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Aim and Scope

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CONTENTS

RESEARCH

An Examination of the Variables Affecting RFID Tag Readability in a Conveyer Belt Environment

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ABSTRACT: There is a growing list of companies implementing radio frequency identification (RFID) systems to help optimize their supply chain processes. These companies realize that a successful RFID system can potentially lead to lower supply chain inventory levels, reduced operating expenses, and greater visibility throughout the supply chain. However, since RFID technology is still relatively immature, a majority of the applications experience less than perfect read rates for tagged items moving through the supply chain. This paper reports the results for a variety of different arrangements of variables that may influence the readability of the RFID tags in a conveyer belt environment. The variables tested for this study were tag placement on the package, tag orientation, conveyer belt speed, tag type, package contents, and the reader antenna distance from the conveyer belt. The goal of this research was to determine how these variables influenced the readability of the RFID tags. The results from this procedure determined that metal and water have a negative affect on the read accuracy of the RFID tags. The read accuracy also decreased as conveyer belt speed increased, and as a function of the distance between the antenna and the conveyer belt. Multiple linear regression was used to create 'Hit Rate' equations that can be used to predict the hit rate for the three types of products tested under various speeds and distances.

1.0 INTRODUCTION

RADIO Frequency Identification (RFID) is a means of identifying unique items using radio waves. Typically, a reader interrogates a

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1557-7244/07/02 061-13

microchip or tag, which holds digital information. RFID is being adopted in three principle areas transportation and distribution, manufacturing and processing, and security and law enforcement [1]. Secondary areas of application, some of which are steadily growing in application numbers, include animal tagging, waste management, time and attendance, postal tracking, airline baggage reconciliation, and road toll management.

The supply chain at its present stage is not as reliable as it needs to be for effectively tracking packages through retail distribution. Every year, billions of dollars are lost because products do not: reach customers on time, in the right climatic conditions, or in the right quantities. Often the wrong products are shipped or the shipments get accidentally misdirected [1]. On occasion, shipments are miscounted or miscoded on the receiving end, and sometimes the loss is created by pilfering, which can occur at various points of the supply chain. RFID based supply chain management systems promises to rectify a majority of the shortcomings of the present day package supply chain [1].

Recent RFID mandates and initiatives at case and pallet levels by supermarkets such as Wal-Mart, Albertson's, Best-Buy, and Target and the US Department of Defense in the United States and several European retailers such as Tesco, Carrefour and Metro who collectively share about 100,000 suppliers, have targeted reducing the cost associated with this technology [1]. There are obstacles in the development, implementation and acceptance of RFID, as is the case with any immature technology. These obstacles include standardization, cost, and privacy/ethical issues. RFID also faces challenges in cases where the product contains liquids and when the tags are located on or near metal packaging. Multinational organizations such as Gillette, Kimberly Clark, and Proctor and Gamble have, in the recent years, initiated RFID pilot studies to foster a new culture of innovation to achieve dramatic efficiencies in their supply chains.

Retailers such as Wal-Mart and Target have identified RFID as a technology to help improve their supply chain management. Wal-Mart is one of the most aggressive retailers in implementing RFID. In 2004, Wal-Mart mandated its top 100 suppliers to tag all their case units and pallets delivered to three of its Texas distribution centers by January 1, 2005 [2]. Despite initial difficulties in coming to grips with the mandate, the top 100 suppliers tagged at least one stock keeping unit (SKU) category in their shipments to Wal-Mart's distribution centers. Another 38 suppliers voluntarily decided to work with Wal-Mart to meet its RFID requirements. Wal-Mart required its next 200 top suppliers to comply with a similar mandate by January, 2006 and further 300 suppliers by January 2007 [1]. RFID provides an opportunity to reduce supply chain costs, speed the flow of merchandise from manufacturing through distribution centers and to the retail stores, and to provide consumers with better product availability. A study by the research group Gartner shows that the use of RFID in supply chains could result in a 90% decrease in location errors, 40% decrease in inventory counting time and 15% increase in productivity [3]. Retailers, at the present time, are requiring suppliers to provide RFID tags at case and pallet level and eventually will move on to item level tagging.

Government agencies such as Department of Defense (DoD) and Food and Drug Administration (FDA) are also considering their suppliers to incorporate RFID tags in their shipments to them. DoD mandated all contracts issued after October 1, 2004 to apply RFID tags to all cases and pallets and to individual high value items ($5,000 or more) shipped to DoD [4]. Due to some forecasting problems and failure to adequately notify DoD's nearly 43,000 suppliers of the RFID mandate and the current RFID tag shortage, the date was pushed back to April 2005 [4]. With increasing drug-counterfeiting concerns, FDA has identified RFID as a major tool in its attempts to combat this problem. RFID is to help create a "pedigree" (a secure record documenting that a drug was manufactured and distributed under safe and secure conditions) for drugs manufactured by pharmaceutical companies. Companies like Purdue Pharma, GlaxoSmithKline and Pfizer have already started pilot programs to incorporate RFID in products deemed susceptible to counterfeiting [1].

Wal-Mart has put forth tag read requirements for case tagging as follows:

- 100% read rate of cases moving on conveyers
- Conveyer speeds of up to 183 meters per minute (600 feet per minute)
- 10 foot read range
- Must be able to read regardless of tag orientation

This research analyzes specific variables that may affect the read accuracy of RFID tags in a conveyer belt environment. Variables tested were the conveyer speed, tag placement on the package, antenna distance from the conveyer belt, package contents, and the type of tag used.

The goal of this project was to determine which alignment of these variables would produce the most accurate and consistent reads of the tags.

2.0 EQUIPMENT AND METHODOLOGY

2.1 Product

Previous studies [1, 5] have shown that RFID tags placed on or near packages made out of metal or containing water do not provide perfect reads. Based on this test packages were selected that had these variables for this project. Table 1 and Figure 1 provide the descriptions of the test cases used for the study. Paper towels, because of their transparency to RF, were used as control.

2.2 RFID Hardware

Alien Technology Corporation's (Morgan Hill, CA, USA) ALR 9780 RFID reader and ALR-9610 circular polarized antennae were used for this study. The ALR-9780 provides both EPC Class 1 Gen 1 support and Gen 2 support and was connected to a computer using RS-232 computer interconnection. It provides up to four ultrahigh frequency (UHF) antennae. Alien Gateway V2.15.08 middleware was used to collect all data. Four ALR-9610 circular polarized antennae were used, since they were less sensitive to the tag orientation and sufficed the read distance requirements for this project.

2.3 RFID Tags

Four UHF, passive, Class 1 Gen 2 RFID tags (Figure 2) were studied with two orientations, horizontal and vertical. These tags were Alien Super Squiggle, Alien "Higgs", Raflatac G2 Short Dipole and Avery AD-222. They all measured approximately 4″ × 1/2″.

2.4 Conveyer System

The conveyer system used for this study was designed to simulate up to a 183 meters per minute (600 fpm) distribution center conveyer line and routing system. The continuous conveyer system was 0.61 m wide and 18.29 m long. The conveyer uses rollers and belts to move cases up

Table 1. *Description of Product.*

Product	Product/Case	Case Dimensions (cm)	Packaging
Kirkland Signature brand paper towel rolls	12 – 27.94 cm x 35.56 cm	55.88 x 40.64 x 27.94	Plastic film used to wrap individual rolls as well as the case
Kirkland Signature brand drinking water bottles	35 – 1/2 L	46.99 x 33.02 x 20.32	Shrink wrapped corrugated board tray
Pepsi (regular) cans	15 – 237 mL	33.02 x 20.32 x 8.89	Paperboard carton

Paper Towel Bottled Water Carbonated Beverage

Figure 1. *Cases of Product used in the Study.*

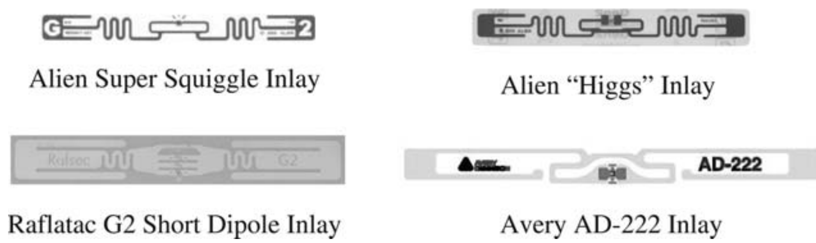

Figure 2. *RFID Tag Inlays.*

inclines, through reader portals at variable speeds and around corners. Three conveyer belt speeds, 61 m/min (200 ft/min), 122 m/min (400 ft/min), and 183 m/min (600 ft/min), were used for this project. The reason for testing at multiple speeds was to find out how the conveyer belt speed affected the readability of the tagged cases.

2.5 Instant EPC Hotspot v2.5 software

Instant EPC Hotspot software contains several tools to map out the RF-performance around a case of packaged-product. The software was used for this research to conduct an in-depth analysis at every 2.54 cm of the three product-package combinations. Easy to comprehend visual results were created to instantly identify the best location for tag placement and tag orientation on cases of each of the three products studied.

This, the first stage of testing, was done using one Alien ALR-9780 circularly polarized antenna mounted on a stand, 91.44 cm from the center of the antenna to the floor. Each of the products tested was placed on top of a 76.2 cm high plastic stand located at 90 degrees and 91.44 cm away from the antenna. With each product tested, the face of the case and the front of the antenna were kept 91.44 cm apart. For each product, two sides of the case were selected to determine an optimal tag location, the front face and back face with respect to the antenna [5].

Each face to be tested was equipped with a 2.54 cm × 2.54 cm grid drawn on a piece of paper that was taped to the face of the case to be tested. The center of the tag was placed at the intersection of each horizontal and vertical line. The tag was moved from intersection to intersection for each read. Once the case and antenna were set up, the dimensions of the case were entered in the software's Case Setup page. The Hotspot test option, which brings up a 3-dimensional version of the product, was selected. The software creates a 2.54 cm × 2.54 cm grid on each face of

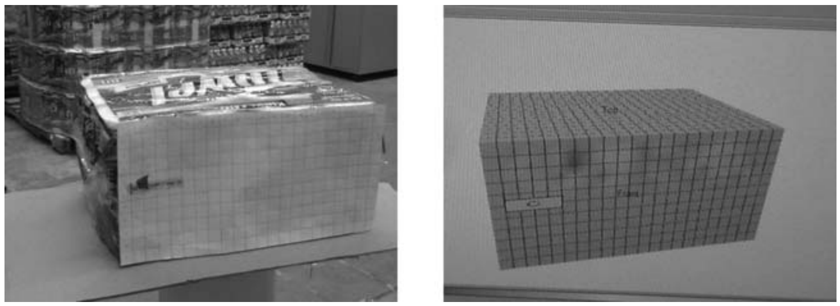

Figure 3. *Test Setup for Optimum Tag Location Testing in the Horizontal Orientation.*

the case. The face representing the face of the case to be tested and the closest size tag were selected from the on screen options. On the 3-dimensional on-screen image, an intersection was selected that allowed the tag to fit completely on the case without overhang, and the actual tag was placed in the same location on the product to be tested (Figure 3).

The tag was placed on the front of the package, the antenna activated, and results were recorded at each grid intersection. When each intersection had been tested, a still image of the face tested was saved, and the tag was moved to the back of the package, and the test was repeated. Again, once all intersections had been tested on the back side of the package, a still image of the face tested was saved. Once both sides had been completed with the tag in the vertical orientation, the tag was repositioned horizontally on the case, and both the front and back side of the case were tested again. This testing procedure was done for all four tags on all three packages.

Figure 4 shows a comparison of the RF performance of the Alien Super Squiggle tag placed on bottled water cases in horizontal and verti-

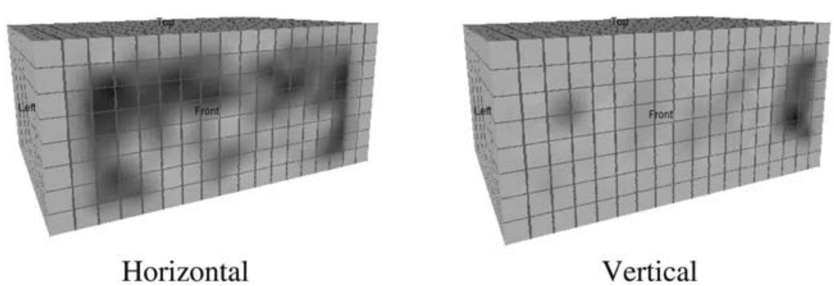

Figure 4. *RF Performance Comparison of Alien Super Squiggle Tags Placed on Bottled Water Cases.*

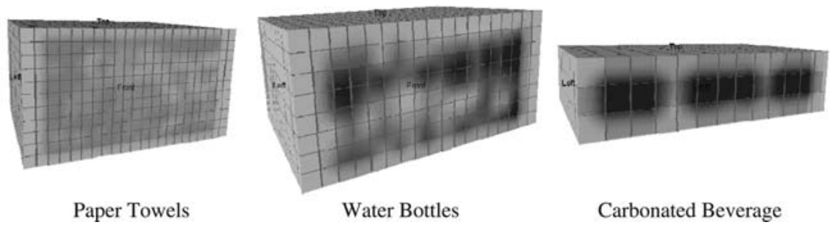

Figure 5. *RF Performance Comparison of Alien Super Squiggle Tags Placed Horizontally for Products.*

cal orientations. Figure 5 shows a comparison of the RF performance map for the same tag used horizontally on the three cases of products used for the study.

