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Packaging Material Implications in RFID Operations

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Radio frequency identification (RFID), although not a new technology, is relatively new to many supply chains and retail store applications. Packaging plays a significant role in the success of RPID retail operations because RFID tags are placed directly on the packages Presently metal is the only packaging material widely known to interfere with RFID operation, though questions exist about the impact of other materials. The objective of this study was to evaluate the effect of commonly used packaging materials and forms on 915 MHz RFID operations in terms of read range and or readability. The evaluated materials were aluminum cans, plastic films, glass and corrugated board. Aluminum cans containing an alcoholic beverage interfered with readability of RHD tags both when tags are visible and invisible to the reader antennae. The impact was much greater when the tags were hidden. A sheet of glass, regardless of its color, reduced the read range of RFID. Corrugated board shows promise for RFID operations for two reasons: it did not interfere with the RFID system and it can also be used as a spacer to increase the readability of packages containing products that interference with RFID readability. However, corrugated board can absorb moisture when subjected to high humidity environments and this moisture adversely-affected RFID readability. The curvature on packages also had impact on RFID operation range Polyethylene stretch film does not have effect on RFID operation.

Introduction

Radio frequency identification (RFID) is one of the newest automatic identification and data capture (AIDC) technologies for supply chain management. It has received a great deal of interest and has begun to be adapted by several suppliers, due especially to the mandates from Wal-Mart and the US Department of Defense (DoD). Wal-Mart required RFID tagging on cases and pallets in January 2005 for its top 100 suppliers [1] and for its next 200 suppliers by January 2006[2]. The Department of Defense now requires RFID tagging on all individual cases and pallets for some products shipped into the Defense Logistics Agency distribution centers in San Joaquin, CA and Susquehanna, PA. It will require RFID tagging on all products shipped to DoD locations by January 2007. [3] Both of these mandates require the use of passive transponders in the ultra high frequency (UHF) range (915 MHz). [2], [3]

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An RFID system consists of RFID transponders (or tags), and a reader with system antennae connected to a computer. RFID transponder consists of a chip, where product information are stored, and antenna, which enable the chip to transmit the information. The system antenna acts as a conduit between transponders and readers. For passive transponders, which contain no battery, the reader will send radio frequency signal and power to the transponder. The transponder will send the signal that contains information in its chip back to the reader. The reader will convert this signal to a useful form and send it to the computer.

RFID systems claim to have several advantages over existing barcode systems including: 1) RFID allows the possibility of locating the object in addition to object identification, 2) the speed of reading is faster, therefore, almost simultaneous reading of several transponders can be achieved, 3) the transponders are more robust than barcodes, 4) the read range is often longer than barcodes, and 5) no line of sight may be required. [4] The latter advantage allows the possibility of placement of transponders inside packages so they do not interfere with packages' appearance or cover vital information on the packages. In case of item or case level tagging, non-line of sight, if allowed, can enhance the flexibility in packing or pallet pattern.

Although the non-line of sight requirement is a very attractive feature of RFID, there has been a lot of controversy on this issue. The non-line of sight requirement can be interpreted as meaning that all materials are radiolucent, meaning they are transparent to radio frequency energy. This is not at all true for at least two common materials, metal and liquid, and may be compromised with other materials. However, this does not mean that RFID cannot be used in these situations, only that care must be taken in the particular application.

One other important issue about RFID is the readability of different transponder orientation. Joe Jiner, Logistics and RFID Development Director at The Kennedy Group, demonstrated that transponder location is critical by using a case of liquid product. He found that only 1 or 2 out of 6 possible transponders locations were successfully read. [5]. Greg Matula, Hewlett Packard's Technical Lead for its RFID program and Worldwide RFID Procurement Manager, mentioned that the tag orientation relative to the face of antenna influenced readability. [6]

From a Japan Electronic Industry Development Association (JEIDA) study, it was found that for 125 kHz RFID systems, readability reduced significantly as the angle between the face of antenna and the face of transponder increased from 0 (parallel) to 90 (perpendicular). Despite the many references that identified interferences that create an obstruction to RFID readability, there is no published research on how much these interfere with RFID operations other than the JEIDA study that was done using a 125 kHz RFID system.

Therefore, the objective of this research was to evaluate the effect of commonly used packaging materials and package forms with 915 MHz RFID operations in terms of read range and/or readability. The evaluated materials were aluminum, plastics film, glass and corrugated board.

Materials and Methods

RFID system

Two RFID systems, Matrics and Alien, were used in this study. The Matrics system now owned by Symbol Technologies, Inc. of Oakland, CA, consisted of 4 antennae and a reader set up on a frame to simulate the dock door portal. The width of the portal was 10 feet. On each side of the portal there were two antennae. The reader was connected to Matrics Tag Tracking 3.0.1 software in a personal computer. The Alien system (Alien Technology, Morgan Hill, CA) consisted of,a single antenna, linear or circular polarized, and a reader. The reader was also connected to Alien software in a personal computer.

