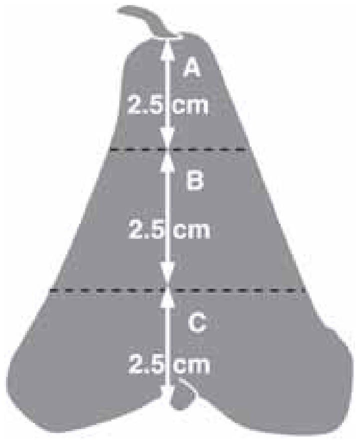


Figure 2. *Fruit Sections of Rose Apples.*

$$\frac{\Sigma[(\text{Total damaged length of a fruit section / Fruit height}) \times 100]}{\text{Total fruit in package}} \quad (1)$$

$$\text{Average damage percentage } (D_y,\ \%) = \frac{\text{Number of damaged fruit of a certain section in a package}}{\text{Total fruit in the package}} \times 100 \quad (2)$$

Fruit height was obtained using a calibrated Vernier caliper. Fruit area was computed using the formula, $\pi(r_1 + r_2)[h^2 + (r_1 - r_2)^2]^{1/2}$ [16]. Where, r_1, r_2 are the radius of base and top of the rose apple (mm) respectively and h is the fruit height (mm).

2.3 Testing of Proposed Wholesale Packaging

Development of the proposed wholesale packaging for rose apples originated from the fact that it is a damage prone fruit and adequate mechanical protection should be provided all around the fruit. The proposed wholesale packaging was designed to cushion the fruit with foam netting and placing it in corrugated partitions to avoid direct lateral contact between the fruits. The layers of fruit were also cushioned vertically using shredded paper (3 gm and 3 mm wide). The two designs of the proposed packaging in 27.5 cm × 41 cm × 37 cm corrugated boxes with 72

Vertical Plane Fruit Orientation   Diagonally Horizontal Plane Fruit Orientation

Figure 3. *The Proposed Wholesale Packaging.*

Thongsamsri rose apples individually wrapped in 3 mm foam nets were (Figure 3):

a. The cushioned fruit vertically oriented in a 3 layer stack
b. The cushioned fruit oriented diagonally in the horizontal plane in a 4 layer stack.

The fruit packaged using the proposed packaging methods were tested using the methodology described in section 2.2.

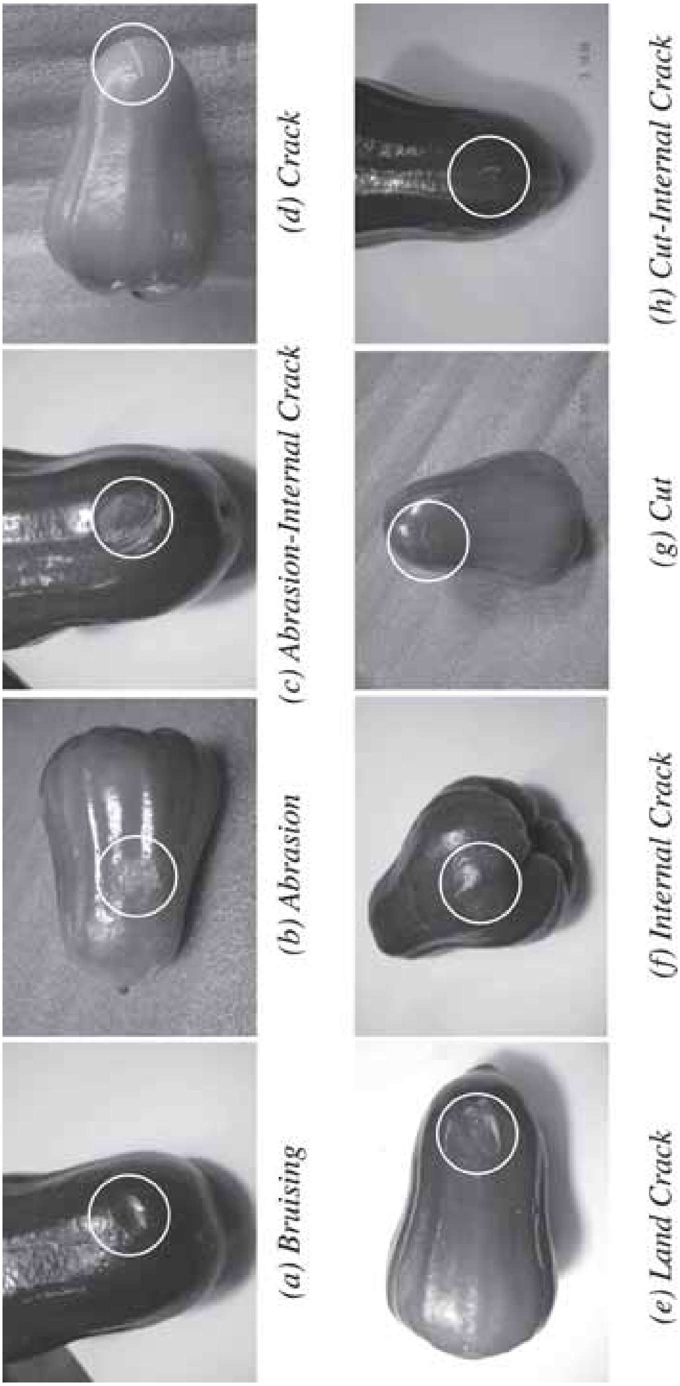
3.0 RESULTS AND DISCUSSION

3.1 Post-Harvest Damage

Figure 4, shows the rose apple post-harvest damage categories, six of which are clearly quantifiable. These are bruising, abrasion, internal crack (crack appearing in bruise), cut, abrasion-internal crack (abrasion with tissue inside the fruit clearly separating), and crack. Land crack is surface break with bruise. Internal crack (inside flesh cracks but epidermis does not) and cut-internal crack (cut is with bruise and tissue separates) were the most difficult to identify.