Using the RF performance maps for the three product cases and the four tags used, an optimal tag location and orientation was selected for all combinations. For the case of paper towels the optimal tag location was on the front of the package in a vertical orientation. The location on the package chosen for all four tags was 5.08 cm down from the top and 5.08 cm over from the right side of the package. For the carbonated beverage cases containing metal cans, the optimal tag location was on the front of the package in a horizontal orientation. The exact location on the package chosen to use for all four tag placements for this product was 2.54 cm down from the top and 10.16 cm over from the left side of the package. For the cases of water bottles, the optimal tag location was on the front of the package in a vertical orientation. The location on the package chosen for all four tags was 5.08 cm down from the top and 12.7 cm over from the right side of the package.

2.6 Conveyer Testing

The second stage of testing utilized the conveyer belt. The conveyer belt testing was done to determine how the package contents, the type of RFID tag, the conveyer belt speed, and the antenna distance would affect the readability of the RFID tags. The tagged faces for all cases were placed on the conveyer belt to face the reader antenna (Figure 6). Conveyer speeds of 60.96, 121.92 and 182.88 meters per minute and the read distances of 0.305, 0.914, and 1.524 meters (1, 3, and 5 feet) were used for all combinations of RFID tags and cases of product. The readability of tags ("hit rate") was recorded using ten passes of the cases in front of the antenna.

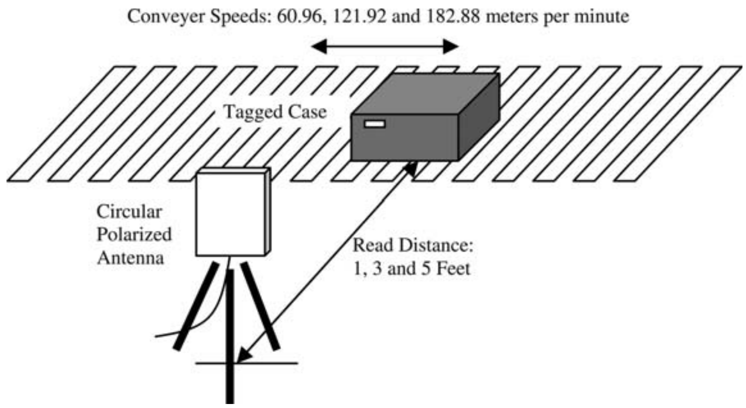

Figure 6. *Experimental Setup Deployed for Conveyer Belt Testing.*

3.0 RESULTS AND DISCUSSION

The "average hit rates" produced by the various combinations of variables are listed in Tables 2–5. Each hit rate is based on 10 individual observations.

The data in Tables 2–5 was then analyzed using multiple linear regression. An analysis of main effects showed that the performance of the four tag types tested were not significantly different ($p > 0.1$). Therefore, the results were pooled to examine the effects of product type (P), speed (S), and distance (D).

Based on our analysis, we found that all the main effects of product type, speed, and distance were significant ($p < 0.006$). First order inter-

Table 2. *Test Results for Alien Super Squiggle Tags.*

Antenna Distance from Conveyor (meters)	Conveyor Belt Speed (m/min)	Avg Hit Rate (% of 10 observations)		
		Paper Towels	Pepsi	Water Bottles
0.30	61.0	100	100	100
	121.9	100	80	100
	182.9	100	80	90
0.91	61.0	100	100	100
	121.9	100	50	100
	182.9	100	20	100
1.52	61.0	100	50	100
	121.9	100	60	90
	182.9	100	0	90

Table 3. *Test Results for Alien "Higgs" Tags.*

Antenna Distance from Conveyor (meters)	Conveyor Belt Speed (m/min)	Avg Hit Rate (% of 10 observations)		
		Paper Towels	Pepsi	Water Bottles
0.30	61.0	100	100	100
	121.9	100	60	100
	182.9	100	60	90
0.91	61.0	100	70	100
	121.9	100	50	90
	182.9	100	50	100
1.52	61.0	100	10	100
	121.9	100	0	50
	182.9	100	0	60

Table 4. *Test Results for Raflatac G2 Short Dipole Tags.*

Antenna Distance from Conveyor (meters)	Conveyor Belt Speed (m/min)	Avg Hit Rate (% of 10 observations)		
		Paper Towels	Pepsi	Water Bottles
0.30	61.0	100	90	100
	121.9	100	60	90
	182.9	100	50	90
0.91	61.0	100	20	100
	121.9	100	20	100
	182.9	100	10	90
1.52	61.0	100	0	90
	121.9	100	0	100
	182.9	100	0	70

Table 5. *Test Results for Avery AD-222 Tags.*

Antenna Distance from Conveyor (meters)	Conveyor Belt Speed (m/min)	Avg Hit Rate (% of 10 observations)		
		Paper Towels	Pepsi	Water Bottles
0.30	61.0	100	100	100
	121.9	100	50	100
	182.9	100	30	80
0.91	61.0	100	90	100
	121.9	100	40	90
	182.9	100	20	90
1.52	61.0	100	10	100
	121.9	100	0	70
	182.9	100	0	30

action terms were also examined. To correct for multicollineary caused by interaction terms, the speed and distance variables were centered using their mean values (i.e. $S_i - \overline{S}$, $D_i - \overline{D}$). This reduced multicollinearity to an acceptable level (Kutner et al., 2004).

The general multiple linear regression model using these centered values for speed and distance with product type and all two-way interaction terms was significant overall at the ($p = 0.000$) level. The model explains approximately 83% of the variation in hit rate. All main effects in the model were found to be significant at at least the ($p = 0.006$) level using t-tests of individual variables. The interaction of centered speed and distance was the only term in the model that was not significant ($p > 0$ .9) and was therefore dropped from further analysis. Partial f-tests found that the dummy variables representing the product types and all groups of interaction terms for speed and distance were significant ($p < 0.000$).

The following general predictive model applies to the range of speed and distances tested:

$$HR = 90.3 - 0.114S_C - 13D_C + 9.72P_1 - 47.8P_2 + 0.144S_CP_1 - 0.144S_CP_2 + 13D_CP_1 - 36.9D_CP_2$$

where:

HR = hit rate % ≤ 100%
S_C = centered speed (m/min) = $S_1 - \overline{S}$
S_i = speed (m/min)
$\overline{S}$ = average speed (m/min) = 121.9
D_C = centered distance $D_i - \overline{D}$
D_i = distance (m)
$\overline{D}$ = average distance (m) = 0.91
$P_1 = 0$, $P_2 = 0$ for water bottles
$P_1 = 1$, $P_2 = 0$ for paper towels
$P_1 = 1$, $P_2 = 1$ for Pepsi cans

The beta coefficients reflect the effect of the model terms on the hit rate. By plugging in the appropriate *Pi* values for each product type, the following product type specific equations are generated:

$$HR_{water\ bottles} = 90.3 - 0.114(S_i - 121.9) - 13(D_i - 0.91)$$

$$HR_{paper\ towels} = 100$$

$$HR_{Pepsi\ cans} = 52.2 - 0.114(S_i - 121.9) - 36.9(D_i - 0.91)$$

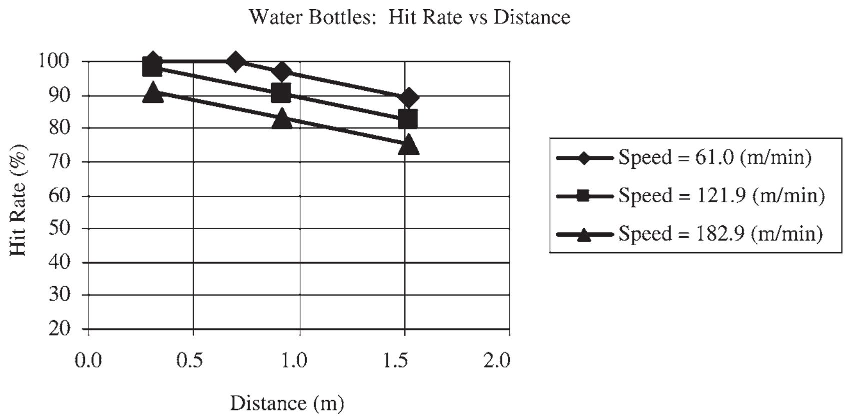

Figure 7. *Plot of hit rate versus distance over range of test speeds for water bottles.*

The family of curves generated for the water bottle and beverage metal can product types are shown in Figures 7 and 8. The predicted hit rate for paper towels is 100% over the ranges tested and therefore was not plotted. The predicted hit rate is also 100% for water bottles moving at the lowest speed for distances between 0.305 and 0.702 meters. An examination of the curves in Figures 7 and 8 and the beta coefficients for their respective equations shows that metal cans are much more negatively affected by distance than water bottles. Metal beverage cans typically have a 36.9% reduction in hit rate per meter versus only a 13% reduction for water bottles. The effect of increasing speed also has more of an effect on metal cans than water bottles, although the difference in ef-

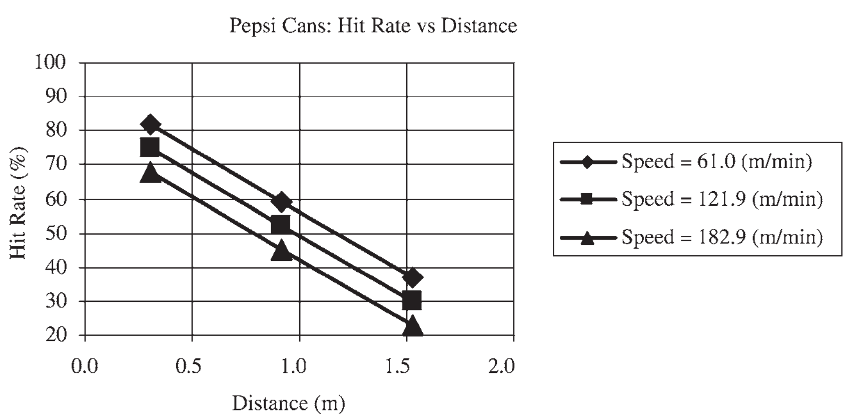

Figure 8. *Plot of hit rate versus distance over range of test speeds for Pepsi cans.*

fect sizes is less dramatic at 14.4% versus 11.4%. A Bonferroni procedure for 90% simultaneous confidence intervals demonstrated that all the predicted hit rates are within ± 0.5% (Kutner et al., 2004).

4.0 CONCLUSIONS

1. The results show that products in metal cans (beverage aluminum cans) show the largest resistance to 100% reads at high conveyor speeds.
2. Speed of conveying product above 183 m/min (600 ft/min) affects readability of tags on both metal cans and water based products.
3. 100% reads of RFID tags from different suppliers are possible on a range of other consumer products such as toilet paper and tissue.
4. Readability of tags (hit rate) as a function of tag orientation and placement can be optimized by the method developed and shown in this paper for varying conveyor speeds and product types.

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Degradation of Polylactic Acid (PLA) Exposed to Steam

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ABSTRACT: Structural integrity and reduction in molecular weight of polylactic acid (PLA) polymer from exposure to steam treatments was investigated. Thermoformed PLA drinking cups were cut into sheets of 6 cm × 4 cm, and exposed to steam at 100°C, 110°C and 120°C for 1, 2, 3, 4 and 8 hours. An additional experiment under extreme conditions of 120°C for 24 hours was used to validate composition of degradation products. Structural integrity was assessed through brittleness and physical damage. Weight-average molecular weight was estimated using the intrinsic viscosity method at 30°C. Results show that PLA structure and molecular weight are severely affected by steam conditions such as humidity, pressure and temperature. Molecular weight fell over time following a first-order reaction model, and kinetic constants showed to be temperature-dependent obeying the Arrhenius relationship with activation energy, *Ea*, of 52.3 KJ/mol. A mass balance demonstrated that 84.7% of the polymer is finally converted to its pure monomer—lactic acid—when subjected to steam at 120°C for 24 hours.