Evaluation of the RFID tag readability

The readability was evaluated by bringing tags on test objects toward the dock door portal at a constant speed. The result of "read" or "no read" was recorded. The readability is evaluated by the probability of tag being read. The data is then analyzed via logistic regression using Minitab^{R}. A Hosmer-Lemeshow test is performed to verify the agreement between the predicted probabilities and the regression to the experimental values (Ho: the predicted and observed value agree).

Evaluation of the RFID tag operation range

The operation range was evaluated by moving a tag on a test object away from an antenna. The height of the tag is approximately the same as the center height of the antenna. The distance when the tag can no longer be read was recorded as an operation range of the RFID antenna.

The effect of moisture content in corrugated board on the tag readability

The interference of various moisture contents with C-flute corrugated board was studied using the Matrics system. Sixty-four empty corrugated board boxes with Matrics dipole tags were exposed to varying storage conditions to alter the moisture content of the corrugated board. The storage conditions included: 22.2°C and 55% RH, 29.4-C and 70% RH, and 37.8°C with 85% RH for approximately 96 hours, the time previously determined for the corrugated board to reach the equilibrium moisture content. The boxes were arranged into 4 × 4 × 4 column stack pallet pattern and the readability was evaluated immediately after removal from the conditioning chamber. The evaluation of readability was done in 25 replicates for each level of moisture content. For each level and concurrent with the evaluation, the moisture content of the corrugated board was determined according to ASTM D644-99 (Standard test method for moisture content of paper and paperboard by oven drying). [7]

The effect of aluminum on the tag readability

The effect of aluminum was studied through evaluation of tag readability in the presence of 12 fluid ounce aluminum cans containing beer. Twelve cans were placed in each carton (11" ×8"×4.5") and 64 cartons were placed in a 4×4×4 stack column pallet pattern. The tags were placed on a side panel or on the top panel of the carton with or with out a C-flute corrugated board spacer (cut to the same size as the surface area of the tag). The placement of spacers was either on the back of the tag, or on both the front and back of the tag (single versus double spacers). The tag readability evaluation was performed using the Matrics system with 25 replicates. The result was then compared with the readability of the tags on the empty cartons.

The effect of pallet stretch film on the tag readability

The readability of Matrics tags under polyethylene (PE) stretch wrap was also evaluated using the Matrics system. Each box contained twelve 32 fluid ounce PET bottles (9 _" tall, 3 _" diameter) filled with water. The water was used to stabilize the load while it was being stretch wrapped. Forty-eight C-flute corrugated board boxes (13"×12"×10") were arranged in a 3×4 ×4 column stack pallet pattern. The Matrics tags were placed so that those on the boxes around the perimeter of the pallet were facing outward. The pallet load was stretch wrapped with PE film using an automatic pallet stretch wrap machine (Highlight Inc., Wyoming MI) with varying degree of stretch and total amount of stretch wrap. The first setting was for the machine to travel up and down twice. This setting was performed twice with percent stretches of 45 and 150. The other setting was for the machine to travel up and down six times. The percent stretch at this setting was 160. The readability of the pallet load with stretch film was compared to the readability of the same pallet load without stretch film.

The effect of glass on the RFID tag operation range

The effect of a flat glass sheet on the operation range of Alien squiggle tag (Alien Technology, Morgan Hill, CA) was studied on clear, amber and green glass. The tag was placed in front of, on the back of, or in between glass sheets, identified in the results as "front",

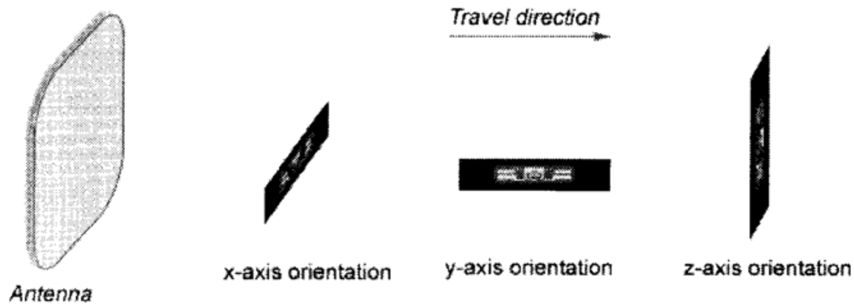

Figure 1. Tag orientation and travel direction of Alien squiggle tag on the glass sheet

"back", and "sandwich". The operation range was evaluated for the antenna for three tags orientation (x, y and z-axis) as shown in Figure 1. The blank was performed in the same manner with the tags placed in the same orientation and location but in the absence of a glass sheet. The percent reduction of operation range is calculated by equation (1).

$$\frac{\text{Operation range of blank - Operation range of sample}}{\text{Operation range of blank}} \times 100 \qquad (1)$$

The effect of container curvature on RFID tag operation

The effect of container curvature on the read range of Alien squiggle tags was studied using different sizes of graduated glass cylinders, ranging between 25 and 1000 mL. The tags were placed in two orientations, the x and y-axis as shown in Figure 1. The studied was conducted using the Alien system with either a circular antenna, linear antenna, or linear antenna turned 90° from its usual orientation. These setting are designated as "circular", "horizontal linear" and "vertical linear", respectively. The operation range was evaluated as previous described.

