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Aim and Scope

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

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Methods and Apparatus for RFID Hotspot Testing

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ABSTRACT: Since the first supplier mandates put forth by Wal-Mart and the Department of Defense, the use of (915 MHz) radio frequency identification (RFID) has been implemented into supply chains with mixed results. When working optimally, RFID can provide valuable information regarding inventory data and shipment locations. However, tag readability issues exist due to a variety of reasons: product and package interference, RFID equipment set-up locations, and even frequency allocations, depending on the country of use.

It is almost inevitable that a package will travel on a conveyor at some point during the manufacturing and distribution process. Since tracking product movement is one of the key aspects of RFID, it is important to determine if RFID antennae are able to track tagged packages on conveyors.

In this paper, we develop the methods and apparatus used to determine if conveyor speed, packaging materials, and product have an affect on the readability of RFID transponders. The variables for this testing were conveyor speed (300 feet per minute (fpm), 600 fpm), package type (case of chips in plastic tubs, case of chips in metalized spiral wound fiberboard containers (MSWFC)), package shape (case of metal cans, case of metal bottles, and case of metal tins), product type (case of bottled ketchup, case of bottled motor oil) and tag generation (Alien Gen 1, Alien Gen 2).

The results shown in this paper demonstrate that a similar facility can be used to identify the RFID tag hotspots. Furthermore, rigorous experiments can be performed to determine if conveyor speed, package type, package shape, and product type all have significant effect on the average amount of tag reads per trial.

INTRODUCTION

RADIO FREQUENCY IDENTIFICATION (RFID) technology is a tool that enables companies to efficiently track products in their supply chain. From raw material through the entire life of the product, RFID can

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provide valuable information regarding inventory data, shipment locations, and even product temperature.

RFID is a data collection technology that is able to communicate information from a tagged item to a computer system. For an RFID system to function properly it must be equipped with four items: a reader (also known as an interrogator), an antenna, a computer equipped with the proper software, and an RFID transponder (tag) placed on an item. Radio waves transfer data between the RFID tag and the reader, which are tuned to the same frequency.

The use of RFID in supply chain applications is currently organized by a worldwide standards organization known as EPCglobal. Undoubtedly one of the most important achievements of this organization was the completion of RFID Ultra-High Frequency (UHF) Generation 2 (Gen 2) protocol, which solved the readability problems associated with Generation 1. This protocol made it possible to read any UHF RFID tag using any UHF RFID equipment. Previously, when using Generation 1 protocol, tag readability was dependent on using one of the two main passive UHF classes, Class 0 or Class 1. A Class 1 tag could not be detected on a Class 0 reader/antenna set up and vice versa.

In the United States, RFID use is currently monitored by the Federal Communications Commission (FCC). The FCC determines both the frequency bandwidth and the power level allocated for use. These allocations have a direct effect on equipment performance and effectiveness.

The use of RFID for supply chain applications has grown immensely since the Wal-Mart mandate to their suppliers became effective January 2005. The mandate stated that the company's top 100 suppliers had to begin shipping select products headed for particular distribution centers (DCs) with RFID tags on each case and pallet. The reason for the mandate was simple: by improving product availability on the store shelves, and by being able to track the whereabouts of expected deliveries, Wal-Mart can improve store operations and increase profits. The Department of Defense (DOD) followed Wal-Mart's mandate with similar RFID requirements for their suppliers, recognizing the technology's ability improve product visibility especially in tracking dangerous and expensive supplies. Additionally, the Food and Drug Administration (FDA) has issued statements to both food retailers and the pharmaceutical industry asserting the desire for improved security within supply chains, to help prevent possible bio-terrorism attacks and to effectively recall products in the event of an emergency.

The use of RFID technology is by no means limited to the United States, as numerous retailers in countries around the world are also using RFID for supply chain applications. Companies in Europe have issued mandates similar to those of Wal-Mart and the DOD to their own suppliers. Tesco, Marks and Spencer, and Metro Group are some of Europe's largest retailers working with RFID technology in their stores and DCs. Additionally, Asian retailers and organizations throughout Japan, Singapore, South Korea, and China are working with RFID systems.

As is the case in the United States, both retailers and suppliers overseas are learning about some of the set backs inherent in RFID technology. For some implementers, RFID performance is hampered by regulations limiting the operation and frequency available for RFID readers. The frequency band allocated for UHF RFID differs from country to country and the amount of availability between 866 MHz to 956 MHz UHF band can have drastic system performance implications. Others working with the technology may find that their product or package absorbs or reflects radio waves, which can hamper their ability to meet mandates effectively, as well as their ability to use all the benefits RFID can offer.