INTRODUCTION

WHILE plastics provide fantastic benefits in many applications, they are mostly produced from nonrenewable resources and ultimately contribute to solid waste [1,2]. Recently, bio-based plastics produced from renewable resources, such as corn, have been gaining attention. Polylactic acid (PLA) is the first packaging plastic material to be produced in commercially significant volumes. Lactide monomer used to produce PLA is a corn sugar fermentation product. PLA has been used to make many commercially available packaging items including trays, cups, bags, bottles, laminations and overwraps [3]. After use, discarded

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1557-7244/07/02 075-13

PLA plastics may be converted back to carbon dioxide and water under composting conditions.

Composting is a well known process that is mainly used to breakdown organic materials such as yard and food wastes. While PLA is susceptible to breakdown during composting, it has been found that PLA degradation kinetics are considerably slower than typical organic compost feedstock. Commercial PLA packages have been shown to be incompletely degraded after one month of composting [4]. Therefore, PLA represents a potential bottleneck to composting operations, which could result in PLA being diverted to landfills for disposal. Since modern sanitary landfills are designed to minimize biodegradation [5, 6], the promise of sustainability by using PLA would not be completely fulfilled. Therefore, a key question for compostable, sustainable plastics is how to improve degradation kinetics without compromising important useful qualities of the polymer.

The objective of this work was to evaluate potential post-consumer use treatments that might be capable improving degradation rates of PLA during composting. Previous related works evaluated gamma irradiation, electron beam irradiation, enzymatic hydrolysis and chemical hydrolysis on PLA degradation kinetics. Results showed reductions in molecular weight and associated loss of tensile strength, which are indicators of PLA breakdown [7, 8, 9, 10]. It is believed that such initial damage to the polymer will help to at least provide a head start and may actually accelerate degradation kinetics of PLA during composting. The goal is to determine the extent of pretreatment required in order to match degradation rates of PLA to that of typical organic compost.

This study evaluated steam treatment of PLA as a pre-composting treatment. Kinetics of molecular weight loss was assessed and a model based on first-order reaction kinetics was proposed. Results show that steam could be an effective pre-composting treatment in order to make PLA more acceptable to typical organic compost streams.

MATERIALS AND METHODS

Materials

Thermoformed PLA drinking cups (Fabri-Kal, Inc., Kalamazoo, MI) were provided by TREEO Center at the University of Florida. Cup di-

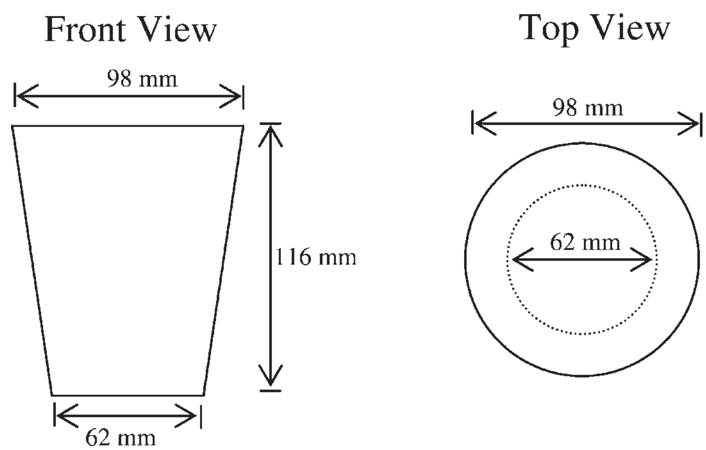

Figure 1. *PLA drinking cups drawing.*

mensions are shown in Figure 1, and were clear except for preprinted artwork.

Test Samples

Rectangular sheets of 6 cm × 4 cm were prepared using the walls of PLA drinking cups. Sample thicknesses were measured and shown to vary from 150 to 200 μm, which is primarily due to thermoforming procedures used by the manufacturer of the cups used in this study.

Steam Exposure

PLA samples (~40g) were placed inside jars and lids were adapted with holes to allow steam transfer. The jars were placed in a vertical still retort (University of Florida) where steam was fed and temperature/pressure was well controlled through a pneumatic system. Treatments at 100, 110 and 120°C, for 1, 2, 3, 4 and 8 hours were performed. After each treatment samples were quickly cooled with air to room temperature and dried in an oven at 105°C until constant weight. To confirm presence of depolymerized lactic acid in drip, an extreme treatment of 120°C for 24 hours was performed. For the extreme treatment, PLA samples were placed in 100ml deionized water (pH 7.5). For all experiments, subjective observations related to structural integrity and physical characteristics were recorded.

Molecular Weight

The standard method of intrinsic viscosity was used to determine weight-average molecular weight of PLA samples affected by steam treatments in accordance to ASTM D2857-95 [11]. Kinematic viscosities of PLA dilutions (0, 0.2, 0.4 and 0.6%(V/V)) were determined at 30°C using chloroform as solvent and a calibrated capillary viscosimeter Cannon-Ubbelodhe Type N° 25. These values were used to determine reduced viscosities, μ *red*, of dilutions and estimate intrinsic viscosities, [μ], of each treated sample. Finally, weight-average molecular weight, *M*, was estimated by the Mark-Houwink (MH) model given in Equation (1), which relates them with the intrinsic viscosity:

$$[\mu] = kM^a \tag{1}$$

Where constants, *k* and *a*, available for PLA dissolved in chloroform at 30°C, were 0.0153ml/g and 0.759 [12].

Kinetics of Change in Molecular Weight

Molecular weight loss of PLA treated with steam at 100, 110 and 120°C followed first order kinetics. The mathematical model follows Equation (2) where k_T is the reaction rate constant at temperature *T*, and *M* is the molecular weight at time, *t*.

$$\frac{dM}{dt} = -k_T M \tag{2}$$

Solving the ordinary differential equation with limits $t = 0$ to t, and $M = M_o$ to M, it results:

$$M = M_0 e^{-kt} \tag{3}$$

Kinetic constants, k_T, use to be correlated with absolute steam temperatures, *T*, in accordance to Arrhenius behavior [13] showed in Equation (4). The activation energy, *Ea*, and parameter k_0 were estimated by linearization.

$$k = k_0 e^{-E_a/RT} \tag{4}$$

A final model for the molecular weight of PLA, which is temperature and time dependent, is showed in Equation (5). This model allows prediction of molecular weight, M, of a PLA with initial molecular weight, M_0, after exposure to steam at temperature, T, after time, t.

$$M = M_0 e^{-kt} = M_0 e^{-k_0 t e^{-E_a/RT}} \tag{5}$$

Extreme Conditions

A mass balance was carried out in order to determine the conversion of polylactic acid to its monomer lactic acid [Equation (6)]. Variables, W_o and W_f are PLA dry solid weights before and after the steam exposure for 24 hours. The value of $(W_o - W_f)$ represents the weight of PLA that was converted to lactic acid.

$$\%\ \text{conversion} = \frac{W_o - W_f}{W_o} \times 100\% \tag{6}$$

Sample drip from treatment jars was collected and analyzed by pH (Accumet® AR60, Fischer Scientific, Pittsburgh, PA) and FTIR-ATR (Nicomet 6700 Smart Orbit, Thermo Scientific, Inc.). The intention of this assessment was to verify that exposure of PLA to steam really undergoes lactic acid production, confirming total de-polymerization.

RESULTS AND DISCUSSION

Steam Exposure

PLA samples exposed to steam for 8 hours displayed shrinking, brittleness and pore formation (Figure 2). These changes tended to be more severe as steam temperature and time increased.

Shrinking is attributed to application of temperatures above the glass transition temperature (T_g = 58–70°C) for PLA [14]. The glass transition is a second-order thermodynamic transition where polymers turn from glassy to rubbery. In this state, change of volume with temperature is intensified and is revealed through shrinking and twisting observed in samples. The mechanism of this phenomenon is the translational motion of entire molecules and, the cooperative wriggling and jumping of segments of molecules, leading to flexibility and elasticity [15].

Increased brittleness was quite noticeable, and samples more intensely treated where more sensitive to subsequent handling. Samples

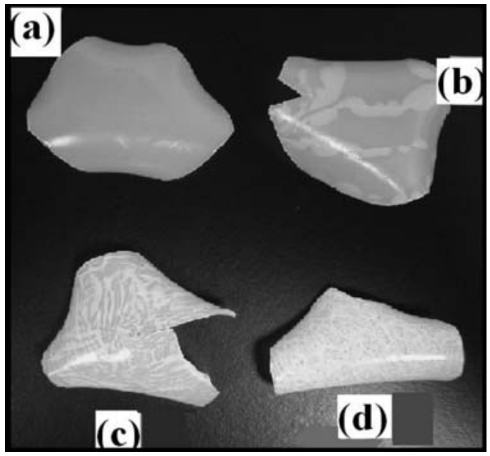

Figure 2. *Steam-treated PLA: (a) 100°C-4h, (b) 110°C–4h, (c) 100°C–8h, (d) 110°C–8h.*

generally exhibited cracks and broke easily. This indicates that steam exposure increase the amorphous regions of PLA and therefore affects its structure integrity. It is believed that the increase of amorphous regions or reduction in the degree of crystallinity of PLA is consequence to a hydrolytic effect of steam treatment. Hydrolysis generates free radicals that recombine within the crystalline regions resulting in more branched and less uniform chains [8].

Pores formed during treatment are shown in Figure 3. This demonstrates severe disruption of PLA structure as well as exposure of greater areas of polymer that can be attacked during composting. The mecha-

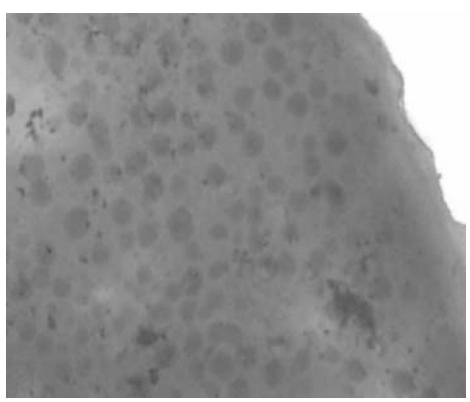

Figure 3. *Pores in steam-treated PLA 120°C–8h (×60).*

nism of pore formation was not determined, but is likely to be related to regional leaching of PLA material to the surrounding medium as a result of hydrolysis, leaving cavities or pores.

Molecular Weight

Molecular weight analysis was conduced for PLA samples exposed up to 4 hours in steam. Beyond this time, molecular weight distributions were too broad for analysis. Figure 4 shows how PLA molecular weight was affected by steam treatments. Initial weight-average molecular weight was about 210,000 g/mol. After 4 hours at 100, 110 and 120°C, samples achieved weight-average molecular weights of 60,000, 29,000 and 12,000 g/mol, respectively. These values represent about 29%, 14% and 6% of the initial molecular weight, for each respective temperature.

Data reported by other authors show that polyamide 11 subjected to high temperatures in acidified water (pH 4) reduces molecular weight by half in about 40 days at 100°C and 15 days at 120°C, respectively [16]. Results here show that PLA exposed to similar treatments reduces molecular weight by half in about 2.2 and 0.5 hours, respectively. While this comparison indicates that PLA is a good candidate for steam hydrolysis, it also suggests that steam treatments may also serve as a means to separate PLA from other plastics in the waste stream.

The dramatic decrease in molecular weight is the result of the hydrolytic effect caused by high temperature and relative humidity, and

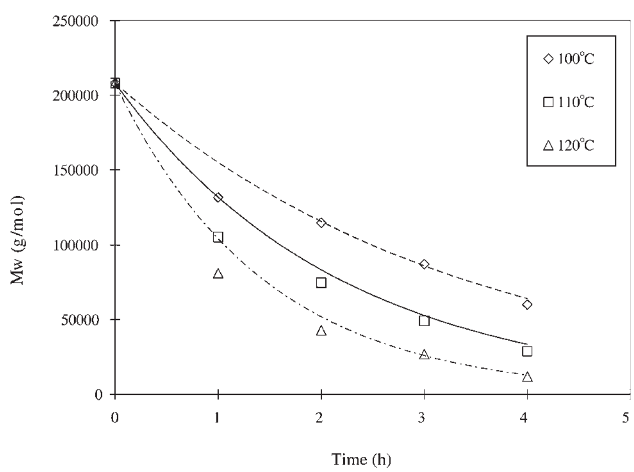

Figure 4. *Steam-exposed PLA molecular weight.*

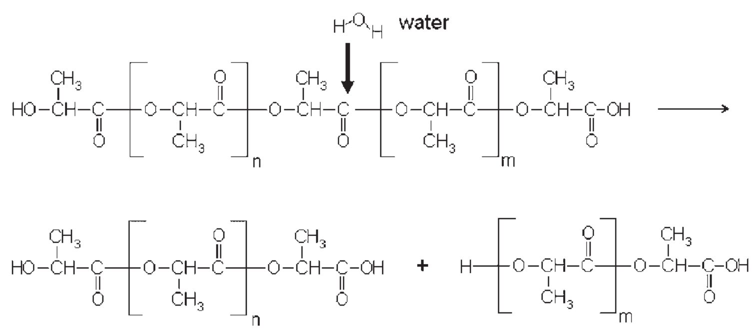

Figure 5. *Hydrolysis of PLA.*

can be regarded as a reverse poly-condensation. This process starts with a water uptake phase followed by a splitting of the ester bonds in a random way according to the Flory principle [17]. High relative humidity and temperature provide the conditions for cleavage of the ester linkages by water uptake and successive reduction in molecular weight [18], as illustrated in Figure 5. More severe treatments provide more energy to the cleavage, yielding higher chain scission, and therefore, lower molecular weights.