Results and Discussions

The effect of moisture content in corrugated board on the tag readability

Corrugated fiberboard is widely used to construct shipping containers for the purpose of containment and protection. Corrugated board has a chance to come into contact with an RFID tag during case level and pallet level tracking. The corrugated board itself has little or no effect on RFID operation since preliminary tests showed tags could be read through a 30-inch thick stack of corrugated board under standard temperature and humidity conditions. However, due to its hygroscopic nature, the absorption of moisture is a concern not only because of the reduced strength caused by moisture but also because of the interference to

RFID operations.

The moisture content (dry basis) of corrugated board subjected to various environmental conditions (temperature and relative humidity) is shown in Table 1. Figure 2 shows the probability of a tag being read when affected by moisture content in the corrugated board. The effect of moisture content on the probability of tag reads was also analyzed by logistic regression. The model is shown in Equation (2)

$$\ln\left(\frac{p(x)}{2-p(x)}\right) = 5.4746 - (0.0122 \cdot \text{Moisture content}) \qquad (2)$$

where p (x) is the probability of tag being read.
However, the value predicted from this equation did not agree with the experimental data (P-valuc of Hosmer-Lemeshow test < 0.05). Therefore, this model was discarded and the exponential decay type equation was used to draw a trend line in Figure 2.

Table 1. Moisture content of corrugated board subjected to various environmental conditions for 96 hours

Storage condtion		Moisture content (dry basis), %
Temperature, ℃	Relatve humidity, %	
22.2	55.0	8.2±0.1
29.4	70.0	9.6+0.1
37.8	85.0	15.3±0.1

Figure 2 indicates the dependency of tag read probabilities on the moisture content of corrugated boxes. As moisture content of corrugated board increases from 8.2 to 9.6% (dry basis), the moisture content had large effect on reduction of tag readability. The tag readability slightly decreased beyond 9.6% moisture content, but at a much lower rate. Most of the unread tags were located in the two bottom tiers of the pallet. Although the change in read probability did not seem very large in magnitude due to the large number of test samples, the standard error of the each value was relatively small (approximately 0.003).

After exposing the corrugated boxes to the high relative humidity environment, they were returned to the standard condition (22.2°C, 55% RH) and kept there for more than 96 hours. The readability of the tags on those boxes was then retested. It was found that the probability of reads dropped from 0.995 (8 tags not read) to 0.981 (29 tags not read). The boxes were, again, returned to a high humidity condition (37.8°C, 85% RH) for 96 hours and the readability was again evaluated. The result of this test shows no difference in the read probability from the previous test for high humidity condition.

The difference in the readability when corrugated boxes were kept at the standard condition was attributed to the hysteresis phenomena. At any given relative humidity, the

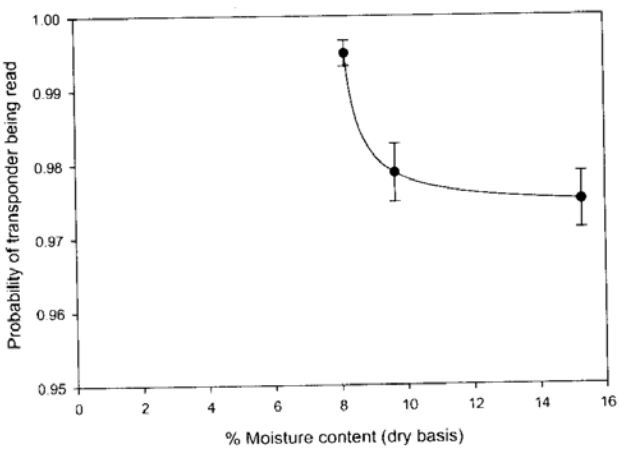

Figure 2. The probability of Matrics tag reads when placed on corrugated boxes with various moisture contents, arranged in 4×4× 4 column stack pallet pattern.

moisture content of the material is greater during desorption than during absorption. In corrugated board, the difference between moisture content owing to the hysteresis phenomena can be as much as 25% depending on the temperature and relative humidity. At 20°C and approximately 55% RH, the difference was around 12.5% (based on absorption moisture content). [8] The moisture content of corrugated board boxes when returned to standard conditions after exposure to high humidity environment could be approximately 9.2% (dry basis), which is slightly lower than the moisture content of corrugated board exposed to the condition of 29.4°C, 70% RH. In agreement with the estimated moisture content, the read probability obtained from this testing was slightly higher than the probability obtained from boxes exposed to 29.4°C, 70% RH.

The absorption of moisture content on corrugated fiberboard can have impact on RFID operation. This is of concern for RFID operations in high humidity environments. In addition, RFID operation in medium to low relative humidity maybe of concern if the corrugated board has been exposed to high humidity. This situation may occur due to the prolonged exposure to high humidity environment, the leakage of liquid products, condensation due to temperature fluctuations, and/or the respiration/transpiration of fresh produce.