There is no one specific method for using RFID technology, nor is there one specific solution to be applied across industries. For RFID to work most advantageously within an organization's supply chain, the implementer must think of each product on an individual level. An RFID tagged product, Product A will not function equally to a tagged Product B if there are differences in the product composition and the package system. Additionally, optimal tag type, tag location and orientation, antenna location and orientation, reader location and broadcast strength, and even the cord length between the reader and the antennae, are among the variables that implementers of the technology need to consider when trying to optimize the readability of an RFID tagged product.

In the event that a retailer has implemented RFID mandates to suppliers, both shipper and receiver must work collectively to optimize performance and usefulness in the supply chain. Specifically, the read location (where the tag is to be detected) can have a significant impact on successful RFID utilization. Suppliers will have to ensure that they have tested their product at each read point in the supply chain process in order to avoid failing to meet mandates which could lead to financial losses. Traditional read locations for RFID tags are warehouse dock doors, stretch wrappers and fork trucks, or conveyors.

This paper focuses on testing methods for conveyors, since retailers such as Wal-Mart use UHF RFID systems to track product traveling on conveyors in their DCs from arrival, to storage, and to their eventual exit, bound for their destination point. With product traveling upwards of 600 feet per minute on conveyor lines, the amount of time for interaction between the mounted RFID antennae and the tagged cases is minimal. The purpose of this research is to determine the effect of conveyor speed on the readability of RFID tagged case goods in a typical warehouse environment.

BACKGROUND

The Electronic Product Code

One of the most important advances aiding RFID technology and its use in industry was the development of the Auto-ID Center. The Auto-ID Center was a non-profit collaboration between private companies and academia that pioneered the development of an Internet-like infrastructure for tracking goods globally through the use of RFID tags carrying Electronic Product Codes [EPC] [1]. When the Auto-ID Center closed in September 2003, EPCglobal, a non-profit organization, was set up to continue the work of developing the use of RFID to produce more visibility and efficiency throughout the supply chain. EPCglobal is achieving this goal through the Electronic Product Code Network™. This network is to serve “as the global standard for immediate, automatic, and accurate identification of any item in the supply chain of any company, in any industry, anywhere in the world” [2].

The EPC is the primary information of concern stored on the RFID tag’s microchip. Used for recognition, the EPC assigns a numeric identification to each packaging unit whether it is an item, case, or pallet. The number used in the EPC consists of four parts: a Header, a Manager Number, an Object Class, and a Serial Number. The Header identifies length, type, structure, version, and generation of EPC. The Manager Number identifies the company that owns the product. The Object Class Number represents the stock-keeping unit (SKU), while the Serial Number is assigned to identify each individual case [3]. The EPC by itself gives no more information about a product than a car’s license plate tells you about the car. To decode information contained in a particular EPC the computer is directed to information located at an Internet address.

The Object Name Service (ONS) is an automated networking service that points computers to sites on the World Wide Web. Once the information is located it can be forwarded to a company's inventory or supply chain data [2].

Generations

Assembled by more than 60 of the world's leading technology companies, EPCglobal recently presented an RFID UHF Gen 2 protocol. This protocol describes the core capabilities required to meet the performance needs set by the end user community [4].

Until the recent ratification of a Gen 2 standard, various vendors (and their end user customers) had adopted incompatible EPC technologies (EPC Version 1), including EPC Class 0 and Class 1 [5]. There are two separate components in a tag class: the air protocol (how the tags communicate) and the programming technique (how the tags get their data). Class 0 and Class 1 tags use different methods in their approach to RFID communication, and thus have different performance capabilities [6]. Class 0 tags use a protocol developed by Matrics, Inc, (now Symbol Technologies), and Class 1 tags use a protocol developed by Alien Technologies. The implications of having two different protocols are straightforward: simply because a product is equipped with an RFID tag does not mean that it can be recognized by an RFID system. A Class 0 tag will not read on a RFID system designed for Class 1 tags.

Gen 2 is a protocol that allows communication between the tag and reader irrespective of the equipment manufacturer. The benefit of Gen 2 is that it offers specifications and regulations that can be applied across the world. Gen 2 offers RFID users the assurance that no matter which type of tag comes through their doors, their readers will be able to detect it. The new EPC Gen 2 standard supports an increased frequency range and regulatory requirements promoting adoption in the US, Europe and Asia. Gen 2 includes password-protected mechanisms to ensure data safety and a kill feature to ensure consumer privacy protection [7]. Gen 2 has the ability to work in dense reader environments, making it optimal for distribution centers loaded with inventory. Additionally, Gen 2 allows users to read and write data multiple times to the same RFID tag [8].