Molecular Weight Reduction Kinetics

Figure 6 shows semi-log plots of molecular weight vs. time at 100,

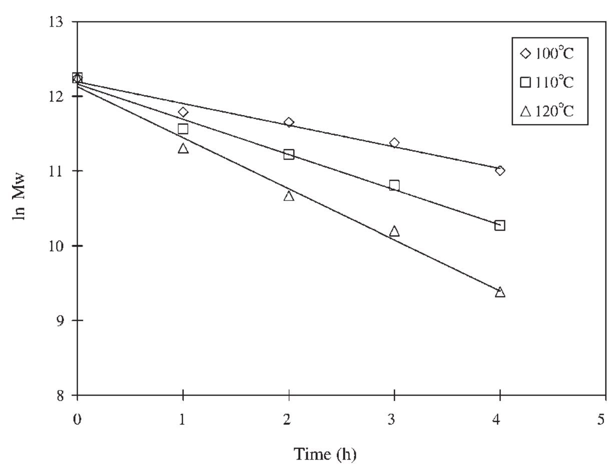

Figure 6. *First-order reaction plots.*

Table 1. *Reaction Rate Constants,* k *(h^{-1}) for Molecular Weight Reductions of Steam Treated PLA.*

	Temperature (°C)		
	100	**110**	**120**
k	0.290	0.470	0.068
r^2	0.975	0.989	0.988

110 and 120°C. Slopes of curves, obtained by regression analysis, represent the respective kinetic constants, k_T, and are shown in Table 1.

Figure 7 shows temperature sensitivity of the reaction rate constants through the Arrhenius plot. Regression provides estimates for activation energy, Ea, and Arrhenius pre-exponential facor, k_o. Regression analysis yields an r-square of 0.996 indicating an excellent goodness of fit of Arrhenius model. Values for Ea and k_o were 52.3 KJ/mol and -6.18×10^6 h^{-1}. Other authors have found Ea of 51 KJ/mol for poly(L-lactic acid) (PLLA) in the melt at 180-250°C [13] and 64.1 KJ/mol for PET in the melt at 250–280°C [19]. This shows that activation energy for reduction of PLA molecular weight is much lower than that of PET, but similar to that for PLLA in a melt at higher temperatures.

These values were used in Equation (5) to predict molecular weight reductions shown in Figure 4. Figure 4 shows experimental and model predicted values.

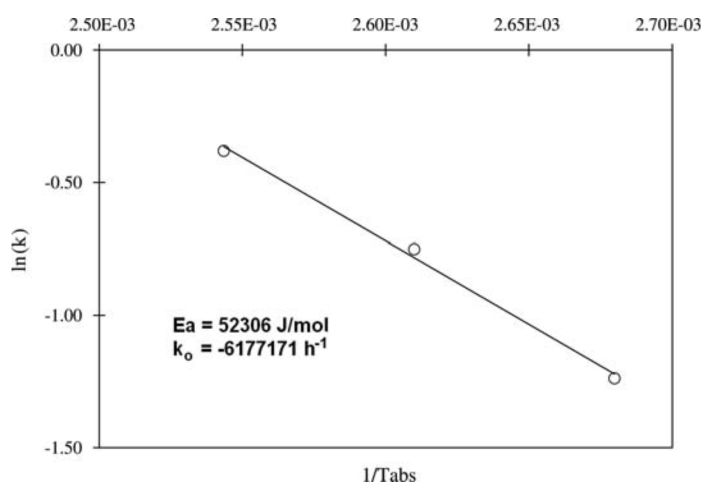

Figure 7. *Arrhenius plot.*

Extreme Conditions

After 24 hours of PLA exposure to steam at 120°C, the dried weight decreased from 30.1g to 4.6 g. This represents a percentage of conversion of 84.7%. Figure 8 shows the mass balance for PLA samples subjected to extreme conditions.

Tsuji et al. [13] studied melt hydrolysis of PLA and found a yield of L-lactic acid from PLLA of 90% at 250°C for 10–20 minutes [13]. Ohkita and Lee investigated the enzymatic hydrolysis of PLA using proteinase K and found a yield of lactic acid from PLA of 38% after 8 days at 37°C [20]. Yields of lactic acid observed here were not much different from those observed by hydrolysis in the melt.

Reductions PLA weight after exposure to steam at 120°C for 24 hours suggests PLA conversion into a water-soluble component of the liquid drip. This soluble component was expected to be lactic acid. pH of the

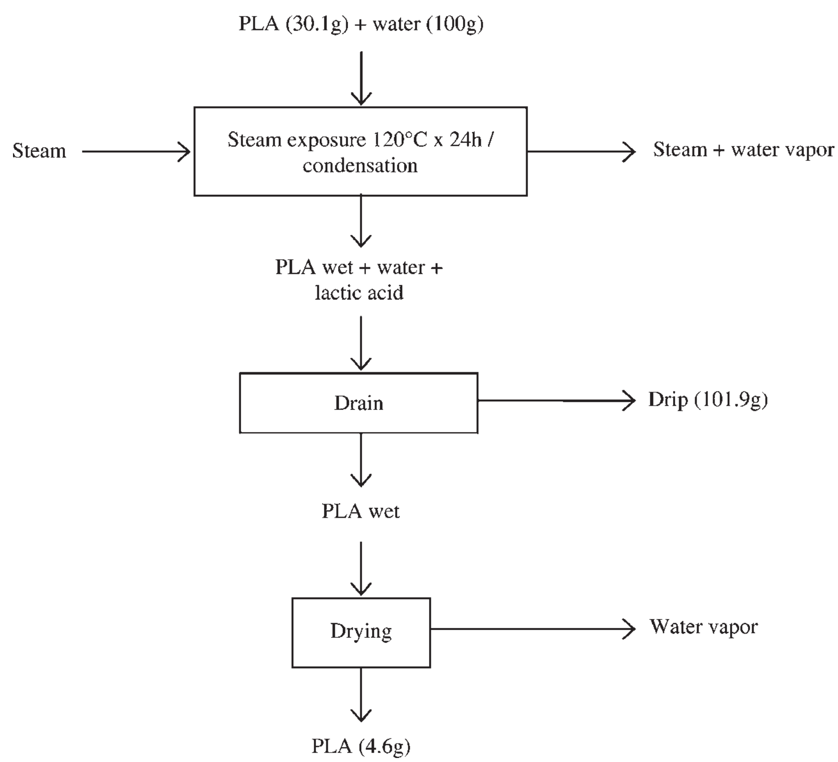

Figure 8. *Mass balance of PLA treated with steam at extreme conditions.*

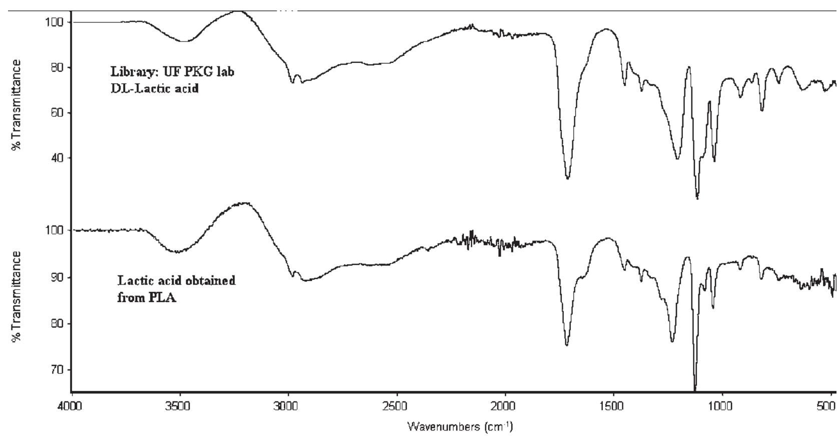

Figure 9. *Spectra of lactic acid obtained by FTIR-ATR.*

drip was about 1.5, suggesting an acidic addition such as lactic acid. Drip samples were analyzed using FTIR-ATR and results confirmed that the liquid by-product was a mixture of lactic acid and water. Figure 9 shows spectra for lactic acid from PLA and of DL-lactic acid control (Acros Organics, Geel, Belgium). These spectra confirm liberation of lactic acid to the treatment medium during steam treatment.

CONCLUSIONS

It is demonstrated that exposure to steam up to 120°C is an excellent method to hydrolyze PLA. Molecular weights of samples exposed to 120°C for 4 hours had molecular weights reduced to about 6% of initial values. Treated samples also became brittle and riddled with pores. Analysis of FTIR-ATR spectra confirmed hydrolytic liberation of lactic acid to the treatment medium. A yield of 84.7% lactic acid was obtained after 24 hours of PLA treatment at 120°C. Finally, a kinetic model describing molecular weight reduction in PLA as a consequence of hydrolytic steam treatments was presented. Degradation followed first order kinetics with activation energy, Ea, of 52.3 KJ/mol. This study shows that steam treatments may be suitable for assisting with separation of PLA from traditional plastic wastes as well as making PLA waste more accommodating to commercial composting operations.

ACKNOWLEDGMENTS

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Variability in Compression Strength and Deflection of Corrugated Containers as a Function of Positioning, Operators, and Climatic Conditions

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ABSTRACT: ASTM D642 is a commonly used standard for measuring the ability of containers to resist external compressive loads applied to its faces, to diagonally opposite edges, or to corners. The procedure recommends testing by centering the specimen on the lower platen of the testing machine in the desired orientation, so as not to incur eccentric loading. It is also recommended by the standard that the load be applied with a continuous motion of the movable platen of the testing machine at a speed of 0.5 ± 0.1 in. (12.7 ± .25 cm)/min until failure or a specified load, has been reached. It is recommended that the tests be conducted at "standard environmental" conditions of 23°C and 50% relative humidity. However, the vast majority of compression testers are not placed in rooms where humidity is controlled and multiple operators may perform the tests thereby increasing the possibility of variation of reported data. No recent studies involving the effect of variation in the container location or the test speed on the compression strength values, however, are available. This study tested over 400 C-flute RSC style boxes for 15 locations of the containers and ten platen speeds. Repeatability for select test conditions was also tested. The results reported in this paper show a significant reduction in the compression values by as much as 10.7% and an increase in defection by as much as 19.2% for the boxes with the variation in location. Changes in platen velocity and operators significantly affect compression and deflection testing.

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1.0 INTRODUCTION

THE role of testing in the development and evaluation of packaging systems has become an important function in today's corporate manufacturing and development practices. The use of lab testing to evaluate the functionality of a product and package is often preferred to real life testing because it can be better controlled and evaluated. Real-life testing, often more representative, is difficult to repeat since the intensity varies with each shipment, and also becomes expensive and time consuming. Various standards organizations use technical committees to develop methodologies that are repeatable and provide a representative simulation of the hazards that will affect a package and the product with a high degree of precision.

The American Standards for Testing and Materials International (ASTM) Committee D-10 is one of the largest sources of packaging test methods both in the United States and overseas. The standards are developed by various technical committees that enjoy a strong participation by industry, federal/state departments, trade organizations and academia. This D-10 committee has been extremely successful in developing a comprehensive set of standards and practices covering both the broad and narrow segments of various aspects of packaging.

ASTM D642, Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads, is a primary test method used to test shipping containers for their ability to resist external compressive loads [1]. This test method is related to Technical Association of the Pulp and Paper Industry (TAPPI) T804, which is similar for fixed platen equipment but does not recognize swivel platen machines [2]. ASTM D648 also fulfills the requirements of International Organization for Standardization (ISO) Test Method 12048 [3].

The ability of a shipping container to resist compressive forces experienced during storage and distribution in the supply chain is often evaluated using a compression tester. Test procedures such as ASTM D642, are typically used to perform laboratory based testing because they implement standardization, may it be within a facility or between different testing labs. This in turn decreases the repeatability and reduces reproducibility errors.

This study was initiated due to a lack of reference studies that reinforce the test procedure described in ASTM D642. Specifically the following steps in the test procedure were targeted for this study:

1. The procedure for compression testing as per ASTM D642 requires centering of the shipping unit on the lower platen of the compression tester in the desired orientation so as not to incur eccentric loading. Although the procedure cautions with regards to obtaining erratic data due to off-centering of the package on the platen, it does not provide references to any studies related to the topic, and the effect of off-centering on measured loads.
2. The procedure also requires the shipping units be tested at the platen speed of 0.5 ± 0.1 in. (12.7 ± 0.25 cm) per minute, whether testing the sample to failure or a specific load. Again, no referenced studies reinforce this.
3. Lastly tests conducted by multiple operators in labs that are generally only controlled for temperature but not for humidity have also not been studied.