Analysis of variance indicated that the distribution destination and fruit section significantly affected the average fruit damage, D_x, of bruising, abrasion and internal crack at the significance level of 5% (Table 1).

The total damage of every section of the packaged Thongsamsri fruit at the wholesaler was less than that at the retailer for bruising (0.64% vs. 1.20%) and abrasion (0.74% vs. 1.30%). This might be because the rose



(a) Bruising (b) Abrasion (c) Abrasion-Internal Crack (d) Crack

(e) Land Crack (f) Internal Crack (g) Cut (h) Cut-Internal Crack

Figure 4. *Post-harvest Damage Categories for Rose Apples.*

Table 1. *Average Fruit Damage* for Packaged Thongsamsri Rose Apple as affected by Distribution Destination and Fruit Section.*

Distribution Destination	Bruising (%)			Abrasion (%)			Internal Crack (%)		
	Fruit Section			Fruit Section			Fruit Section		
	A	B	C	A	B	C	A	B	C
Retailer	1.043±0.529c	0.033±0.026a	0.126±0.105ab	0.687±0.428d	0.165±0.144ab	0.444±0.312c	0.032±0.022ab	0.0073±0.0027a	0.047±0.024b
Wholesaler	0.323±0.152b	0.138±0.062ab	0.183±0.152ab	0.473±0.274c	0.057±0.052a	0.212±0.096b	0.056±0.017b	0.024±0.021ab	0.166±0.092c

*The value of fruit damage followed by the same letter of the same damage type implies the fruit damage of insignificant difference at the significance level of 5%.

Table 2. *Effect of Fruit Section on Average Fruit Damage* of Abrasion and Internal Crack and Crack of Packaged Thongsamsri Rose Apples.*

Fruit Section	Abrasion and Internal Crack (%)	Crack (%)
A	0.022±0.020a	0.545±0.498b
B	0.0088±0.0086a	0.158±0.095a
C	0.044±0.034b	0.025±0.021a

*The value of fruit damage followed by the same letter of the same damage type implies the fruit damage of insignificant difference at the significance level of 5%.

apple experienced more handling when shipped to the retailer than that to the wholesaler. Bruising and abrasion together contributed towards the most amount of damage in the packaged rose apples. For bruising or abrasion for the same distribution destination, the largest, the medium and the smallest amount of damage appeared at the fruit section A, C and B respectively. This was similar to crack damage that was greatest at section A and the smallest at section C (Table 2).

Fruit section significantly affected abrasion and internal crack, and crack, while the significant influence of distribution destination, was upon the cut and internal crack (Table 3).

Based on the size of bruising and abrasion, crack also contributed a significantly large amount of damage while the amount of internal crack, abrasion and internal crack, and cut and internal crack was too small to be of concern. For the packaged Toonklao, distribution destination and fruit section significantly affected bruising and abrasion at the significance level of 5% (Table 4).

Similarly for Thongsamsri, for either bruising or abrasion, the sum of the average fruit damage at every section in a rose apple at the retailer was greater than that at the wholesaler. Handling effect on the growth of bruising and abrasion between the retailer and the wholesaler was found to be 1.87 and 1.76 for Thongsamsri, and 3.18 and 2.15 for Toonklao re-

Table 3. *Effect of Distribution Destination on Average Fruit Damage* of Cut and Internal Crack of Packaged Thongsamsri Rose Apples.*

Distribution Destination	Cut and Internal Crack (%)
Retailer	0.0012 ± 0.0011a
Wholesaler	0.0061 ± 0.0059b

*The value of fruit damage followed by the same letter of the same damage type implies the fruit damage of insignificant difference at the significance level of 5%.

Table 4. *Average Fruit Damage* of Bruising and Abrasion Type for Packaged Toonklao as Affected by Distribution Destination and Fruit Section.*

Distribution Destination	Bruising (%) Fruit Section A	Bruising (%) Fruit Section B	Bruising (%) Fruit Section C	Abrasion (%) Fruit Section A	Abrasion (%) Fruit Section B	Abrasion (%) Fruit Section C
Retailer	0.660±0.341c	0.108±0.086a	0.443±0.205b	0.505±0.395c	0.303±0.263b	0.875±0.497d
Wholesaler	0.106±0.090a	0.118±0.080a	0.156±0.072a	0.324±0.275b	0.128±0.119a	0.324±0.165b

*The value of fruit damage followed by the same letter of the same damage type implies the fruit damage of insignificant difference at the significance level of 5%.

Table 5. *Average Damage Percentage* per Package of Various Damages of Packaged Thongsamsri as Affected by Distribution Destination and Fruit Section.*

Distribution Destination	Bruising (%) Fruit Section A	Bruising (%) Fruit Section B	Bruising (%) Fruit Section C	Abrasion (%) Fruit Section A	Abrasion (%) Fruit Section B	Abrasion (%) Fruit Section C	Internal Crack (%) Fruit Section A	Internal Crack (%) Fruit Section B	Internal Crack (%) Fruit Section C
Retailer	57.415±27.462b	6.667±4.288a	19.637±16.149a	77.923±9.334b	32.536±17.632a	66.546±8.454b	12.343±6.548ab	4.710±3.462a	23.454±6.398b
Wholesaler	23.334±20.817a	7.778±6.698a	11.111±10.715a	72.223±23.413b	22.222±13.472a	61.111±15.753b	22.222±18.359b	16.667±13.333ab	53.333±26.458c

*The value of average damage percentage followed by the same letter of the same damage type implies the damage percentage of insignificant difference at the significance level of 5%.

Table 6. *Effect of Fruit Section on Average Damage Percentage* of Abrasion and Internal Crack and Crack of Packaged Thongsamsri Rose Apples.*

Fruit Section	Abrasion and Internal Crack (%)	Crack (%)
A	4.614±2.317a	4.444±3.195b
B	2.862±2.564a	0.833±0.714a
C	13.533±9.785b	0.417±0.346a

*The value of average damage percentage followed by the same letter of the same damage type implies the damage percentage of insignificant difference at the significance level of 5%.

spectively. Apart from variation of orchard and transport, the mechanical properties of the different varieties of rose apples would also cause a greater growth of bruising and abrasion in Thongsamsri. A past study has found that the mature rose apple of Thongsamsri exhibits greater firmness than the Toonklao variety [17]. This means that the Thongsamsri variety should have a higher resistance to mechanical damage than Toonklao. The distribution destination and fruit section significantly influence the average damage percentage, D_y of bruising, abrasion and internal crack at the significance level of 5% (Table 5).