It is thought that with a global standard set, Gen 2 will create more competition in the market place, hence lowering the price of RFID equipment and tags. Additionally, in some cases, costs of RFID materials are decreasing.

With Gen 2 comes more than just cost benefits. It has a lot more selectivity, which means that there is less reader on reader interference. In addition, claims have been made stating Gen 2 to be five to 10 times faster than Gen 1 [8]. In most cases Gen 2 readers are capable of reading Class 0, Class 1 and Gen 2 tags, easing the transition for those moving away from Gen 1 systems [9].

Although Gen 2 offers many positive features necessary for a global RFID deployment, some companies are reluctant to move on from Gen 1 at short notice. EPCglobal plans to certify three different levels of Gen 2 compliant readers. At the lowest level, readers will be certified to work only when there are no other readers within a 1 km radius. The next level will be for readers capable of being deployed with several readers within a 1 km radius. The highest level will be certified to work alongside 50 or more readers within a 1 km radius. Impinj's founder and chairman, Chris Diorio, is convinced that users have to get educated that not all EPC compliance is the same. If you can upgrade only to the lowest grade, you are not going to get multi-reader performance [10].

The Gen 2 standard put forth by EPCglobal is royalty-free. The organization engaged legal counsel to examine claims made by Intermec Technologies, a RFID systems provider, which claims the Gen 2 spec contains intellectual property that it has patented. It was concluded that Intermec's patents are not essential to implementing the Gen 2 standard. However, Intermec President Tom Miller claims that using the royalty-free protocol does not mean the UHF RFID products will be royalty-free; companies who offer UHF RFID products will still require a license to use Intermec intellectual property [11]. It is the hope of EPCglobal and RFID companies alike that possible intellectual property battles with Intermec will not slow down the development of Gen 2 technology and implementation.

RFID Tag Classifications

A wide variety of RFID tag types currently exist, each with different capabilities. Although current RFID mandates focus on passive RFID tags, other tag types such as semi-passive and active tags exist. As opposed to passive tags, semi-passive and active tags contain their own source of power, a battery. These types of tags tend to be used for tracking large or expensive items. In contrast, passive tags are powered by the electromagnetic waves transmitted from the RFID reader. The RF induces a current in the tag's antenna, powering up the accompanying microchip which contains information that is sent back to the reader (Figure 1). Passive tags are currently being used for case and pallet application for inventory tracking purposes, but can also be used for tracking children in amusement parks, skiers on mountains, luggage in airports, and sports race timing [12].

Multiple variations of passive tags exist. To help understand an RFID tag's capabilities, the tags are placed into certain generations and classes. Gen 1 Class 0 RFID tags are the most basic passive tags, arriving to the end user factory programmed and in a read-only format—meaning that the RFID tags cannot be changed unless the microchip is reprogrammed electronically" [1]. Gen 1 Class 0+ and Class 1 RFID tags are known as Write Once Read Many (WORM) passive tags, which allow end users to program the tag as opposed to the tag arriving preprogrammed. Gen 1 Class 0, 0+, and 1 tags have all been approved for meeting the mandates put forth by Wal-Mart and the DOD. Gen 1 Class 0 tags can contain either 64 or 96 bits of memory, while Gen 1 Class 0+ contains 96 bits of memory. Gen 1 Class 1 tags contain 96 bits of user programmable memory [13,14]. With the current movement towards Gen 2 it is important to note the emergence of Gen 2 tags. Gen 2 tags offer 128 bits of user programmable memory [12].

RFID in the United States

RFID technology and its use in the United States is monitored and regulated by the FCC. The FCC has set aside rules for the use of RFID in the

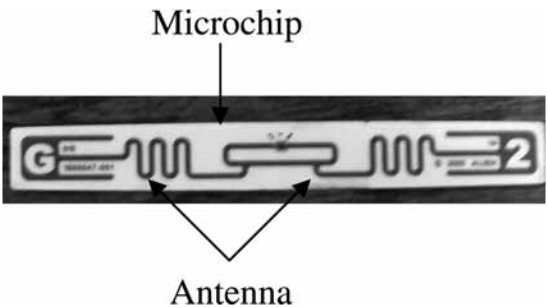


Figure 1. *ALL-9440 "Gen 2 Squiggle™" Class 1 Tag with Description of Parts.*

Code of Federal Regulations, specifically 47 CFR Part 15, which is reserved for low power devices. Since these devices are low power, owners and operators do not require a license to operate the machinery. However, it is required that RFID readers must meet the FCC's emissions limitations and power restrictions. The FCC classifies RFID readers as intentional radiators, and therefore they require certification by the FCC. This certification process is generally performed by the manufacturer of the reader. After the certification process the reader is properly labeled and can be marketed and operated in the U.S. [15].