The goal of this study was:

1. To study the effect of variation in platen velocity and corrugated box placement on the bottom platen of the compression tester on the measured compression strength and deflection.
2. To study the effect of variation of humidity levels in labs that only have temperature controlled environments using the same boxes but different operators during different parts of the year.

2.0 MATERIALS AND METHODS

A Lansmont Model 152-30 compression test unit was used for this study. This machine was calibrated at the initiation of the study. The servo-hydraulic compression test system used had a 60 inch (1.52 m) square platen, an 84 inch (2.13 m) opening and a maximum force rating of 30,000 pounds (13,608 kg).

Approximately 400, 20″ × 16″ × 10″ (50.8 × 40.6 × 25.4 cm) Regular Slotted Container (RSC) style corrugated shippers were constructed using ArtiosCAD software and Kongsberg sample cutting table. The corrugated board used was 200 pound (90.72 kg) C-flute in construction. The manufacturer's edge on all boxes was sealed with polymer based glue and all flaps were taped using a two inch wide pressure sensitive tape. All shippers were conditioned for 24 hours at 23 ± 1°C (73.4 ± 2°F) and 50 ± 2 % relative humidity as per ASTM D4332-01 [4].

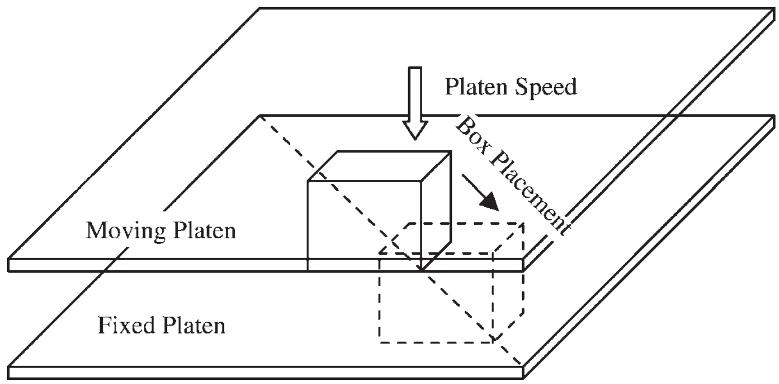

Figure 1. *Experimental Setup.*

After being formed the compression tests were conducted in a temperature controlled lab. The temperature and humidity conditions associated with the measured values were documented for each box tested.

2.1 Test Method

The corrugated shippers were centered on the diagonal between diagonally opposite corners and moved outwards from the center of the bottom platen in increments of four inches. The platen speed was varied between 0.1 in (0.25 cm) per minute and 1.0 in (2.54 cm) per minute with speed increments of 0.1 in (0.254 cm) per inch. Figure 1 shows the experimental setup.

The test method included of the following steps:

1. Using a plumb line and bob, the boxes were centered at the desired location. The center of the bottom platen was the starting point for all tests and the boxes were moved outwards on one of the diagonal lines between two diagonally opposite corners in increments of four inches (10.2 cm) till 28 inches (71.12 cm) from the center of the platen.
2. Using increments of 0.1 in (0.25 cm) per minute, the platen speed was varied between 0.1 in (0.25 cm) per minute and 1.0 in (2.54 cm) per minute.
3. Compression testing was conducted till failure and the maximum compression strength and deflection measured.
4. Replicates for all variables (box location and test speed) are shown in Table 1.

Table 1. *Average Compression and Deflection Chart.*

			Distance from Center of Platen (cm)														
			0.0	**5.1**	**10.2**	**15.2**	**20.3**	**25.4**	**30.5**	**35.6**	**40.6**	**45.7**	**50.8**	**55.9**	**61.0**	**66.0**	**71.1**
Compression Avg (N)		**2867**	**2968**	**3010**	**2830**	**2845**	**2930**	**2894**	**2900**	**2948**	**2903**	**2783**	**2946**	**2839**	**2691**	**2833**	**2651**
Deflection Avg (cm)		**1.07**	**0.99**	**0.99**	**0.95**	**1.02**	**1.00**	**1.08**	**1.08**	**1.14**	**1.09**	**1.06**	**1.19**	**1.17**	**1.15**	**1.08**	**1.18**
Sample size		**191**	**24**	**8**	**15**	**10**	**15**	**10**	**15**	**10**	**15**	**9**	**15**	**9**	**15**	**7**	**14**
Velocity of Platen (cm/minute)	0.25	2556															
		1.10															
		12	*	*	1	1	1	1	1	1	1	1	1	1	1	*	1
	0.51	2732															
		1.02															
		15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	0.76	2827															
		1.08															
		22	2	1	2	1	2	1	2	1	2	1	2	1	2	*	2
	1.02	2848															
		1.05															
		23	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
	1.27	2864															
		1.04															
		33	12	1	2	1	2	1	2	1	2	1	2	1	2	1	2

*Data point removed as outlier. See section on check of regression assumptions.
Temperature range from 17.2°C to 20.3°C with a mean of 19.9.
Humidity from 31.2 to 47.8% RH with a mean of 40.4.

(continued)

Table 1 (continued). *Average Compression and Deflection Chart.*

			Distance from Center of Platen (cm)														
			0.0	**5.1**	**10.2**	**15.2**	**20.3**	**25.4**	**30.5**	**35.6**	**40.6**	**45.7**	**50.8**	**55.9**	**61.0**	**66.0**	**71.1**
Compression Avg (N)		**2867**	**2968**	**3010**	**2830**	**2845**	**2930**	**2894**	**2900**	**2948**	**2903**	**2783**	**2946**	**2839**	**2691**	**2833**	**2651**
Deflection Avg (cm)		**1.07**	**0.99**	**0.99**	**0.95**	**1.02**	**1.00**	**1.08**	**1.08**	**1.14**	**1.09**	**1.06**	**1.19**	**1.17**	**1.15**	**1.08**	**1.18**
Sample size		**191**	**24**	**8**	**15**	**10**	**15**	**10**	**15**	**10**	**15**	**9**	**15**	**9**	**15**	**7**	**14**
Velocity of Platen (cm/minute)	1.52	2913 1.09 23	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
	1.78	2968 1.06 23	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
	2.03	3048 1.17 14	1	1	1	1	1	1	1	1	1	1	1	1	1	*	1
	2.29	2909 1.09 15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	2.54	2933 1.14 11	1	*	1	1	1	1	1	1	1	*	1	*	1	1	*

*Data point removed as outlier. See section on check of regression assumptions.
Temperature range from 17.2°C to 20.3°C with a mean of 19.9.
Humidity from 31.2 to 47.8% RH with a mean of 40.4.

3.0 DATA AND RESULTS

This study examined the effect of platen speed, location of the box, and humidity variations on the compression strength and deflection values resulting from testing the box as representative in a majority of the package testing labs. This section provides the summarized data and statistical analysis of the same.

Deflection is the difference between the box heights at the beginning of the test to that at the end. It is a measure of how much a box is compressed at the end of a test. Compression strength values of packages commonly include the deflection at failure or at the end of a specific load application. The table below shows the average results for compression strength and deflection for a given velocity and location.

The data in Table 1 shows the relationship between the location of the box, the platen speed, and the two dependent variables of interest: compression strength and the deflection. It accounts for the variability of operators and climatic conditions that occurred during the tests. It shows that as the box gets further and further away from the center of the platen, the box defection increases and compressive strength decreases. The data also shows that the velocity of the platen does not greatly affect either deflection or compression strength values. During the four month period of the study, the temperature range varied from 17.2 to 20.3°C with a mean of 19.9°C and the relative humidity ranged from 31.2 to 47.8% with a mean of 40.4%.

3.1 Statistical Analysis

Three analyses pertaining to the study were performed using multivariate statistics. The first involved verifying the repeatability of the tests. The second examined whether the mean velocity of the platen and the distance from the center of the platens significantly affected the compression strength and deflection results. The third analysis examines whether the variability or repeatability of the test is affected by velocity and distance. In all analyses, temperature and humidity were either included in the analysis with no significant effect or treated as random control variables.

3.1.1 Verification of Test Repeatability

To verify that the test results were repeatable, a gage repeatability

ANOVA was run for compression strength and deflection on a subset of the data ($n = 80$) for which two repeated measures were made for each of five platen velocities (45.7 to 106.7 cm/minute) over a range of eight distances (0 to 71cm). The measures made under repeated conditions of velocity and distance were not significantly different for either compression ($P = 0.24$) or deflection ($P = 0.06$) indicating that the test is repeatable. The average difference in repeated measures for compression was 99.1 N with a standard deviation of 315.6 and for deflection was 0.072 cm with a standard deviation of 0.26. Temperature and humidity were not explicitly controlled in this analysis, however the non-significant result indicates that repeatability is not affected by temperature and humidity over the range tested.

3.1.2 Test of Platen Velocity and Distance Main Effects

The main objective of this research was to evaluate if the platen velocity and distance from the center have a significant effect on compression and deflection test results. To analyze the effects of velocity and distance a regression model was created with compression and deflection as the dependent variables. The data consisted of 200 individual tests. Table 1 provides a summary of the data. Temperature and humidity entered the model first as control variables. The dependent variables of interest were velocity, distance, and their interaction.

3.1.2.1 Check of Regression Assumptions

Regression assumptions and influential observations were evaluated [5]. Initial regressions were run for compression and deflection, followed by tests for violation of regression assumptions regarding normality, constant variance, and unusual observations and outliers. Nine data points were removed after being identified as unusual based on having high Cook's Distance values relative to the other 191 data points based on examination of box plots. Cook's Distance measures a combination of high leverage and high residual values. Constant variance was verified by examining plots of residuals versus predicted fits. Normal plots of residuals were relatively straight. This observation, along with the large final sample size of 191 data points, makes problems associated with non-normality unlikely.

3.1.2.2 Compression Results

The results of regression analysis are provided in Table 2. Only the

Table 2. *Regression Analysis for Compression.*

Model Summary[c]

					Change Statistics				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**	**R Square Change**	**F Change**	**df1**	**df2**	**Sig. F Change**
1	0.241[a]	0.058	0.048	275.7212	0.058	5.783	2	188	0.004
2	0.424[b]	0.180	0.158	259.3147	0.122	9.181	3	185	0.000

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

ANOVA[c]

Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	879292.5	2	439646.234	5.783	0.004[a]
	Residual	14292171	188	76022.185		
	Total	15171463	190			
2	Regression	2731304	5	546260.886	8.124	0.000[b]
	Residual	12440159	185	67244.101		
	Total	15171463	190			

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

(continued)

Table 2 (continued). *Regression Analysis for Compression.*

Coefficients[c]

Model		Understandarized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	4877.637	795.465		6.132	0.000
	humidity	–21.236	6.350	–0.252	–3.344	0.001
	temperature	–57.853	33.673	–0.129	–1.718	0.087
2	(Constant)	4072.539	797.863		5.104	0.000
	humidity	–13.390	6.396	–0.159	–2.094	0.038
	temperature	–33.999	32.418	–0.076	–1.049	0.296
	velocity	83.507	59.038	0.186	1.414	0.159
	distance	–4.278	2.100	–0.344	–2.037	0.043
	vxd	0.016	0.024	0.133	0.663	0.508

[a]Dependent Variable: Compression

distance from the center of the platen had a significant effect ($p < 0.04$). Velocity of the platen is not significant and no interaction between velocity and distance is evident for the range studied in this experiment and what represents most paper corrugated box test equipment. The overall model is significant and the adjusted R-Sq value is relatively low at 15.8% i.e., the model only explains 15.8% of the variability in the compression test results. Although this may seem like a relatively low value for scientists trying to explain the total compressive strength of a box, it is high for only considering nuisance or control variables. Usually the primary variables of interest are box design, construction, and materials. The model indicates that on average compressive strength is reduced by 4.3 N for each 1 cm the test piece (corrugated box) is off center with all other variables held constant.

3.1.2.3 Deflection Results

The deflection regression analysis results provided in Table 3 are similar to the compression results. Once again only the distance from the center of the platen had a significant effect ($p < 0.004$). Neither the velocity nor the interaction between velocity and distance is significant. The overall model is significant with an adjusted R squared value indicating that the model explains only 9.1% of the variability in the deflection test results. The model indicates that on average deflection is increased by 0.005 cm for each 1 cm the test piece is off center with all other variables held constant.

3.1.3 Test of Platen Velocity and Distance Variance Effects

The question whether the compression and deflection results are more or less variable at various velocity and distance levels is also interesting to researchers. This has implications for test repeatability and reliability. To test for differences in variability Levene's Test of Equality of Error Variances was performed on each dependent variable (i.e. compression and deflection) at all 10 velocity and 15 off-centered distance levels. None of the tests indicated a significant difference in the level of variation. The non-significant result indicates that variation is not affected by temperature and humidity over the range tested.