For either bruising or abrasion, the sum of the average damage percentage for every section of the packaged Thongsamsri variety at the retailer was greater than that at the wholesaler. Besides, the largest, the medium and the smallest D_y were at the fruit section A, C and B respectively. In contrast, the largest, the medium and the smallest D_y of the internal crack were at the fruit section C, A and B respectively. Fruit section significantly affected D_y of abrasion and internal crack, and crack (Table 6).

The greatest and the smallest D_y occurred at sections A and C for crack and sections C and A for abrasion and the internal crack. Distribution destination significantly affected D_y of the cut and internal crack (Table 7).

D_y at the retailer was observed to be lesser than that at the wholesaler. This might be due to additional handling operations in the distribution channels for the wholesaler. D_y of bruising, abrasion and crack of the packaged Toonklao was significantly affected by distribution destination and fruit section at the significantly level of 5% (Table 8).

The sum of D_y for the whole fruit for either bruising or abrasion at the retailer was greater than that at the wholesaler, except crack for which the D_y at the wholesaler was greater than that at the retailer. Wholesaler

Table 7. *Effect of Distribution Destination on Average Damage Percentage* of Cut and Internal Crack of Packaged Thongsamsri Rose Apples.*

Distribution Destination	Cut and Internal Crack (%)
Retailer	0.370±0.247a
Wholesaler	2.593±1.925b

*The value of average damage percentage followed by the same letter of the same damage type implies the damage percentage of insignificant difference at the significance level of 5%.

damage (D_y) of bruising and abrasion for the packaged Thongsamsri and Toonklao rose apples increased by 1.98 and 1.13, and 2.73 and 1.54 times respectively for the retailer damage. Abrasion and bruising were first and the second in terms of the severity of the damage for the packaged rose apples. Referring to the previous transport packaging testing studies for apples and tangerines, bruising was the dominant type of damage with ignorable abrasion [18, 19 and 20]. For rose apples the significant mechanical damage included abrasion and bruising. The occurrence of abrasion might be due to the fact that the mechanical strength of the skin of a rose apple fruit is less than that of an apple fruit. A mechanical strength test was performed for the skin of the Thongsamsri rose apple and Chinese Fuji apple for comparison. Thirty replications of each variety of 15 mm × 35 mm sample size were mounted to the grips of the universal testing machine (INSTRON 5569, USA) for tensile testing. The mechanical strength expressed at the force needed to rupture the skin of the Thongsamsri rose apples and the Chinese Fuji apple was 3.81 and 5.99 N respectively. The sum of D_y for the whole fruit sometime exceeded 100% because one rose apple could have the same damage at more than one section of the fruit.

3.2 Performance of the Current and the Developed Wholesale Packaging

Packaging and fruit section significantly influenced the average fruit damage (D_x) of bruising, abrasion, crack and internal crack at the significance level of 5% (Table 9).

The corrugated boxes I and II, and the plastic basket mainly created bruising and abrasion and very small abrasion and internal crack (0.01% or less) (Table 10).

In particular, corrugated box I generated both internal cracks and very

Table 8. *Average Damage Percentage* of Various Damages of Packaged Toonklao as Affected by Distribution Destination and Fruit Section.*

Distribution Destination	Bruising (%)			Abrasion (%)			Internal Crack (%)		
	Fruit Section			Fruit Section			Fruit Section		
	A	B	C	A	B	C	A	B	C
Retailer	61.429±30.64b	19.259±2.357a	61.958±11.785b	72.116±7.071bc	58.783±7.071ab	90.476±4.714 c	1.587±1.357a	0a	0a
Wholesaler	15.000±13.499a	11.667±7.071a	26.667±14.142a	58.333±21.213ab	36.667±9.428a	48.333±21.213ab	16.667±14.823b	0a	0a

*The value of damage percentage followed by the same letter of the same damage type implies the damage percentage of insignificant difference at the significance level.

Table 9. *Average Fruit Damage* (D_x) of Various Damages for the Packaged Thongsamsri as Affected by Packaging and Fruit Section.*

Packaging	Bruising (%)			Abrasion (%)			Crack (%)			Internal Crack (%)		
	Fruit Section			Fruit Section			Fruit Section			Fruit Section		
	A	B	C	A	B	C	A	B	C	A	B	C
Corrugated Box I	0.156±0.126ab	0.0254±0.0205a	0.0246±0.0240a	0.805±0.448c	0.357±0.280b	0.817±0.448c	0a	0a	0.0485±0.0440b	0.0714±0.0699b	0.0182±0.0171a	0.0975±0.0958c
Corrugated Box II	0.880±0.414de	0.248±0.213ab	0.177±0.151ab	0.421±0.348b	0.439±0.208b	1.121±0.600d	0a	0a	0a	0a	0.00179±0.00162a	0a
Plastic Basket	3.642±1.713h	1.027±0.899e	0.733±0.521cde	0.410±0.339b	0.429±0.314b	1.097±0.628d	0a	0a	0a	0a	0.00627±0.00613a	0a
EPS Container	2.632±1.253g	0.122±0.108ab	0.481±0.387bcd	0.0127±0.0102a	0a	0.00067±0.00065a	0a	0a	0a	0a	0a	0a
Diagonal	0.350±0.268abc	0a	0.0149±0.0096a	0.0081±0.0079a	0a	0.0051±0.0050a	0a	0a	0a	0a	0a	0a
Vertical	1.545±0.869f	0.0174±0.0141a	0.129±0.094ab	0.0089±0.0087a	0a	0.0236±0.0225a	0a	0a	0a	0a	0a	0a

*The value of fruit damage followed by the same letter of the same damage type implies the fruit damage of insignificant difference at the significance level of 5%.