Should the purchaser of the certified reader make changes to its operational capabilities, FCC rules state that the modifying party automatically becomes responsible for complying with the FCC standards. Should the modifying party make changes to the power level or otherwise alter the equipment, they are subject to sanctions and monetary forfeitures if the reader is not recertified.

The certification process is important because it ensures the performance of RFID technology from being hampered by readers interfering with one another. The more unlicensed devices in operation, the more likely it is that interference will occur. To encourage licensing, the FCC has imposed sizeable monetary fines on various parties who operated noncompliant Part 15 devices [16].

UHF RFID systems operating in the U.S. use a frequency allocation between 902 MHz and 928 MHz, providing 26 MHz of bandwidth. UHF readers are allowed to operate at 1 watt and can go up to 4 watt if they have directional antennae and if they hop across at least 50 channels [15].

With the use of RFID increasing in the U.S., both federal and state governments have introduced RFID privacy bills. Most bills deal with requiring retailers to notify customers when RFID tags are on the products they are purchasing, and to remove tags at the point of sale.

The Wal-Mart Effect

Wal-Mart was the first retailer to realize the possible cost savings that could be attained by using RFID technology in its supply chain and distribution centers. In June of 2003, Wal-Mart mandated that its top 100 suppliers would have to ship selected pallets and cases RFID-tag-equipped beginning January 2005. In this trial run, Wal-Mart selected 3 of its 99 U.S. distribution centers to receive these tagged shipments [17]. By late 2005, the company extended its trial run to include a total of five distribution centers. Later, the mandate was expanded to include an additional 200 suppliers to ship their pallets and cases RFID-tag-equipped by January 2006.

The product receiving process begins at Wal-Mart's regional distribution centers. When tagged cases and pallets arrive they are scanned by a reader and antennae set up near the distribution center's dock doors. Data about the shipment are collected and sent to Wal-Mart's operations and merchandising teams. Additionally, the supplier is notified within 30 minutes, through a website that links retailers to real time data, that a specific shipment has arrived [18]. The next step that occurs at the distribution center is pallet disassembly. Cases are removed from their pallets, placed onto conveyors, sent through another RFID read point on the conveyor line, and placed into storage. When product is needed at a Wal-Mart retail center, order pickers in DCs gather the required cased goods, and place them back onto conveyors at the end of which products are re-palletized and shipped out via truck. This re-palletizing of a variety of products allows the Wal-Mart retail center placing the order to receive exactly what they need for restocking purposes. Wal-Mart aims to read 100 percent of all tagged pallets entering through distribution center and store dock doors, as well as 100 percent of all tagged cases on conveyors within the distribution centers [19].

After more than a year of receiving tagged shipments from suppliers, Wal-Mart determined that the technology provided a 16 percent reduction in out-of-stock merchandise and a 70 percent drop in the time it takes to receive new shipments from suppliers. The key to the vast improvements arose from in-store inventory tracking. Prior to receiving RFID tagged shipments, knowing when to restock shelves at Wal-Mart was based on visual observation. Now, Wal-Mart associates receive shelf restocking data that are linked to real time product sales. Ensuring that Wal-Mart stores are receiving the desired product from their distribution center is critical to avoiding out-of-stocks and empty shelves. Using RFID technology allows Wal-Mart to know specific details about when product arrives at their distribution centers, and how long it takes for the product to be redirected. For example, Wal-Mart was able to determine that a particular product arrived at its distribution center on August 4, that it was put on the conveyor system five days later and that it departed shortly thereafter. Upon arrival at the store (12 hours after it left the distribution center), the product was whisked to the store's back room and moved to the sales floor the following day [20]. This type of information could help improve inventory turnover, determine distribution center efficiency, and track bottlenecks in the supply chain.

With the arrival of Gen 2 equipment and tags, Wal-Mart has decided that as of July 2006 they will no longer accept EPC Gen 1 tags on cases and pallets received from suppliers. Internal tests performed at Wal-Mart determined that EPC Class 1 Gen 2 tags showed improved performance compared to their Gen 1 predecessors. Wal-Mart polled suppliers and concluded that most could be ready to deploy Gen 2 tags by the second quarter of 2006 [21].

What's the Business Value of Reading or Not Reading a Tag?

The business-value of reading (or detecting) tags at checkpoints throughout the supply chain are numerous. For the supplier merely meeting the mandates, tag readability on both pallet and case loads are critical to ensure they receive payment for their shipments. If the retailer doesn't know it has received a supplier's shipment (the RFID tag on the pallet or case load isn't detected), the retailer doesn't know it has received any product, and therefore, would not likely pay for the product. Additionally, tag reads are crucial for the retailer because it makes them aware of product availability, and therefore, can help to avoid dreaded out-of-stock situations.