3.1.4 A Note on Temperature and Humidity

Temperature and humidity were not explicitly examined in this study.

Table 3. *Regression Analysis for Deflection.*

Model Summary[c]

					Change Statistics				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**	**R Square Change**	**F Change**	**df1**	**df2**	**Sig. F Change**
1	0.105[a]	0.011	0.000	0.2209350	0.011	1.043	2	188	0.354
2	0.340[b]	0.115	0.091	0.2106428	0.104	7.274	3	185	0.000

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

ANOVA[c]

Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	0.102	2	0.051	1.043	0.354[a]
	Residual	9.177	188	0.049		
	Total	9.279	190			
2	Regression	1.070	5	0.214	4.823	0.000[b]
	Residual	8.209	185	0.044		
	Total	9.279	190			

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

(continued)

Table 3 (continued). *Regression Analysis for Compression.*

Coefficients[c]

Model		Understandarized Coefficients		Standardized Coefficients		
		B	**Std. Error**	**Beta**	***t***	**Sig.**
1	(Constant)	1.972	0.637		3.094	0.002
	humidity	–0.006	0.005	–0.086	–1.109	0.269
	temperature	–0.034	0.027	–0.096	–1.248	0.214
2	(Constant)	1.549	0.648		2.391	0.018
	humidity	–0.003	0.005	–0.050	–0.638	0.524
	temperature	–0.027	0.026	–0.078	–1.043	0.298
	velocity	0.078	0.048	0.222	1.622	0.107
	distance	0.005	0.002	0.504	2.877	0.004
	vxd	–2.4E-005	0.000	–0.258	–1.239	0.217

[a]Dependent Variable: Compression

However, it is notable that humidity was a significant factor in affecting the compression results and, therefore, was a necessary control factor in the analysis. Humidity in the testing ranged only from 31.2–47.8%. Measured compressive strength decreases by 13.4 N for a one percent increase in humidity. This is the same as a 3.1 cm increase in distance from the center of the platen. Interestingly, humidity was not a significant factor in defection measurements and temperature was not significant in any of the tests.

4.0 CONCLUSIONS

Based on the results of this study it is clear:

1. Compression strength results may vary by as much as 15.8% due to of-center loading and varying platen speed.
2. Variations in humidity (approximately 15%) in labs with "temperature control" only, have a small affect on compression strength results. This is only true for relative humidity of all conditions below 50%.
3. Even though ASTM D642 requires a platen speed of 0.5 ± 0.1 in. (12.7 ± 0.25 cm) per minute, platen speeds between 0.1 (0.25 cm) to 1 in. (2.54 cm) per minute do not produce significant variation in compression strength results.

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Measurement and Analysis of Vibration Levels on Warehouse and Retail Store Material Handling Equipment

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ABSTRACT: Material Handling Equipment (MHE) is widely used to move packaged goods from manufacturing to warehousing, storage, transportation, in both warehouses and distribution centers to retail stores. Moving product between facilities is done by different types of equipment ranging from manually pushed carts to automated vehicles. A considerable amount of research has been conducted to evaluate the ergonomics of manual or mechanized MHE in the past. There is, however, no published work documenting vibration conditions that occur when transporting packages using MHE. This study measured the vibration levels for typical MHE used at warehousing facilities. Power spectral density plots were generated for both loaded and empty configurations of the seven types of MHE. Vibration levels for both the inside and outside floor and pavement surface conditions at warehouses were also studied.

1.0 INTRODUCTION

In recent decades, there has been a steady increase in the development of free trade agreements in all regions of the world. Products once produced for domestic markets must now be able to compete in international markets without trade barriers. The complexity of managing global supply chains demands equipment and systems that is responsive, flexible, and aligned. According to the Material Handling Industry of America, *material handling and logistics is the movement, protection, storage and control of materials and products throughout the process of their manufacture and distribution, consumption and disposal* [1]. One

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of the largest and fastest growing industries, the consumption of material handling and logistics equipment in the US, exceeds $125 billion annually [1].

The MHE industry, with leaders such as NACCO Industries in the US, Linde AG in Europe and Toyota in Asia, is considered to be highly fragmented, with the 50 largest companies accounting for 35 percent of the market [2]. In the US alone approximately 4000 distribution outlets for MHE generate combined annual sales of $15 billion, about half due to fork lift truck sales [2]. The US market for MHE and systems is estimated to reach $20.4 billion in 2008 [3]. This demand is expected from technological innovations such as material handling robots, automated guided vehicles and high end services.

Material handling equipment (MHE) is primarily used for the movement and storage of goods within a facility or at a single site. MHE can be broadly categorized into the following [4]:

1. *Transport equipment:* includes equipment, such as carts, pallet jacks and trucks, conveyors, cranes and industrial trucks, used to move material between locations. The locations could be between workplaces, between a loading dock and a storage area, etc.
2. *Positioning equipment:* includes equipment, such as hoists, industrial robots and dock levelers, used to handle material so that it is at the desired location and position for subsequent handling, machining, transport, or storage.
3. *Unit load formation equipment:* includes equipment, such as pallets, totes, intermodal containers and stretch wrappers, used to control materials so that they maintain their integrity when handled as a unitized load during distribution.
4. *Storage equipment:* includes equipment, such as racks, carousels and mezzanines, used for holding materials over a period of time for an optimum throughput.
5. *Identification and control equipment:* includes equipment, such as bar codes, RFID and machine vision, used to collect and communicate information needed to coordinate proper flow of materials within or between facilities as well as between suppliers and customers.

Material Handling Equipment (MHE) is widely used to move packaged goods through the supply chain, from manufacturing to warehousing, to storage, and for transportation, in both warehouses and distribution centers. Product moving within a facility is carried by different equipment ranging from manually driven carts to automated vehicles. A considerable amount of research has been conducted to evaluate the ergonomics of manual or mechanized MHE in the past.

A superstore stocker spends nearly 74% of his shift duration in manual material handling [5]. During a shift a stocker's activities involve nearly 200 handling operations which include handling of fragile and unstable merchandise [5]. Material handling in a grocery store or warehouse is commonly carried out using various types of carts, pallet jacks and forklift trucks. Such MHE encounters various surfaces during transportation both inside and outside a facility. The force required to push carts over surfaces depends on its coefficient of friction (COF) [6]. It has been established that the maximum acceptable weight to push a cart on a low COF surface is 31% lower than high COF surface. Also, the initial and sustained force required to push the cart has been found to be significantly lower for low COF surfaces than high COF surfaces [6]. However, the vibration levels associated with hand pushed cart either on a low or high COF floors has not yet been studied.

The importance of measuring and quantifying the vibration levels occurring during transportation (inside tractor trailers) as it relates to damage has been established in previous study [7]. It is also known that the vibration forces experienced by a truck traveling on various road surfaces generate different vibration levels leading to product damage [8]. Similarly a manually operated cart can generate different vibration levels as a result of different wheel design (casters), floor surface and load on cart. Resnick and Chaffin [9] studied the optimum handle height and maximum load on carts to reduce biomechanical stress among operators. They recommended that the maximum load on a four wheel cart should be 225 kg from a biomechanical stand point. Regardless of this recommendation it has been observed that load weight on a four wheel cart can be as high as 1500 kg [10]. Therefore, it may be hypothesized that the vibration levels may vary on a four wheel cart depending on the weight transported. Previous studies conducted have had a major focus on measuring and analyzing transportation vibration levels. There is, however, no published work documenting vibration conditions for MHE.

The focus of this study was to compare the difference in vibration levels for commonly used MHE in warehousing operations and develop methods to simulate these conditions in a laboratory environment using tests methods such as American Society of Testing and Materials (ASTM) D4728 [11]. The results of the vibration data analysis are presented as Power Density Spectra. A Power Density Spectrum is a plot of energy (Power Density) versus frequency [12] and this is commonly used to measure and compare vibration levels].

The levels of acceleration occur in a random manner over a range of frequencies when vibration data is collected in truck shipments. The average power density within a band of frequencies is calculated as follows:

$$PD = \frac{1}{BW}\sum_{i=1}^{n}(RMS\ G_i^2)\ /\ N$$

where, $RMS\ G_i$ is a sampled root mean square acceleration value measured in g's within a bandwidth (BW) of frequencies, and N is the number of instants sampled. The corresponding PD levels are then plotted against the center frequency of the bandwidth to develop the power density spectrum for the data set analyzed. For this study a bandwidth of 1 Hz was used.

A PSD plot is an important tool used in simulating real life transportation environments using vibration equipment in a laboratory. Figure 1 below shows an example of an actual PSD plot for loaded trailer with leaf spring suspension going over interstate expressway used to simulate a truck ride on a vibration table. Some of the typical sources of vibration are also defined [13].

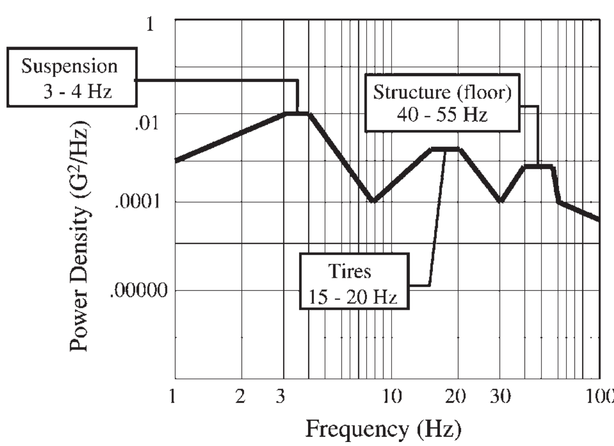


Figure 1. *A Typical PSD Plot for Truck Transportation.*

Due to a lack of data from past studies, this research focused on measuring and analyzing the vibration levels for MHE for various floor surfaces. Specifically it had the following objectives:

1. Measure vibration levels in all three axes of the MHE (latitudinal, longitudinal and vertical).
2. Determine the range of vibration levels between empty and fully loaded (by weight capacity of MHE) MHE on a range of surface conditions.
3. Measurements of vertical vibrations on empty MHE both on the inside and outside surface conditions representative of warehouse and retail store conditions.
4. Recommend a vibration test to simulate these conditions.

2.0 MATERIALS AND INSTRUMENTATION

A field data recorder SAVER™ 3X90 by Lansmont Inc. (Monterey, CA) was used to capture vibration levels for all MHE studied. This self-powered instrument provides 16 bit resolution, internal tri-axial accelerometer, temperature and humidity sensors, USB connectivity, and is operable in the field for up to 90 days [13]. The SAVER™ 3X90 provides information about motion, vibration, temperature and humidity. An internal clock marks the exact time when each event occurs. The SAVER™ 3X90 units were mounted on carts and fork lifts using magnetic mounts or clamps. Figure 2 shows a SAVER recorder mounted on a cart for vibration measurement.