Table 10. *Effect of Packaging on Average Fruit Damage* of Abrasion and Internal Crack of Packaged Thongsamsri Rose Apples.*

Packaging	Abrasion and Internal Crack (%)
EPS container	0a
Diagonal	0a
Vertical	0a
Corrugated box II	0.0099±0.0045b
Plastic basket	0.0099±0.0043b
Corrugated box I	0.0109±0.0047b

*The value of fruit damage followed by the same letter of the same damage type implies the fruit damage of insignificant difference at the significance level of 5%.

small cracks (≅ 0.05%). The plastic basket was the container of the greatest bruising ($D_x \cong 5.40\%$), while the corrugated boxes I and II were the containers that exhibited the greatest abrasion ($D_x \cong 1.98\%$). The plastic basket was also the container with the highest damage type of bruising and abrasion ($D_x = 7.34\%$). The high amount of the combined damage might be because the packaged rose apples were wrapped without any cushioning. Bare fruit, in direct contact with each other, received these types of damages whenever subjected to vibration [21, 22]. With the EPS container, abrasion was very small ($D_x \cong 0.01\%$) while bruising was high ($D_x \cong 3.24\%$). This might be because the rose apples were cushioned with foam net. The foam net protected the fruit skin from directly contacting adjacent fruit. Nevertheless, due to either improper vacuum or an ill-fitting plastic bag inside the EPS container, the packaged rose apples were able to shift. When exposed to vibration, each fruit or the entire bag of fruits displaced and impacted the inside surface of the container, giving rise to bruising. However, the EPS container did not create cracks, internal cracks and abrasion or internal crack damage. The current wholesale packaging with the lowest damage was the corrugated box I with a total D_x of 2.43%.

For the developed wholesale packaging, abrasion for both the diagonal and the vertical orientations of the fruit was very low (D_x = 0.02–0.03%) due to foam net cushioning around each fruit. Bruising for the vertical orientation (≅ 1.69%) was about 5 times greater than that of the diagonal (≅ 0.36%). Jarimopas et al. reported that the power spectrum density (PSD) of the tangerine fruit in wholesale packaging in the vertical direction was greater than that in the horizontal direction [20]. Therefore, the vertical PSD probably caused more bruising than the horizontal PSD did.

Packaging and fruit section significantly affected the average damage percentage D_y of bruising, abrasion, cracks and internal cracks (Table 11).

The average damage percentage for every package of Thongsamsri rose apples mainly generated bruising and abrasion; especially the corrugated box I, which also produced internal cracks (39.6%) and very small crack. Each current package type exhibited a high value of the combined bruising and abrasion (more than 100%). The plastic basket was the container with the greatest bruising ($D_y \cong 223.0\%$), while corrugated box I was the container with the greatest abrasion ($D_y \cong 173.4\%$). The plastic basket was also the container with the highest damage due to bruising and abrasion ($D_y = 373.2\%$). The EPS container was the current package type with the lowest D_y, featuring very small abrasion ($D_y \cong 1.0\%$), high bruising ($D_y \cong 122\%$) and was free from crack and internal crack.

For the wholesale packaging developed, abrasion in both the diagonal and the vertical orientations was very low ($D_y \cong 2–3\%$) owing to foam net wrapping around individual rose apples. Bruising for the vertical orientation ($D_y \cong 78.6\%$) was about 2 times greater than that of the diagonal ($D_y \cong 38.9\%$). The influence of PSD on D_x was more severe than that on D_y. In every package of the Thongsamsri variety, the bruising of the fruit section A was greater than that of the section C. This occurrence was further explored by conducting compression tests using a 4 mm plunger contact loading on Thongsamsri rose apples with the Universal Testing Machine (INSTRON 5569, USA). The rupture force of the fruit at the fruit section A and C was found to be 5.50 and 8.89 N respectively. This suggests that the fruit section with the smaller rupture force would probably get bruised more easily than that with the larger force. The post-harvest damage of rose apples in the predetermined packaging subjected to simulated vibration test was markedly characterized by bruising and abrasion type of damage. This result complied with the damage types found in the present practice of handling and transportation of rose apple packaging.

For the diagonal oriented packaging, based on D_x and D_y, was not only free from crack and internal crack but also generated about 1/3 of the bruising and abrasion as compared to the EPS container. Therefore, the diagonal orientation was considered to be the rose apple packaging that caused the minimum damage.

Table 11. *Average Damage Percentage* (D_y) of Various Damage Types for the Packaged Thongsamsri Rose Apples as Affected by the Packaging and Fruit Section.*

	Bruising (%)			Abrasion (%)			Crack (%)			Internal Crack (%)		
	Fruit Section			Fruit Section			Fruit Section			Fruit Section		
Packaging	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Corrugated Box I	11.371±0.496a	3.187±0.776a	4.703±3.855a	60.672±6.342c	40.395±14.505b	72.315±7.293d	0a	0a	0.452±0.342b	15.7782±4.536b	6.777±5.367a	17.012±0.780b
Corrugated Box II	67.241±5.718c	31.698±8.449b	38.281±8.269b	40.395±15.071b	38.219±19.865b	76.676±8.846d	0a	0a	0a	0a	0.853±0.611a	0a
Plastic Basket	87.771±4.267e	69.957±5.348cd	65.231±5.518c	34.699±9.728b	41.238±8.816b	74.222±5.927d	0a	0a	0a	0a	1.967±1.273a	0a
EPS Container	85.157±4.567de	7.991±7.748a	28.872±8.480b	0.726±0.530a	0a	0.241±0.181a	0a	0a	0a	0a	0a	0a
Diagonal Orientation	34.167±10.036b	0a	4.722±3.333a	0.833±0.764a	0a	1.389±1.283a	0a	0a	0a	0a	0a	0a
Vertical Orientation	69.998±8.457cd	1.667±1.443a	6.944±4.872a	1.111±0.481a	0a	1.944±1.368a	0a	0a	0a	0a	0a	0a

*The value of average damage followed by the same letter of the same damage type implies the damage percentage of insignificant difference at the significance level of 5%.