Meeting the Mandate

Suppliers to retailers such as Wal-Mart have more often than not applied a "slap and ship" approach to tagging their products with RFID tags. In this approach, placing RFID tags on the case and pallet is done in the final stages of the manufacturing and distribution process. With this "slap and ship" approach, at no point does the supplier attempt to use the RFID-tagged goods for their own internal purposes, thus creating nothing more than an additional cost to the supplier. The lowest price currently reported ranges from 7.9 cents for an inlay to 12.9 cents for a self-adhesive tag for orders of 1 million or more [22]. Smart suppliers will try to take advantage of the benefits of RFID, especially by tagging product early in the manufacturing process.

One such example comes from Paramount Farms, the world's largest supplier of almonds and pistachio nuts. Paramount owns 50,000 acres of orchards and processing facilities, and is responsible for growing about 60 percent of the U.S. pistachio crop. To meet its pistachio needs, Paramount also networks with nearly 400 grower partners. In an average harvest season, incoming green product totals a half a billion pounds over a six-week period. Given this time constraint, efficiency and productivity must likewise increase [23].

After forming a committee within Paramount to brainstorm ideas about technology features necessary to make the processing job easier, it was determined that the Grower Receiving System would need to provide multi-site distribution of information from a central server at Paramount Farms. This could easily be done in a web based environment, and allows the company's two pistachio processing plants, as well as its sales and marketing offices in Southern California, to access the system with only an Internet-compliant browser.

Productivity was enhanced by providing growers with handheld computers, access points, and RFID tag readers. Load processing time at Paramount Farms' pistachio nut farms was improved by 60 percent. As processing time decreased, Paramount noticed an increase in revenue. The receiving department became so efficient at equipment logistics that it reduced leased trailer usage by 30 percent. After implementing RFID, Paramount became more confident than ever of their data system's integrity and the accuracy of the information, since more of the data is collected using radio-frequency tags and barcode scanners [23].

Paramount receives 20 million pounds of product per day for recording, weighing, pre-cleaning, sampling, and processing. RFID-tagged trailers filled with pistachios arrive and are interrogated by a reader. The reader captures the tag's unique identification number and wirelessly transmits it to the central server. The database relays the pre-recorded profile of the identified trailer back to the scale house worker's mobile computer. Now the worker knows the trailer's net weight, license plate number, equipment number, and owner name. Next, the scale house workers take the product load details. The grower name, ranch, field, product temperature, and harvest method are all sent wirelessly to the database. The trailer's gross weight is automatically retrieved from the truck weigh scale and a weight certification is printed. During processing, the nuts are cleaned. Sifters remove foreign debris such as leaves and branches. The Grower Receiving System automatically weighs the debris, subtracts it from the original load weight and sends the corrected weight to the database [23].

Both weight and quality play a role in the amount a grower gets paid. An automatic sampler scoops 20 pounds from each 50,000-pound load for quality testing. While this sample is peeled, hulled, dried and tested, the rest of the load travels on to the main processing line, where it is mixed with the rest of the day's harvest. This mass of nuts is processed and stored within 24 hours. Sample testing determines the grade of the nut, and the pay rate to the grower. It is imperative for Paramount to ensure that the volume and quality they pay for is the volume and quality received. Their new RFID-based Grower Receiving System helps do all these things [23].

The Paramount Farms RFID implementation is an excellent demonstration of a supplier employing RFID early in the manufacturing process to attain a return on investment (ROI). If the Wal-Mart mandate were to include products from Paramount Farms, the company's familiarity with the technology and ability to attain a profit from its use would make tagging shipments not nearly as painful as it would be to a company utilizing a "slap and ship" approach. In fact, tagging retailer-bound shipments will provide even more traceability to the Paramount Farms outgoing supply chain, shedding light on other areas of the product life cycle that could be improved. A likely impact of incorporating the use of RFID into a supply chain will be RFID working its way into the supplier's own vendor supply chain system. This will increase the demand for RFID tags and result in lowering the cost per tag [24].

The Department of Defense

The United States DOD also recognized the benefits that RFID technology could provide in terms of logistics support, asset management, and overall supply chain optimization. Another advantage is hands-free data capture, which allows efficient recording of material transactions. In July of 2004, the DOD released requirements to their suppliers. The Defense Federal Acquisition Regulations Supplement (DFARS) became effective in November of 2005 and required suppliers to affix passive RFID tags at the case and pallet level for shipments of certain commodities to two specific locations: Susquehanna, PA, and San Joaquin, CA. The commodities included four classes of supplies: Shipments of Packaged Operational Rations, Clothing/Equipment/Tools, Personal Demand Items, and Weapon System Repair Parts [25]. In 2006 the tagging requirements added three more classes of supplies and an additional 19 locations. By 2007 all locations will be instrumented and all classes of supply will require RFID tagging.