The effect of aluminum on the tag readability

Metal, a common packaging material for the food and beverage industry has a very large impact on the transmission of radio frequency. Metal does not allow radio frequency to pass through it. It also changes the inductance of antennae (on both reader and tag) and retunes its resonance frequency. In addition, there are published statements that metal also absorbs radio frequency. In UHF, this may increase the read range of RFID system if enough air gap between the metal and tag are provided. [9] To date, there is only one published data on the effect of metal as an interference in operation range of low frequency RFID system (125 kHz). It was reported that a metallic substance in front of the tag reduced the RFID system operating range by 30-50%. The effect of metal behind the tag depends on the distance between the tag and the metal. The distance between 3-6 cm (or more) will minimize the effect of metallic substance behind the tag.

Table 2 shows the read probability of tags on 64 cases of beer cans in a pallet load. When cases contained no aluminum beer can, the tag read almost all the time as indicated by the high read probability. The presence of beer can support the statement that metal has an effect on RFID operation, particularly in the case of hidden tags where the read probability reduced from almost 1 to almost 0. The visible tags on the side panel were affected by the presence of metal can at a much lesser extent. The effect of metal on the visible tag placed on the top panel was much greater than those on the side panel. This may be a result of tag orientation or proximity to the metal cans, but more research is required to tell which has the greater impact.

Table 2. The probability of tag reads when placed on beer cases, with and without corrugated board spacer, when visible or hidden within the pallet.

Tag visibility	Product	Spacer	Read probability	
			Side panel	Top panel
Visible	None	No spacer	1.000	1.000
	Alumnum beer can	No spacer	0.927	0.250
	Alumnum beer can	On the back	1.000	0.768
	Alumnum beer can	On the back and front	0.972	0.720
Invisible	None	No spacer	0.997	0.998
	Alumnum beer can	No spacer	0.087	0.031
	Alumnum beer can	On the back	0.013	0.024
	Alumnum beer can	On the back and front	0.063	0.103

The addition of one or more corrugated board spacers between the tags was an attempt to improve the readability by increasing the air gap between the metal and tag. In the UHF frequency range, the air gap may increase the operation range. [9] The data of read probability was analyzed by logistic regression to determine the effect of corrugated board spacer(s). The regression equation is shown in equation (3) and (4) for the tags on the side and top panel, respectively

$$\ln\left(\frac{p(x)}{1-p(x)}\right) = \beta_0+\beta_1 H+\beta_2 Vis+\beta_3 x_1+\beta_4 x_2+\beta_5 x_1\cdot H+\beta_6 x_2\cdot H$$
$$+\beta_7 x_1\cdot Vis+\beta_8 x_2 Vis+\beta_9 H\cdot Vis+\beta_{10} x_1\cdot H\cdot Vis+\beta_{11} x_2\cdot H\cdot Vis \quad (3)$$

$$\ln\left(\frac{p(x)}{1-p(x)}\right) = \beta_0+\beta_2 Vis+\beta_3 x_1+\beta_4 x_2+\beta_7 x_1\cdot Vis+\beta_8 x_2\cdot Vis \quad (4)$$

where H is height from the floor (H: 20.75, 32.75, 44.75 and 56.75 cm),
Vis is tag visibility (Vis: 0=hidden, 1=visible), and
x_1 and x_2 are dummy variable representing the presence of corrugated board spacer (presence on the back of the tag side (1, 0), presence on both side (0,1), and not present (0,0)).

The regression result (data not shown) indicates that the 3rd and the 2nd order interaction term in equations (3) and (4) were significant ($p<0.05$). Therefore, this model cannot be used to evaluate the main effect of corrugated board spacer because the effect is dependent on location of tag. To determine the spacer effect, the data from hidden and visible tags were analyzed separately for each tier in the pallet. The new logistic regression model is shown in equation (5) and the regression coefficients are presented in Table 3 and 4 for tags on the side and top panel, respectively.

$$\ln\left(\frac{p(x)}{1-p(x)}\right) = \beta_0+\beta_3 x_1+\beta_4 x_2 \quad (5)$$

The p-value of H-L test in Tables 3 and 4 indicates that the regression model can be used to predict the read probability for tags with interference of metal ($p>0.05$). The regression coefficients from the model show the impact of the parameter on the probability of the tag being read. Larger values indicate higher impact. The mathematical sign of the coefficients shows the direction of impact. The positive sign means the probability increases with the increasing value of the parameter. [10]

For tags on the side panel (Table 3), the addition of spacers did not have a significant effect on the readability of visible tags, with the exception of the improvement in readability in the bottom tier of the pallet for tag placed in between two spacers. For the hidden tags, the addition of one spacer on the back had a negative effect on the readability while the addition of two spacers (front and back) had a negative effect on the two bottom tiers, but had no effect on the top two tiers.