4.0 CONCLUSIONS

1. The post-harvest damage of packaged rose apples mainly consisted of abrasion and bruising with abrasion greater than bruising. The combined damage of bruising and abrasion at the retailer was greater than that of wholesaler.
2. The current wholesale packaging with the greatest damage was the plastic basket while that with the lowest damage was the EPS container.
3. Of all the package types tested, the wholesale packaging featuring diagonal and horizontal rose apple packaging exhibited the minimum damage with negligible abrasion.
4. Simulated vibration testing reflected a true picture of post-harvest damage of abrasion and bruising in the packaged rose apples as compared to the present practice of handling and transportation of the produce packaging.
5. The damage parameters used, i.e. average fruit damage and average damage percentage, sufficiently expressed the extent of damage to a fruit and the distribution of damage in the packages respectively.

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Measurement and Analysis of the Shocks Generated During Egg Production

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ABSTRACT: In their journey from the laying cage to shipments out of an egg production operation, table eggs encounter multiple shock events. While all agricultural commodities run the possibility of damage during the course of production, shell eggs are particularly susceptible to being cracked or broken during the production operation. A typical egg production facility experiences 2% to 7% checks (a partial mechanical failure to the egg shell) during handling, packaging and transportation of shell eggs. It has been estimated that the total losses to the U.S. egg industry due to checks and breakage of eggs during production amounts to over $247 million per year. Research was conducted using a data recorder at Cal Poly Eggs (San Luis Obispo, California) to evaluate shocks sustained by the eggs going through the production operation. The production line for this operation resembles a typical commercial egg production facility. This study evaluated shock levels sustained by the eggs going through a typical production operation. The results and recommendations to help decrease damage due to shocks are presented in this paper. This data can be used to improve production lines at any egg production facility to decrease the amount of checks or breakage and to increase the profits.

1.0 INTRODUCTION

ACCORDING to the USDA, the U.S. egg production during June 2006 was 6.56 billion table eggs and the total U.S. egg production during 2005 was 76.98 billion table eggs [1]. In 2005, of the 213.9 million cases of shell eggs produced in the U.S., 68.2 million cases were further processed, 125.5 million cases went to retail, 18.2 million cases went toward food service use and 2 million cases were exported [1].

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California Polytechnic State University's (San Luis Obispo, CA) egg production program currently has 14,000 chickens and produces more than 3.3 million eggs a year [2]. Cal Poly Eggs is an enterprise project and its sales have enabled the College of Agriculture's poultry program to be largely a self-funded. Profits from egg sales support supplies, equipment and students who gain work experience in the commercial egg industry. Cal Poly eggs are currently sold to restaurants and grocery stores from San Simeon in northern San Luis Obispo County to Orcutt in northern Santa Barbara County [3].

At the time of this study (April 2006), Cal Poly Eggs', laying operation was producing approximately 1.2 million eggs per year or 100,000 dozen eggs [4]. The operation was averaging 50 to 70 dozen checks (a "check" refers to a partial mechanical failure to the egg shell, which is a precursor to a complete breakage of the shell) per week at a loss of approximately $4,200 annually [4]. This rate yields 2.6% to 3.64% checks annually. A majority of damage was due to improper production line settings and operator errors.

While the figures for Cal Poly Eggs are modest compared to large commercial producers, the operations are similar. The same test methods employed using the data recorder to map the degree of shocks in the production environment could be applied to larger facilities. Following is an overview of Cal Poly Eggs at the time of this study [4]:

- *Flock age:* 60 weeks
- *Flock Strain:* Hy Line W-36
- *Flock Breed:* White Leghorn
- *Feed:* Standard Layer Mash
- *Packaging:* Molded wood pulp flats stacked 5 high in B-Flute RSC cases
- *Holding Temperature:* 44.8°F (7.1°C)
- *Holding Humidity:* 99% Relative Humidity
- *Holding time:* 1 to 2 weeks
- *Production Volume:* 1.2 million eggs per year
- *Sales breakdown:* Currently 98% of eggs are sold in molded paper flats to restaurants

1.1 Production Flow at Cal Poly Eggs

A RFID (Radio Frequency Identification) enabled instrumented egg

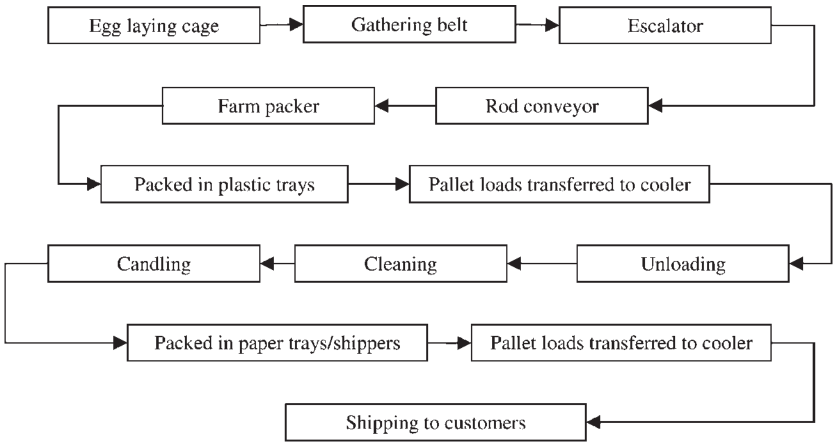

Figure 1. *Flow Chart of Cal Poly Eggs Operation.*

(Section 1.2) was used to monitor the production components at Cal Poly Eggs with a minimum of ten repetitions at each station. The results are described in section 3. The production flow at Cal Poly Eggs is as described in Figure 1. It is expanded upon in Section 2.0 of this paper.