Figure 2. *Mounting of Recorder on Push Carts.*

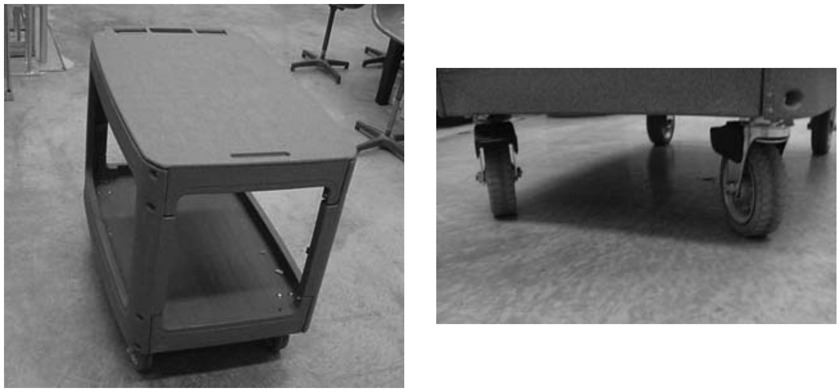


Figure 3. *Grey Plastic Cart.*

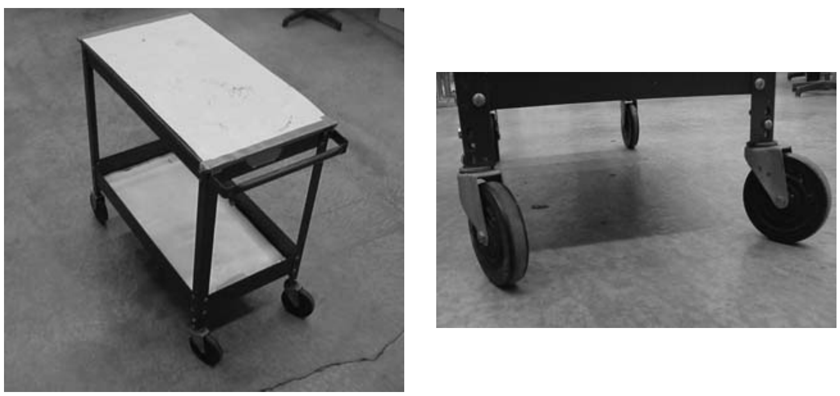


Figure 4. *Grey Metal Cart.*

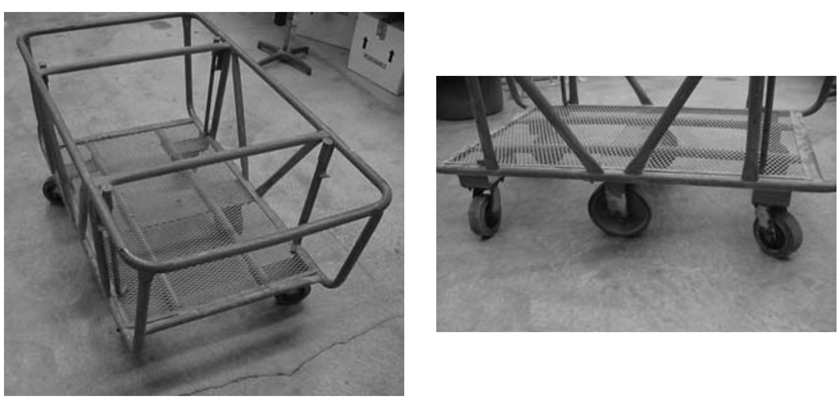


Figure 5. *Red Metal Cart.*

Figure 6. *Green Metal Cart.*

Figure 7. *Pallet Jack.*

Figure 8. *Fork Lift Truck.*

Figure 9. *Stacker.*

Table 1. *Material Handling Equipment Tested.*

	Length (in)	Width(in)	Height (in)	Capacity (lb)
Plastic Grey	40-1/2	25-1/2	33-3/4	400
Metal	36	24	32	400
Pallet Jack	53	26-1/2	47 (Ground to Handle)	5500
Green Wooden	72	36	30 (Ground to Handle)	1200
Red Metal	60	30	30	2000

This study measured the vibration levels experienced by four commonly used manual push carts and a manually operated pallet jack (Figures 3, 4, 5, 6 and 7), and two types of powered fork lift trucks (Figures 8 and 9). Table 1 shows the size and weight capacity of the different equipment used in this study and Figures 3–9 show pictures of the MHE and their wheel and casters.

Vibration levels for all MHE were observed for both loaded and empty configurations. The gray plastic and metal carts (Figure 3 and 4) were loaded with the maximum manufacturer recommended capacity of 91 kilograms and the red and green metal carts (Figures 5 and 6) were loaded with the maximum capacity of 182 kilograms. The various carts and MHE were tested both empty and fully loaded at the rated cart or MHE capacity. This produced a range of vibration levels, and as expected, a fully loaded cart or MHE showed lower vibration levels than an empty or partially loaded one. The vibration analysis on these MHE and carts was only done on the vertical orientation, since these levels were the highest.

In order to capture the vibration levels experienced by the MHE on different operating surfaces, the study was conducted both inside and outside a warehouse facility. The internal floor surfaces used for this study comprised of PVC tiled flooring, concrete flooring and ceramic tiled flooring. The external surfaces were asphalt and concrete. The vibration levels were recorded for a distance of approximately 550 meters inside and approximately 1100 meters outside the facility. Vibration levels were also recorded for the fork lift truck and stacker at medium speeds and high (Figure 8 and 9) of 2 and 4 MPH. Table 2 shows the various settings used to capture the vibration levels for the MHE studied.

4.0 RESULTS

The recorded vibration levels were analyzed to determine power den-

Table 2. *Experimental Design for Vibration Measurements for MHE.*

Empty	
Inside Warehouse	**Outside Warehouse**
Grey plastic cart	Grey plastic cart
Grey metal cart	Grey metal cart
Red metal cart	Red metal cart
Green metal cart	Green metal cart
Pallet jack	Pallet jack
Inside Warehouse	
Stacker and Fork Lift Truck	
Outside Warehouse	
Fork lift: medium speed—2MPH	
Fork lift: high speed—4 MPH	

sity (PD) levels for frequencies ranging between 2–250 Hz. This analysis was performed on data collected from all 3 channels (latitudinal, longitudinal, and vertical). The data obtained from the vertical channel was further analyzed to determine the top 20% power density (PD), lower 80% PD and average PD levels as a function of frequency. For the analyzed data power spectral density (PSD) graphs were plotted for each type of cart and fork lift for respective surfaces. For comparison between the loaded and the empty carts the vibration levels were calculated from the data collected from the vertical channel and were analyzed for the observed the PD for the upper 20% and lower 80% besides the average PD.

The vibration data was analyzed and the PSD plots are presented below in Figures 10–22.

Table 3. *Vibration Analysis.*

Vibration Analysis in the Vertical Channel	
Inside Warehouse	**Outside Warehouse**
Green metal cart: loaded	Green metal cart: loaded
Green metal cart: empty	Green metal cart: empty
Grey plastic cart: loaded	Grey plastic cart: loaded
Grey plastic cart: empty	Grey plastic cart: empty
Grey metal cart: loaded	Grey metal cart: loaded
Grey metal cart: empty	Grey metal cart: empty

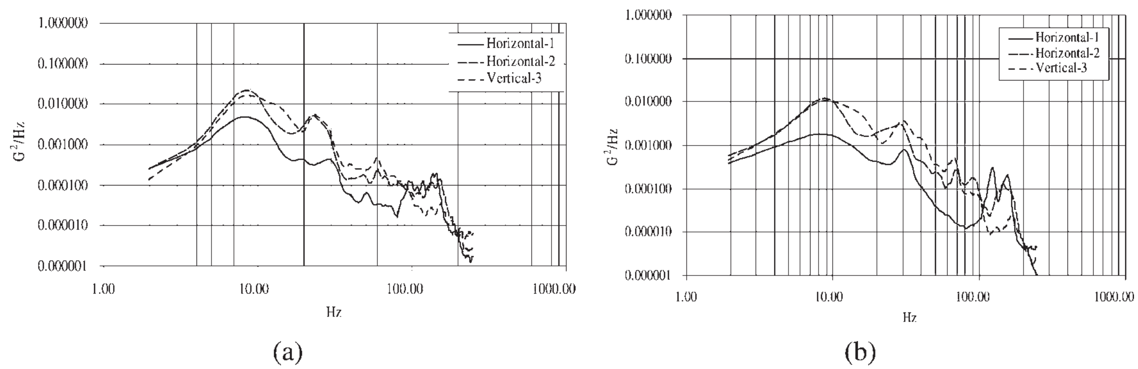


Figure 10. *PSD for Empty Grey Plastic Cart (a) inside and (b) outside the Warehouse.*

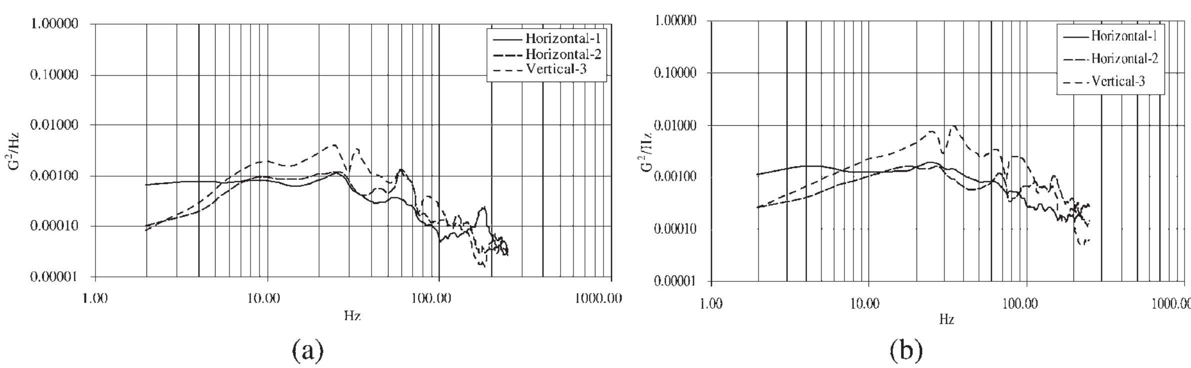


Figure 11. *PSD for Empty Grey Metal Cart (a) inside and (b) outside the Warehouse.*

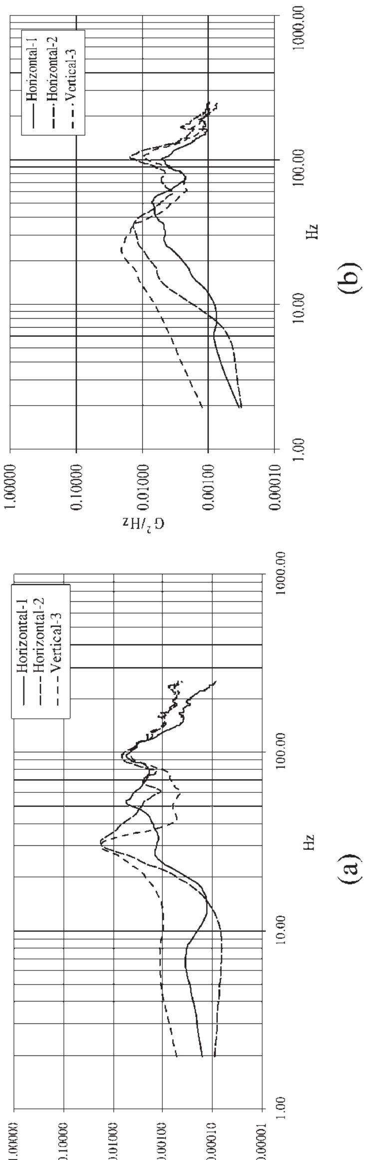


Figure 12. *PSD for Empty Red Metal Cart (a) inside and (b) outside the Warehouse.*

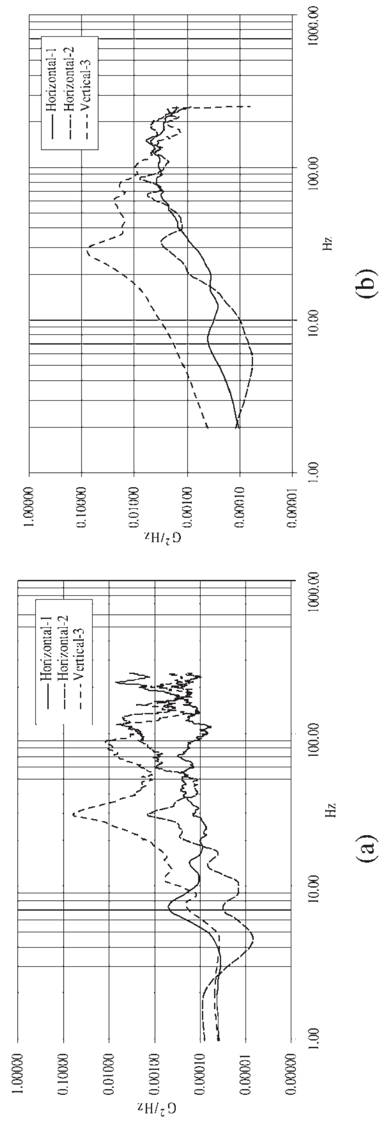


Figure 13. *PSD for Empty Green Metal Cart (a) inside and (b) outside the Warehouse.*