Table 3. Regression coefficients from logistics regression and the p-value and Hosmer-Lemeshow (H-L) test results for cases with tags on the side panel

Visibility	Height, cm	Parameter		Tag on side panel	
				Regression coef	p-value
Visible	20.75	β_0	Intercept	1.3249	14.2116
		β_3	x_1	1.8531	<.0001
		β_4	x_2	0.9521	0.0011
		p-value for H-L test		0.9203	
Visible	32.75	β_0	Intercept	3.1781	<.0001
		β_3	x_1	1 1.7458	0.9462
		β_4	x_2	0.7138	0.4162
		p-value for H-L test		0.9203	
Visible	44.75	β_0	Intercept	4.5951	<0.0001
		β_3	x_1	1 0.7302	0.9598
		β_4	x_2	1.1190	0.3362
		p-value for H-L test		0.9203	
Visible	56.75	β_0	Intercept	3.4761	< 0001
		β_3	x_1	11.6281	0.9513
		β_4	x_2	0.4157	0.6528
		p-value for H-L test		0. 09203	
Hidden	20.75	β_0	Intercept	-2.0907	<.000l
		β_3	x_1	-2.2132	<0.0001
		β_4	x_2	-1.0038	0.0030
		p-value for H-L test		0.9999	
Hidden	32.75	β_0	Intercept	-3.1780	<.000l
		β_3	x_1	-2.5220	0.0157
		β_4	x_2	-1.8259	0.0175
		p-value for H-L test		0. 9997	
Hidden	44.75	β_0	Intercept	-2.4423	<.000l
		β_3	x_1	-1.4495	0.0018
		β_4	x_2	-0.5021	0.1395
		p-value for H-L test		1.000	
Hidden	56.75	β_0	Intercept	-1.9924	<.000l
		β_3	x_1	-2.3116	<.000l
		β_4	x_2	0.2837	0.2356
		p-value for H-L test		1.000	

For tags on the top panel of the cases (top panel), the addition of one and two spacers to the visible tags improved the readability in a similar manner. For the hidden tags, the addition of one spacer on the back did not improve the readability while the addition of two spacers increased the probability of tag being read in the two bottom tiers. The effect was less in the bottommost tier.

Metal has a tremendous impact on RFID operation, particularly when the RFID tags are hidden or in a less than ideal location. This may cause a lot of problems when trying to read several tags at once in the pallet load. When reading a tag one by one as in case level conveyor tracking or pallet tag tracking, the problem may not be as serious as long as the tag is facing at least one of the antennae. A corrugated board spacer can improve the readability of RFID in the presence of metal interference in some situations, but it is not very effective. A larger size or a thicker spacer may be more efficient in improving the readability, or a better design of the

Table 4. Regression coefficients from logistics regression and the p-value and Hosmer-Lemeshow (H-L) test results for cases with tags on the top panel

Height, cm	Tag visibility	Parameter		Tag on side panel	
				Reg.coef	p-value
Hidden	20.75	β_0	Intercept	-2.7081	<.0001
		β_3	x_1	-0.2903	0.3536
		β_4	x_2	0.5383	0.0417
		p-value for H-L test		0.9997	
Hidden	32.75	β_0	Intercept	-3.6636	<.000l
		β_3	x_1	-0.3642	0.4645
		β_4	x_2	2.2457	<.000l
		p-value for H-L test		1.000	
Hidden	44.75	β_0	Intercept	-5.2933	<.000l
		β_3	x_1	0.4080	0.6559
		β_4	x_2	0.6982	0.4217
		p-value for H-L test		1.000	
Visible	56.75	β_0	Intercept	-1.0986	<.000l
		β_3	x_1	2.2929	<.0001
		β_4	x_2	2.0431	<.0001
		p-value for H-L test		1.000	

tag antenna might be devised.

The effect of pallet stretch wrap on the tag readability

Polyethylene (PE) is a commonly used pallet stretch wrap material. The impact of the stretch wrap radiolucency is very important to pallet level tracking. It is important to know before hand if the stretch-wrap material will interfere with the pallet readability. This will determine if the pallet tag needs to be placed on the outside of the stretch wrap or it is acceptable to place under the stretch wrap.

Figure 3 and equation (6) shows the read probability as a function of the weight of polyethylene stretch wrap around the load.

$$\ln\left(\frac{p(x)}{1-p(x)}\right) = 1.4645 - 0.00002 \cdot W \qquad (6)$$

The parameter "W" in equation (6) is the weight of PE stretch wrap. The H-L test p-value of 0.98 indicates the validity of the model to the experimental data. The slope of equation (6) is not significant (p = 0.92), indicating that neither the presence nor the weight of this PE stretch wrap interfered with tag readability. This agrees with the relatively straight line shown in Figure3.