The Food and Drug Administration

The FDA is asking food retailers for help against the war on terrorism by keeping detailed data about the food shipments in their supply chain. The agency announced that it is the responsibility of everyone in the food supply chain to keep logs of where they received food from and where they shipped it to.

If contamination in the food supply chain takes place, companies must be able to make their records available within 24 hours if the FDA has reason to believe that an article of food presents a serious threat. During his resignation speech, Tommy Thompson, Secretary of Health and Human Services, may have prompted the new policy when he made reference to the ease of attacking the country's food supply [26].

RFID stands to play an important role in helping food retailers improve their supply chain records. With the ratification of Gen 2, RFID solution providers should be excited about the new FDA mandates. RFID is capable of being the technology of choice for food retailers, allowing them to meet FDA standards while offering improved traceability of their products in the supply chain. Food retailers, manufactures and distributors have until January 2006 to bring their operations into compliance with the ruling [27].

The FDA has also been vocal in their desire for the pharmaceutical supply chain to become more secure, and has endorsed the use RFID to combat the growth of counterfeit drugs. A Finnish drug maker, Orion Pharma, recently performed a trial tracking passive tags on the cartons of individual bottles of drugs as they moved through the supply chain. The test stemmed from the anticipation of stricter policy in the United States with respect to tracking medication [28]. The FDA desires that each product moving through the supply chain have an electronic pedigree (e-pedigree) that shows each bottle's chain of custody. Specifically, an e-pedigree is a secure file that stores data about each move a product makes through the supply chain, thus helping reduce counterfeiting of drugs while improving supply chain safety. It is the goal of the FDA that RFID technology be used widely throughout the pharmaceutical industry by 2007 to improve security and safety. Until the Orion Pharma trial run, the only pharmaceutical companies to actively test and report data were Purdue Pharma and Pfizer. Purdue Pharma performed the pharmaceutical industry's first electronic drug pedigree using RFID tags to match each bottle of a drug with a corresponding record detailing the drug's movement through the supply chain.[29] Pfizer's use of RFID tags concentrated on allowing wholesalers and pharmacies to verify that the product they were receiving was genuine, but did not focus on the tracking aspect utilizing e-pedigrees [30].

European Adoption

RFID technology is not limited to suppliers and retailers in the United States. In Europe, companies like Tesco, Marks and Spencer, and Metro Group have implemented RFID technology into their supply chains. European companies have been using RFID for tracking reusable containers for years, albeit utilizing both low frequency and high frequency. Since UHF is the accepted frequency for most pallet and case level supply chain applications, a bandwidth of 866 MHz to 956 MHz is available for use. Since regulations governing the use of the radio spectrum differ across the globe, ease of implementation and use varies accordingly. For UHF applications, the European Radio Communications Office (ERO) and the European Telecommunications Standard Institute (ETSI) of the European Union has specified a range from 865.6 MHz to 867.6 MHz. The FCC determined that companies in the United States are able to use between 902 MHz and 928 MHz. Although 26 MHz of bandwidth in the United States versus 2 MHz of bandwidth in Europe may seem insignificant, "think of data from tags as cars driving on a two-lane highway in Europe, compared to a 26-lane highway in North America. John Clarke, CTO of Tesco, claims that European companies are not going to get the same performance from their UHF systems as their North American competitors and that the European deployment of EPC RFID is slowed greatly by regulations limiting the operation and frequency available for RFID readers [31]. The European readers use a listen-before-talk function that can limit the time a reader can operate if there is too much activity or noise in the same radio frequency spectrum. Another aspect that impedes European RFID technology functionality are the lower power limits which reduce an antenna's read field [32].

For U.S. companies planning to deploy RFID in Europe, testing the reader at the European frequency can be difficult while on U.S. soil, since the spectrum is currently used for police telecommunication. Conversely, European companies testing RFID readers operating at the United State's frequency can encounter interference with wireless phone handsets [30].

European Retailers

In April 2004 Tesco, the United Kingdom's largest retailer, started tagging cases of non-food items at its distribution center, and tracking them to their retail stores. The company's approach differs slightly from that of Wal-Mart, who had their suppliers provide the tagged product for tracking purposes. Tesco plans to have suppliers ship their goods tagged but has not set a deadline when all suppliers must tag their cases. As of April 7, 2006, 40 of 1400 Tesco stores were equipped with RFID technology. Tesco has stated that complications from using UHF RFID under European Union Regulations have slowed its attempts to make full use of the technology. Nevertheless, Tesco's research proved to them that RFID could provide "greater supply chain visibility and simpler processes for its staff, while resulting in improved product availability, better service and cheaper prices for its customers" [33].