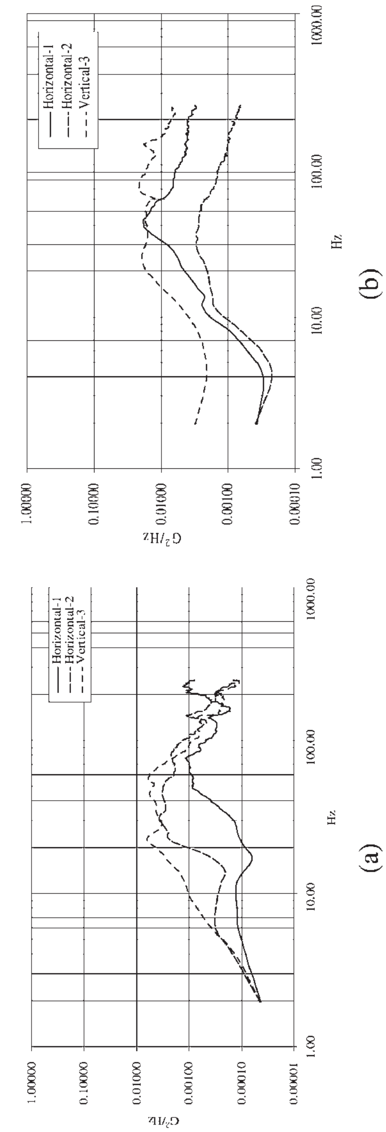


Figure 14. *PSD for Empty Pallet Jack (a) inside and (b) outside the Warehouse.*

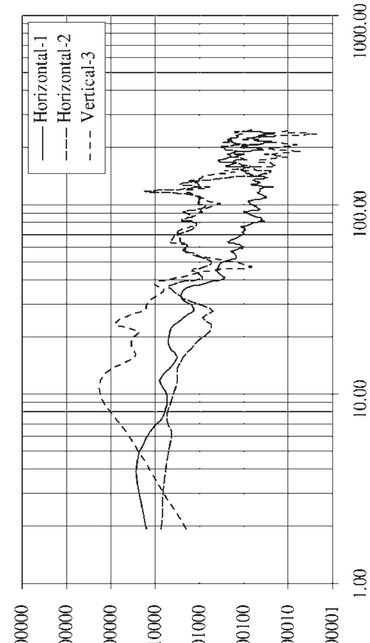
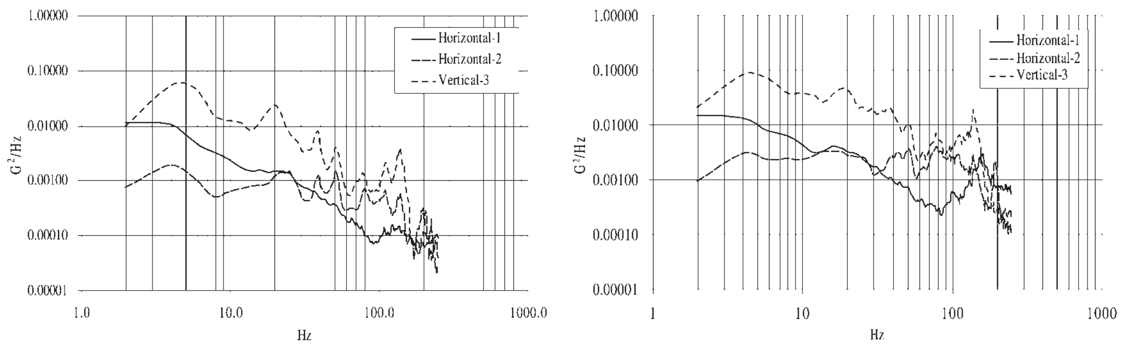
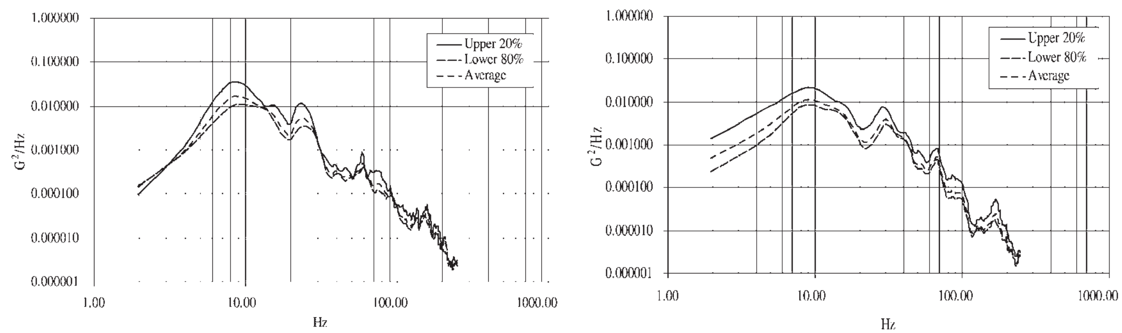


Figure 15. *PSD for Empty Stacker inside the Warehouse.*



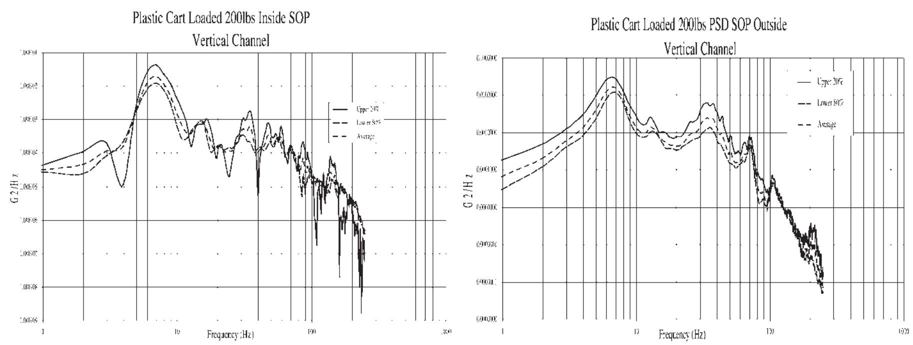
(a) (b)

Figure 16. *PSD for Empty Stacker outside the Warehouse at (a) Medium and (b) High Speeds.*



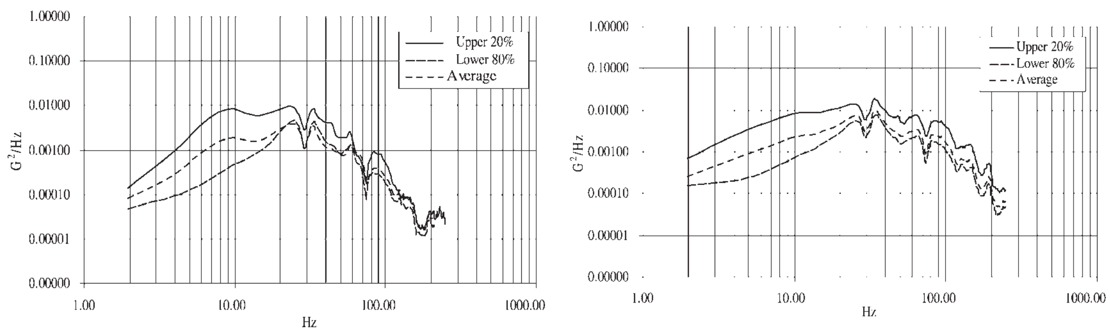
(a) (b)

Figure 17. *PSD for Vibration Analysis in Vertical Channel for Empty Grey Plastic Carts (a) Inside and (b) Outside the Warehouse.*



(a) (b)

Figure 18. *PSD for Vibration Analysis in Vertical Channel for Loaded Grey Plastic Carts (a) Inside and (b) Outside the Warehouse.*



(a) (b)

Figure 19. *PSD for Vibration Analysis in Vertical Channel for Empty Grey Metal Carts (a) Inside and (b) Outside the Warehouse.*

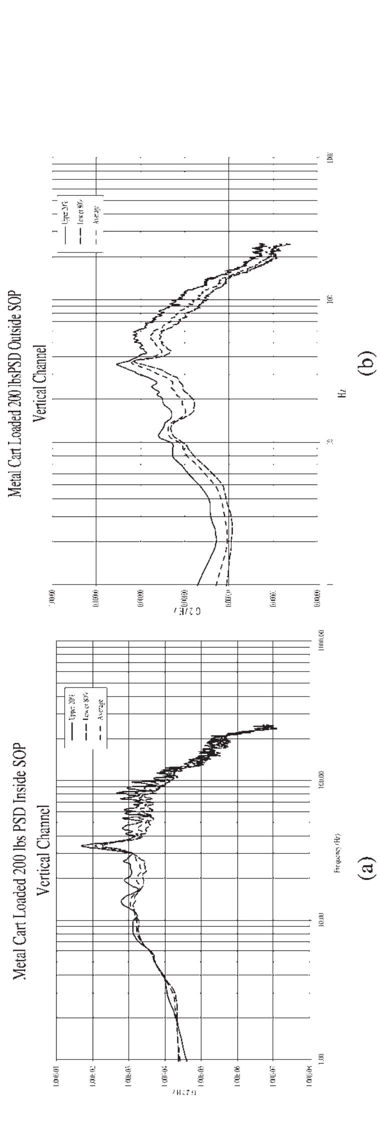


Figure 20. *PSD for Vibration Analysis in Vertical Channel for Loaded Grey Metal Carts (a) Inside and (b) Outside the Warehouse.*

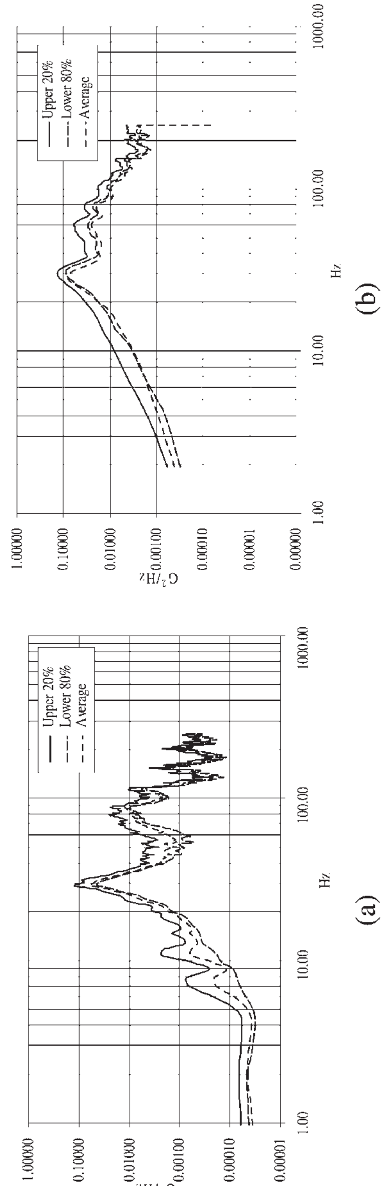
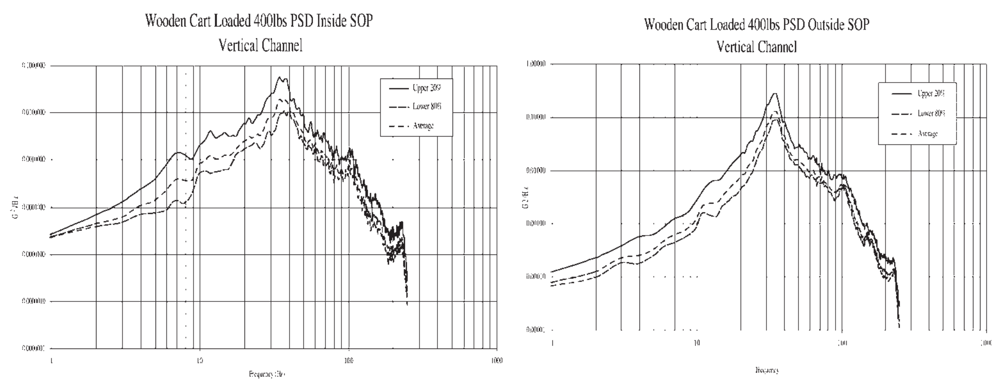


Figure 21. *PSD for Vibration Analysis in Vertical Channel for Empty Green Metal Carts (a) Inside and (b) Outside the Warehouse.*



(a) (b)

Figure 22. *PSD for Vibration Analysis in Vertical Channel for Loaded Green Metal Carts (a) Inside and (b) Outside the Warehouse.*

Table 4. *Composite Spectrum for Warehouse and Retail Store Material Handling Equipment.*

Frequency (Hz)	Power Density (G^2/Hz)
2	0.001
5	0.01
15	0.1
25	0.1
30	0.01
100	0.001

4.0 DISCUSSION

Based on reviewing the data from the various Power Density Spectra, it is clear that vibrations levels in the 4–20 Hz range found in these type of product and package conveying equipment are much higher than those found in transport systems such as truck and rail. Also the recent shift by various vibration test method development bodies such as the International Safe Transit Association to lower the vibration intensity levels when simulating for truck transport in this frequency range may not adequately test packages. Previously developed truck composite spectra such as those proposed by ASTM D4169 account for these vibration levels, however it may be important to differentiate transport vibration from material handling vibration as products and packages are exposed much longer in transportation than material handling.

The following composite spectrum has been developed to simulate various forms of manually driven carts and powered material handling carts used in manufacturing and retail.

5.0 CONCLUSIONS

1. The lateral and longitudinal orientations generally show lower vibration levels as compared to vertical. Therefore the vertical vibration levels were measured for empty and loaded MHE.
2. Vibration levels were higher in the outside track as compared to the inside track because of the surface irregularities.
3. Empty carts produced higher vibration levels than the loaded carts.
4. Plastic carts showed lower vibration levels than metal carts.
5. The vibration level and frequencies measured from MHE occur at a higher frequency (8–30Hz) as compared to most transportation vehi-

cle vibrations (2–8Hz). This needs to be included in the ASTM Random Vibration Standards that currently do not test at these levels.
6. A composite spectrum was developed to simulate MHE.

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Epoxy (MY720)	235	30
C379: H795 = 1.4	285	53

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