In term of pallet load tracking, the tags can be placed under the PE stretch wrap without interfering with an RFID operation. Placement of the tag under pallet stretch wrap is more desirable in order to prevent tags from being damaged, lost or stolen during shipping/handling. This also allows the possibility of reading individual tags on cases in a pallet load without

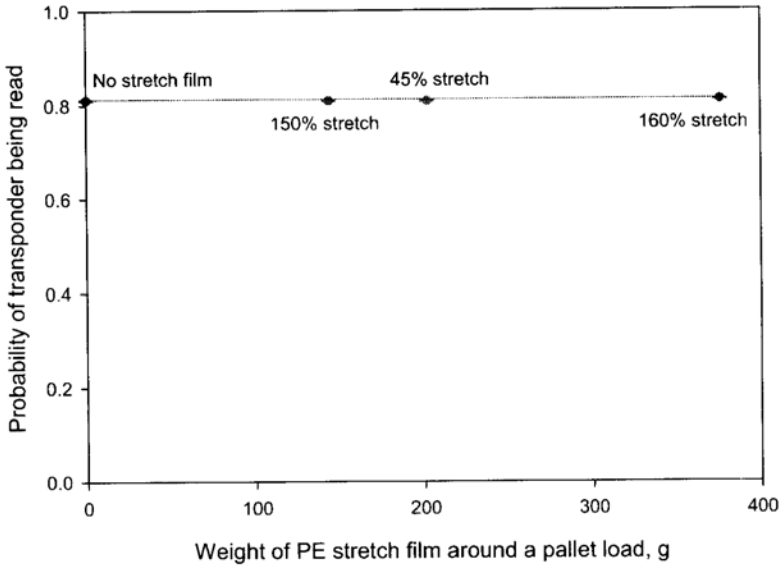

Figure 3. The read probability of tags on a pallet load with of water filled cases and varying weights of polyethylene stretch wrap and % stretch

removing the stretch wrapping provided that the packaging and the product do not interfere.

The effect of glass on the RFID tag operation range

Glass, an inert and high barrier packaging material, is used extensively for primary packages. This is particularly true for the pharmaceutical industry, where the FDA has recommended widespread use of RFID for item level tracking by 2007. [9] To date, there are no published studies covering the effect of various glass types on RFID operation.

Figures 4 and 5 shows the operation range of tags on glass sheets when evaluated with circular and linear-polarized antennae, respectively. When looking at the same tag orientation and placement on a glass sheet, it was found that the color of glass does not have an effect on RFID operations. Therefore, for this study, the effect of glass color was ignored and a t-test for comparing one population to a single value was used to analyze the data. Glass was found to significantly reduce the read range for all tag locations and orientations for all antenna types (α=0.1).

In Figure 4, the operation range for a circular antenna system was about 60 inches for all both x and z-axis tags when they were placed in front of, or behind, the glass sheet. The range was much shorter for the same orientation when the tags were placed in between two glass sheets of the same material. The read range for y-axis tag orientation, where the tags are facing

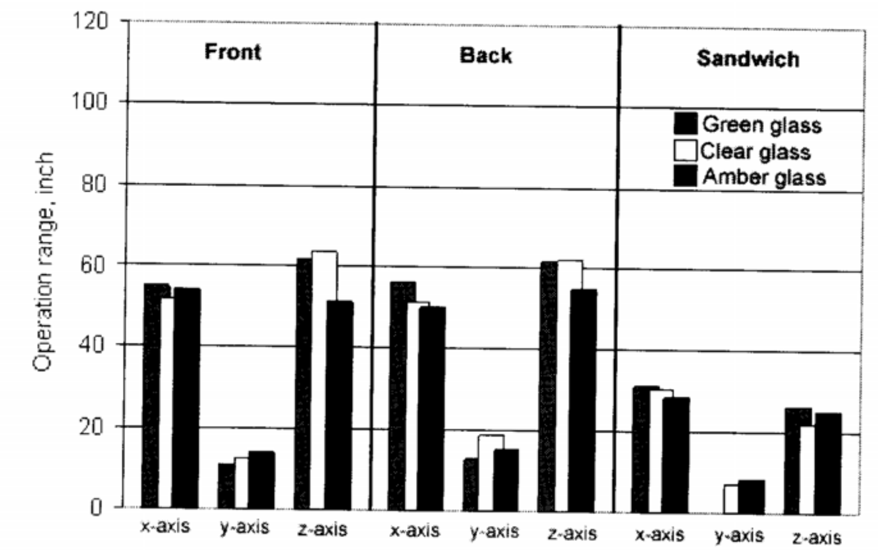

Figure 4. Operation range of Alien RFID system with circular-polarized antenna for transponder in 3 orientations (x, y and z-axis) with the presence of a glass sheet. The transponder was in front (front), on the back (back) or placed in between (sandwich) glass sheets.

90° away from the antenna, was much shorter than the range of other orientations.

The effect of glass on a linear antenna system, shown in Figure 5, is similar to the effect on the circular antenna system, but the effect of orientation is different. The z-axis orientation has the longest read range, which is longer than the read range of z-axis orientation for the circular antenna system. Unlike the circular antenna system, the x-axis orientation tags could not be read at all. The difference between the two types of reader antenna is how they emit radio wave. The circular-polarized antennae emit radio waves in a circular pattern while linear-polarized antenna focuses the radio energy in one orientation. [11] Therefore, when tags are not aligned with the orientation of the signal, an RFID system using linear antennae cannot pick up the signal.