1.2 Instrumentation

A variety of data recorders exist today with measurement capabilities such as temperature, pressure, relative humidity, light, speed, pressure, impacts and vibration. Depending on their capabilities these devices commonly involve such applications as field studies, transportation monitoring, troubleshooting, quality studies and general research. Recent advances and an increasing use of RFID technology in the past decade have enhanced the capabilities of data recorders by providing a portable and wireless means of capturing and transferring data. A data recorder with RFID features is typically designed for applications where portability and wireless data transfer is required. The communicating reader/writers can be mounted in a fixed location such as a portal or can be portable as well. One such device was obtained for a quality control application in the shell-egg industry.

While all agricultural commodities run the possibility of damage during the course of production, shell eggs are particularly susceptible to being cracked or broken during the production operation. In an effort to save a greater number of eggs and substantially increase the profitability of egg operations at Cal Poly Eggs, Sensor Wireless Inc.'s "CrackLess Egg®" (Sensor Wireless; P.E., Ontario, Canada) data recorder was adapted for this study. The instrumented egg used was a battery powered replica of a Large Grade "A" egg which was equipped with a tri-axial accelerometer that measured shocks in G's (sample rate of 10 kHz), and transmitted the measurements via radio frequency (DC to 5kHz) to a handheld device (Palm® handheld computer) [5]. Once events were recorded, the handheld could be hooked up to the serial port of a computer and the files could be imported to the Agent QC® software that was included with the kit. A customizable chart was made available for each file as well as the raw and combined event data. The storage capacity of the handheld device was 36 MB or up to 100 files, depending on size, and a storage rate of ten samples for each channel per second [5].

The instrumented egg was designed to be placed anywhere in the egg gathering, conveying, or packaging systems so that it traveled amongst the real eggs through the production process, identifying abuse points and reporting location and magnitude of abuse instantly to the user in real time. If the data recorder dropped, rolled, or came into contact with a solid object, it sent a reading to a hand-held computer; the egg also transmitted a temperature reading and flagged high-pressure areas.

A study was conducted by the manufacturer of the instrumented egg for the Prince Edward Island Egg Commodity Marketing Board in 2002 [6]. This study was part of a bench marking for Large Grade "A" eggs most commonly available in consumer markets. The eggs in this study were rolled and dropped onto plastic, metal and padded surfaces from a height respective of the target threshold (45 G's and 85 G's) and visually inspected for shell damage (Figure 2).

Results of this study found that at an impact magnitude of 45 G's, Large Grade "A" eggs did not fail. However, when the same egg was subjected to more than three impacts at a level of 45 G's, it failed consis-

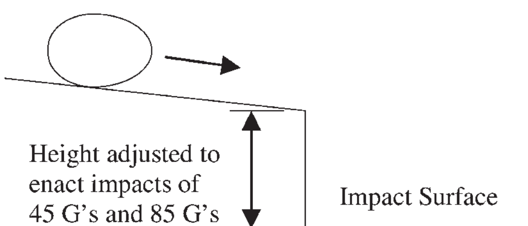

Figure 2. *Experimental Setup for Benchmarking Study.*

tently [6]. The same grade eggs when subjected to an impact magnitude of 85 G's also failed consistently by exhibiting visible cracks or damage on the egg shell [6]. This bench mark was re-established through testing at Cal Poly Eggs.

A study conducted at University of California, Davis estimated the economic loss due to checks and complete breakage [7]. This study estimated that unblemished eggs valued at $0.55/dozen could revert to $0.20/dozen due to checks and were usually processed for applications other than table eggs. This typically results in a loss of 0.3 cents/dozen of $0.08/hen/year for each 1% of egg breakage [7]. For eggs completely damaged during production (no income), 1% is equivalent to 0.5 cents/dozen or $.11/hen/year [7]. The same study, using 1998 production numbers, reported total losses to the U.S. egg industry due to checks and breakage of eggs during production amounted to $247.5 million per year. In addition, there were other associated costs such as candling and the purchase of equipment to detect breakage, labor and packaging costs, costs for rehandling rejected eggs, clean-up and customer dissatisfaction and human health risks associated with consuming mishandled checked eggs.

2.0 METHODOLOGY

The test protocol used for this study evaluated the shock levels at each section of the production operation with a minimum of ten repetitions. The position and orientation of the instrumented egg was also varied to estimate as many conditions as possible. Following the testing, data was analyzed and suggestions developed to decrease checks. Data was collected in terms of average shock count, and minimum and maximum shocks for all components of the production operation. Explanation for testing conducted at various sections on the production line is provided below.

2.1 Test Protocols for the Production Line

Egg Laying

Egg laying was analyzed using three practical scenarios.

a. *Cage to Empty Gathering Belt:* the instrumented egg was placed onto the cage floor and allowed to roll down onto the empty gathering belt.

Figure 3. *Cage to Loaded Gathering Belt.*

Figure 4. *Cage to Metal Support on Gathering Belt.*

b. *Cage to Loaded Gathering Belt:* the instrumented egg was placed onto the cage floor and allowed to roll down onto the gathering belt loaded with eggs (Figure 3).
c. *Cage to Metal Support on Gathering Belt:* the instrumented egg was deliberately allowed to roll into the metal support (Figure 4).

Gathering Belt to Elevator to Rod Conveyor

The instrumented egg was placed on the gathering belt just upstream from the transition to the elevator. The eggs moved from the gathering belt onto the elevator (Figure 5) and down onto the rod conveyor (Figure 6).

Farm Packer

The instrumented egg was placed onto the rod conveyor upstream from the farm packer and the data was gathered until the test egg dropped into a thirty count plastic farm packer tray. Critical events to be moni-

Figure 5. *Gathering Belt to Elevator.*

Figure 6. *Elevator to Rod Conveyor.*

Figure 7. *Orienter at Farm Packer.*

Figure 8. *Eggs Picked Up and Dropped into Trays.*

tored included the transition from rod conveyor to the farm packer, the transition to the orienter (Figure 7), pickup, and drop (Figure 8).