Marks and Spencer (M&S), a United Kingdom retailer of clothing, food, and home products, began testing RFID's capabilities in 2003. The preliminary trial concentrated on placing tags on clothing items, specifically men's suits, shirts, and ties. By 2004, M&S expanded the operation to nine stores, but decided to concentrate only on tagging men's suits. After three years of testing, as of spring 2006, M&S has decided to extend the RFID trial to 53 stores and encompass additional articles of clothing. M&S has determined that by using RFID they are more aware of their inventory and have reduced the time it takes to record inventory by 7 hours per week for a single store. Additionally, constant inventory updates ensure that a full range of sizes is available for any product. In addition to finding the right size, customers are provided with an informational label advising consumers that the RFID tag on the clothing is being used by M&S for stock-control purposes. In addition to informative labels, as well as pamphlets posted around the store, M&S offers to remove the RFID tag at the checkout counter. These methods appease most issues raised by consumer privacy groups in regards to the RFID tagging of products. M&S surveys have concluded that most consumers do not even recognize the RFID tag on the items, but recognize improved product availability [34].

The third largest retailer world-wide, Metro Group, began utilizing RFID in its supply chain in November 2004. Metro Group wanted to focus on tracking incoming and outgoing shipments, and automatic reconciliation of shipments with shipping documents across three retail sales divisions. The three divisions bring in a variety of products. Metro's Cash and Carry (groceries/general merchandise), Kaufhof (department store), and Real (hypermarket) began receiving tagged shipments from 20 suppliers in total. These shipments included groceries, general merchandise, textiles, and apparel [35]. In addition to using RFID in supply chain trials, Metro recently took up more than 30,000 square feet at a German electronics fair, allowing attendees to see the real life applications of RFID in their everyday life. Metro Group simulated a future store, which contained RFID technology on shopping carts, scales, clothing racks, and check-out stations. Other areas demonstrated RFID technology's ability to help out the consumer at home. RFID equipped washing machines, microwaves, and refrigerators were all a part of the future home demonstration, all designed to make everyday chores less time consuming [36].

RFID in Asia

Countries in Asia have also begun allocating UHF ranges for RFID. Through the Ministry of Public Management, Home Affairs, Posts, and Telecommunications, Japan has allocated 6 MHz of bandwidth from 950 MHz to 956 MHz for UHF reader operation. One particular Japanese electronics firm, NEC Tokin, plans to sell EPC Gen 2 readers for use in the Japanese market [37]. The company worked in part with Impinj, a Seattle-based semiconductor manufacturer. Companies in Japan have been eager to show off the future applications that RFID technology can offer. In January 2006, Mitsukoshi Ginza department store (owned by Fujitsu) performed a pilot in which 5000 pairs of jeans were tagged for inventory management and improvement of store operations. The jeans were then placed on smart shelves, which allowed employees to monitor what is available for the customer, and also what sizes they had in stock rooms. Additionally, the pilot included six smart fitting rooms, which provided the customer with information about the clothing they were trying on, what sizes were available, as well as outfit ideas and accessories that the customer might be interested in based on what they had brought into the fitting room [38].

South Korea is another Asian country that is supporting the growth of RFID and its use in industry. Currently South Korea has set aside between 910 MHz and 914 MHz for UHF reader operation. In 2004, GS1 Korea organized an RFID pilot project with Samsung Tesco, a large Korean retailer. The objective of the pilot was to determine technical reliability using EPC standards. Benefits identified in the pilot included accelerated receiving and shipping with less human intervention.[39] Other RFID progress in South Korea is currently being provided by Sun Microsystems. The company is developing a RFID test center in Busan, South Korea, in collaboration with Busan National University (BNU). BNU is known for the focus on manufacturing in their curriculum, and Sun Microsystems hopes that the university will attract local manufacturers to the RFID test center [40].

Singapore has recently enacted legislation that increased the spectrum for UHF RFID systems from 920 MHz through 925 MHz. Infocomm Development Authority (IDA) believes the added bandwidth will improve the performance of RFID technology in Singapore by reducing read-errors because systems will be able to select from more channels to achieve less interference. IDA has reported that over 25 companies use RFID in their supply chain, all of which have combined to invest over 16.5 million dollars in RFID projects [41].