Figure 6 shows the percent reduction of operation range for circular and linear polarized antennae. The greater number implies the greater impact of the presence of glass. From this figure, it is obvious that glass has the same magnitude of effect on the operation range when tags are placed on either side of a sheet of glass regardless of orientation and type of antenna. The read range is reduced by approximately 50%. The placement of tags between two glass sheets reduced the read range by about 80% for both type of antenna. One exception to this is for the linear antenna system when the tag is oriented in the x-axis where 100% reduction occurred when either one or two glass sheets were presented.

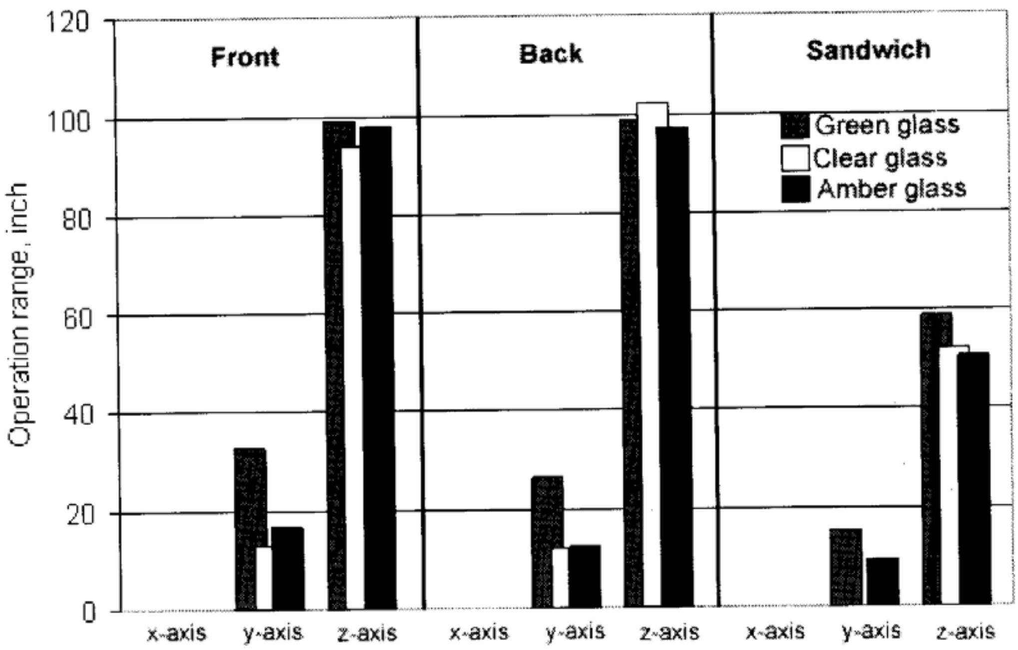

Figure 5. Operation range of Alien RFID system with linear-polarized antenna for transponder in 3 orientations (x, y and z-axis) with the presence of a glass sheet. The transponder was in front (front), on the back (back) or placed in between (sandwich) glass sheets.

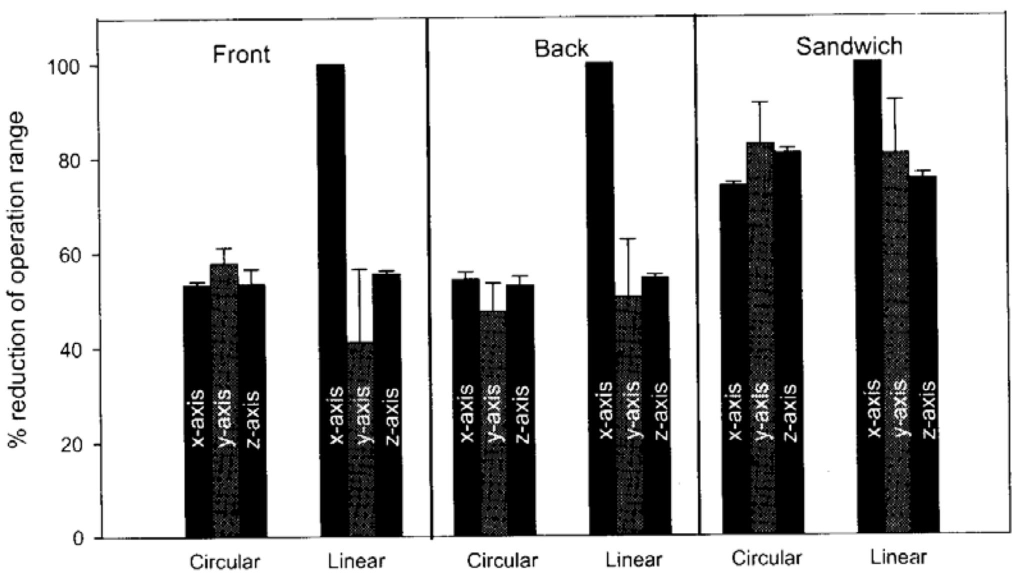

Figure 6. The percent reduction of operation range for Alien RFID system with circular and linear-polarized antennae with transponders in 3 orientations (x, y and z-axis) in the presence of a glass sheet. The transponder was in front (front), on the back (back) or placed in between (sandwich) glass sheet.