Palletizing from Farm Packer

The instrumented egg measured the forces produced along the conveyor belt before being stacked six trays high and finally being loaded onto a pallet.

Pallet Moving

The shocks experienced by eggs on a pallet as it is transferred from the farm packer to the holding cooler were monitored.

Loader

The instrumented egg was substituted for a real egg on a tray staged on the timing conveyor before the loader. This test focused on the forces created by the loader (Figure 9). The loader essentially unloads the eggs

Figure 9. *Loader Operation.*

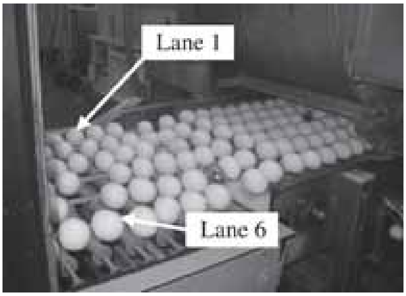

Figure 10. *Transition between Washer and Candling Area.*

from the farm packer plastic trays and loads them on the washer conveyor.

Washer Transition

Focusing on the transition from the washer to the candler, this part of the study spanned the distance past the loader. Trials were done for each of six lanes by substituting the instrumented egg for a real one. The farthest lane pictured in Figure 10 was referred to as "Lane 1," or "Far Lane", and the nearest lane as "Lane 6," or "Near Lane."

Candler

Shocks induced by transitioning into the candling area were recorded for each individual lane. Candlers (Figure 11) are typically used to check egg quality and progression of embryos.

Sorter

The sorter picks up the washed eggs and grades them based on the measured weight. The eggs are then dropped into molded pulp trays.

Figure 11. *Candling Area.*

Figure 12. *Eggs Transferred to Sorter.*

Figure 13. *Eggs Moved and Sorted.*

Two major events, the pickup and the drop were monitored. Figures 12 and 13 show the sorter operation.

Case Loading by Hand

The molded paper trays loaded with sorted eggs are then visually inspected and loaded into B-flute RSC shippers by operators (Figures 14 and 15).

Palletizing

The instrumented egg was incorporated into a full case of eggs and then moved from the packing platform to the pallet. The location of the test egg within the case was varied and the shock levels were monitored.

Transportation

Since the palletized cases of eggs are shipped within short distances to the customers and past studies have revealed absolutely no impact levels

Figure 14. *Visual Inspection and Case Packing.*

Figure 15. *Visual Inspection and Case Packing.*

of concern [10], measurements of this segment of the distribution were not conducted.

2.2 The Effect of Drop Orientation

The complex structure of an egg which provides everything needed for the developing embryo is probably the best package provided by nature. An egg which can normally withstand extreme pressure due to its shape is also very susceptible to impacts. In addition to monitoring the various elements of the production line at Cal Poly Eggs, supplementary tests were also conducted to study the effect of orientation of the eggs on recorded shocks. Ten drops were conducted for each orientation drop, large end, narrow end and side, from three inches onto the rod conveyor (Figure 6). This location was selected due to the highest average shock count exhibited (Table 1). The drops were conducted on the large end, the narrow end and the side of the instrumented egg.

3.0 RESULTS

As identified in Table 1 and Figure 16, a highest level shock of 120 G's was observed for the production line event 4 between the gathering belt and the rod conveyor. Also of the fourteen operations mapped, seven displayed highest shock levels at or above the threshold value of

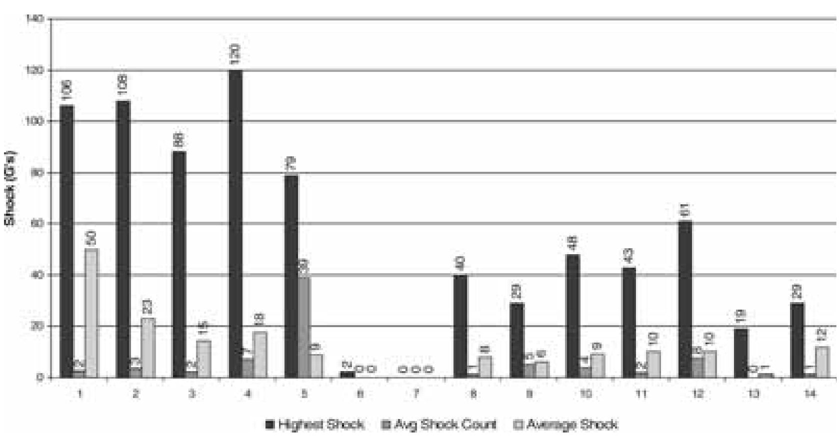

Figure 16. *Graphic Presentation of Results from all Production Operations.*

Table 1. *Summary of Results from all Production Operations.*

Data Summary	**Production Line Event**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Highest Shock	106	108	88	120	79	2	0	40	29	48	43	61	19	29
Avg. Shock Count	2.2	3.2	2.0	7.1	39.0	0.2	0.0	1.1	5.3	4.1	1.8	7.5	0.2	1.0
Avg. Max. Shock	68.7	56.8	26.0	53.9	49.7	0.4	0.0	9.7	15.9	25.0	15.0	30.7	1.9	13.0
Avg. Shock	49.9	23.2	14.6	17.7	8.8	0.4	0.0	8.0	6.3	9.3	10.1	10.4	1.0	12.0
Avg. Std. Dev.	21.0	29.0	10.6	19.8	12.3	0.0	0.0	1.6	6.8	12.1	4.5	11.9	1.3	1.4

1 = Cage into Metal Support;
2 = Cage to Loaded Belt;
3 = Cage to Empty Belt;
4 = Belt, Elevator, Rod Conveyor;
5 = Farm Packer Loaded;
6 = Palletizing at Farm Packer;
7 = Pallet Moving;
8 = Loader;
9 = Washer Transition Lanes 1–5;
10 = Washer Transition Lanes 6;
11 = Transition to Candler;
12 = Sorter;
13 = Case Packing;
14 = Palletizing Cases

45 G’s and four events above the critical value of 85 G’s. This shows a need for considerable improvement at the production setup at Cal Poly Eggs.