Glass has a large impact on reduction of operation range of RFID particularly when the tags arc enclosed between two sheets of glass or when tag orientation is a problem. This may affect the item level tracking but it does not mean that item level tracking of glass packages is not possible. When reading a single tag, this will not create a problem since the tag can still be read. The problem may arise when attempting to read several tags at high speed. Because the read range is much shorter when glass is presence, the tags must remain in the operation range longer for the reader to detect the existence and collect the data from all tags.

The effect of curvature on RFID tag operation

Packaging can come in several shapes and some shapes do not provide enough flat surface area for RFID tags, especially on primary packages. Many UHF tags arc relatively large, and without redesigning the tag, they have to be deformed to adhere to some packages. This may cause distortion of the re-emitted frequency waves and thus, interfere with the RFID operation. [9]

Figure 7 shows the read operation of tags on graduated cylinders of various diameters. The figure indicates that the operation range of these tags in the system with circular-polarized antenna was slightly larger than that of a horizontal linear antenna when the tags are in x-axis orientation, yet very similar when the tags are in y-axis orientation. The reason for this discrepancy with the data from previous section may be that the linear antenna system is more sensitive to the curvature of the tag. In both systems, the curvature starts to have effect when the diameter of cylinder is below 1.5 inches. A tag on 0.7-inch diameter cylinder, where there

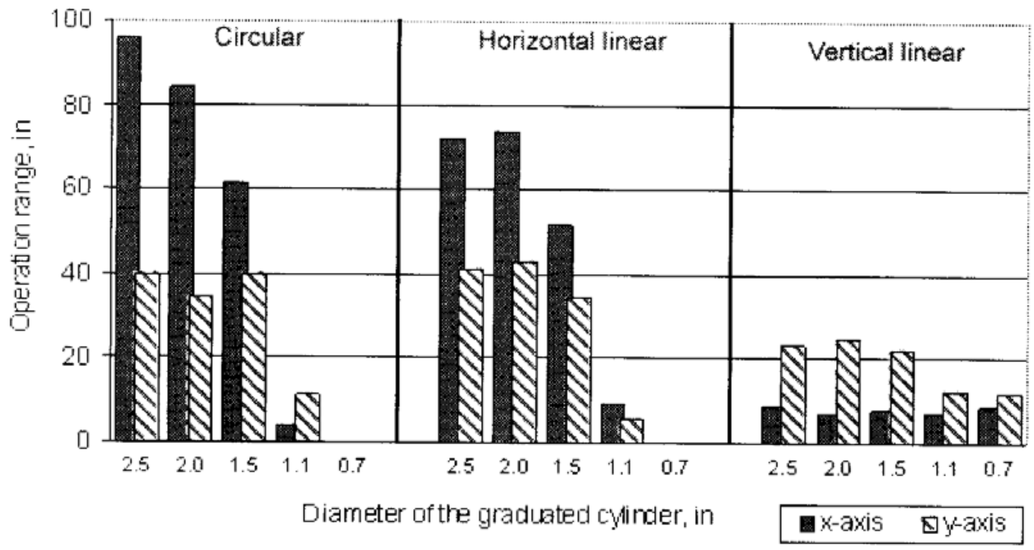

Figure 7. The operation range of Alien system with circular and linear antennae for tags on graduate cylinders with different diameters, when the tags are placed in x and y-axis orientations

was an overlap of the tag antenna, could not be read. The interference may be a result of detuning of the signal or the reduction of exposure to reader energy.

Since linear-polarized reader antenna is orientation sensitive, it is as expected that when turning the reader antenna 90°, the read range was shortened. Unlike the horizontal linear system, y-axis orientation tags in a vertical linear system have a larger operation range than x-axis tags. The range did not change much with the reduction of diameter of graduated cylinder. This indicates that the curvature did not have as much influence as with the previous two systems.

Like the effect of glass sheet, the curvature of packages may or may not interfere with RFID operation in item level tracking. This depends largely on the degree of curvature as well as the amount of tags being read at the same time.

Conclusion

From our research, packaging materials were categorized, based on their interference in RFID operation into 2 groups. The first group is those that have no effect on the operation. This group includes polyethylene stretch wrap and corrugated boards that are not or have not been exposed to high humidity. The second group is those that have effect on the operation. Aluminum can, glass and corrugated boards that are or have been exposed to high humidity are in this group. The curvature of packages, when the diameter reduces to a critical dimension (e.g. 1.5 inch in our case), also can interfere with the RFID operation. However, this result does not indicate that the materials from the latter group and the packages with curvature cannot be used in RFID operation. The result is intended to show that care must be exerted when the RFID interference is presence in the RFID operation.

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