3.1 Production Lines

For the egg laying and collection segment (events 1–3), all three scenarios tested produced shock levels beyond threshold value of 45 G’s. The average shock of 49.9, observed during event 1, was the highest of the three. The eggs that impact the support rod while rolling down to the gathering belt have a possibility of cracking instantly or a later event. During event 4 (gathering belt to elevator to rod conveyor), a highest shock during any operation of 120 G’s was observed. Also the average maximum shock noted for this event of 53.9 G’s was the third highest noted for all events. Most of the high level shocks for this event were observed at the transition between the vertical elevator and the rod conveyor, specifically at the point of drop on to the rod conveyor.

Event 5 (farm packer), delivered an average of 39 shocks per test, the highest for any event. This was due to the reliance on the back pressure of other eggs to advance the eggs across the transitions. With an average maximum shock of 49.7 G’s the farm packer on average delivers a weakening blow to the egg shell, which may cause it to fail instantly or at a later event. At the loader (event 8), approximately 60% of the shocks observed were no greater than 3 G’s. The highest shock of 40 G’s could be an anomaly since the next highest shocks observed were considerably lower. Most of the shocks were observed as the eggs were released from the loader to the conveyor system.

For events 9 and 10 (washer transition), shocks were separately observed for lanes 1–5 and lane 6 after a preliminary observation of greater shocks in lane 6. The maximum shock of 48 G’s observed for lane 6 was considerably higher than that for lanes 1–5 (29 G’s). During the transition to the candler (event 11), a maximum shock of near threshold level of 45 G’s was observed. This shock was observed in the farthest lane. Overall the shocks were not considered severe for this event. During its transition through the sorter (event 12), on average each egg received three shocks in the 20–30 G’s range. The shocks tended to occur during pick up, drop and tray advance. A high of 61 G’s was observed at this part of the production operation.

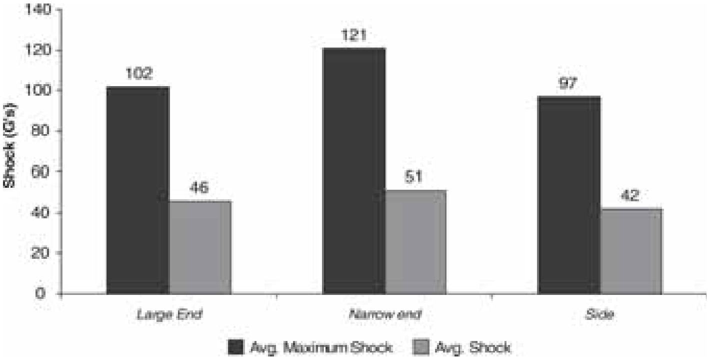

Figure 17. *Graphical Representation of Drop Orientation Test Results.*

3.2 Drop Orientation

As mentioned earlier, supplementary tests were conducted to study the effect of orientation of the eggs on recorded shocks. Ten drops were conducted for each orientation drop on the large end, narrow end and side, from three inches onto the rod conveyor. This location was selected due to the highest average shock count exhibited (Table 1). Table 2 and Figure 17 display the results of this supplementary test. A maximum average shock of 121 G's was observed when the egg was dropped on its narrow end and the least value of 97 G's was observed for egg dropped on its side.

4.0 CONCLUSIONS

A data recorder such as the one used in this study is a valuable tool for the egg production operations. Based on the observed shock levels at various components of the production line at Cal Poly Eggs, the follow-

Table 2. *Summary of Results for Drop Orientation Testing.*

	Egg Orientation		
Data Summary	**Large End**	**Narrow End**	**Side**
Highest Shock	159	168	170
Avg. Maximum Shock	102	121	97
Avg. Shock	46	51	42
Avg. Standard Deviation	44	51	44

ing suggestions were produced to decrease the damage levels and hence increase the profits:

- *Retrofit the metal support rods at the egg gathering belt area:* A solution to avoid high shock levels observed during events 1 (cage into metal support) and 3 (cage to empty belt) could be to route the support rod outside of the present location or to pad them.
- *Increase the egg gathering frequency:* For event 2 (cage to loaded belt), the frequency of egg gathering could be increased from once to twice per day. This could possibly decrease the egg on egg impacts.
- *Retrofit the landing area at the rod conveyor:* A solution to reduce the high levels of shocks observed when the eggs are transitioned from the vertical escalator to the rod conveyor could be to introduce a cushioned landing pad for the transition to the rod conveyor.
- *Evaluate the farm packer:* The construction and mechanism of the rod conveyor and the orienter material could be evaluated to decrease the high number of impacts. Also proper synchronization of the dropping of eggs into the farm packer tray should be looked at.
- *Evaluate the lanes for washer and candler transitions:* The construction and mechanism of the conveyor system for all lanes should be individually evaluated.
- *Evaluate the sorter speeds:* An estimated twenty to fifty dozen eggs are lost due to mishandling by the sorting equipment. The speed of all the operations occurring during this event need to be evaluated.
- *Egg Orientation:* Although, due to the nature of the moving mechanism in the production operations at Cal Poly Eggs, a majority of the eggs advance on their sides, some measures could be taken to ascertain that this occurs throughout the operation.
- *Feed management:* With damage levels reaching a predetermined point, it may be economic to switch to a feed with more calcium

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   Table 5. Comparison of state-of-the-art matrix resins with VPSP/BMI copolymers.

Resin System	Core Temp. (DSC peak)	Char Yield, %
Epoxy (MY720)	235	30
C379: H795 = 1.4	285	53

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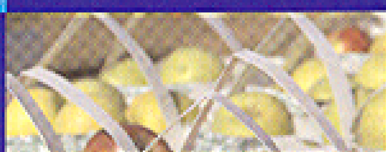

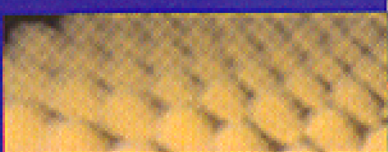

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