The Chinese government has shown great interest in RFID technology, but is undecided on whether to cooperate with non- Chinese standards organizations. The Standardization Administration of China currently has plans to make its own RFID standard to protect its information security and enterprise interests, but will consider compatibility between its own and foreign standards. The Chinese government has not fully authorized frequencies for RFID use in China [42]. While standards talks continue, RFID research is being carried out throughout China. Dan Dingyi, deputy director of China Logistics Network Alliance, says that RFID had been widely adopted in a large variety of fields including anti-counterfeiting systems, traffic monitoring, logistics, and manufacturing [43].

Retailers are also becoming involved with RFID in China. Bailian Group, one of China's largest retailers, has developed plans for the second phase of the China Implementation Reference Project. The program seeks to expand usage of EPCs and RFID. The second phase will track the movement of actual products tagged with EPC-enabled RFID tags. Bailian is talking to suppliers based on their level of interest in integrating RFID technology into the supply chain. Participating suppliers will tag shipments in their originating distribution centers, and send those shipments to a Bailian Group distribution center in Shanghai. The movement of these products will be recorded, enabling all participants to gain a more accurate view of inventory levels [44].

RFID Read Locations

It is evident that retailers, suppliers, and organizations are working with RFID systems across the globe. However, at what point in the supply chain implementers determine to set up an RFID system to gather data, known as read point or location, varies. In retail applications, an obvious point to set up an RFID system and collect data is by a dock door. The purpose of a dock door is to provide a medium where all products arrive and depart, making it an excellent location for tracking inventory. Generally, a portal contains, but is not limited to, four antennae positioned in various locations around the door, in order to accurately detect tags entering and exiting the facility.

A shrink wrap station is another typical data collection point. This is an excellent data capture point because most stretch wrappers offer 360 degrees of visibility of the product (more importantly, of the tags), and, the stretch wrapping process takes more time than walking through a dock door, which increases the chance that all tags are detected. Multiple stretch wrap machines exist, and how they operate determines where the RFID system will be set up. In some instances, a portal similar to that used in the dock door situation can be placed around the stretch wrapper. Other stretch wrap machines are equipped with an arm that rotates around the pallet, in which case an RFID antenna can be affixed to the arm itself.

Fork trucks, used to transport product into, out of, and within warehouse facilities, provide another medium for an RFID system placement. An antenna placed on the front of the fork truck is capable of reading the tags located on the pallet load, ensuring that drivers are carrying the correct product and placing it in the desired area, whether it is the back of a destination-bound truck, or in storage.

Of all the examples discussed, dock doors, stretch wrappers, and fork truck read locations focus on the detection of products on a unit load, like a pallet. Unit loads generally contain a large number of caseloads, which contain the individual product(s). During the distribution process these case loads either need to be placed onto, or removed from, the unit load. DCs generally use conveyors to move the case loads to and from storage [45]. Thus, conveyors offer an excellent location for a RFID read point by confirming that the correct case has been pulled from storage, and is bound for the correct re-palletization area.

Types of Conveyors

Conveyors generally operate by using either gravity or power to move an object from point to point. A wide variety of conveyors exist, each performing a specialized function. Some of the most common types of conveyor are those containing either a belt or roller bars.

A belt conveyor is composed of fabric, rubber, plastic, leather, or metal and operates over drive, tail end and bend terminals [46]. Belt conveyors are versatile, provide a continuous flow of product, and are low maintenance. They are mainly used for carrying units, cartons, and bags. However, a modern-day example is the use of the belt conveyor as a people mover in high traffic areas such as airport terminals.

Roller conveyors tend to use gravity for product movement. On a roller conveyor the load is supported over a series of rolling bars, turning on fixed bearings that are mounted between side rails at fixed intervals. Product moving on a roller conveyor requires three rollers under the load at all times. Product movement is controlled by gravity; therefore, heavy loads on roller conveyors can be dangerous, since they could accelerate beyond control. Slides in parks for children are often built in roller bar conveyor form, because the acceleration due to gravity can be a source of excitement [46].

A wide variety of other conveyor types exists, including bucket, chain, chute, pneumatic, screw, vibrating, and wheel conveyors. Although they are mainly used for material handling, conveyors also function throughout society as people movers. Ski chair lifts on mountains are another functional example [14].

METHODOLOGY

Since conveyors are critical to moving case loads within DCs, our work focuses on developing RFID tag testing procedures for conveyor mechanisms. In this section, we present a proposed system for testing RFID tag placement and read ratest for case loads on conveyors.

The reader was an Alien ALR-9780 Reader (Alien Technologies, Morgan Hill, Ca) (Figure 2). It is a Gen 2 reader, able to read and send data from Electronic Product Code (EPC) Gen 1 and Gen 2 Class 1 tags to a computer for analysis using a RS-232 computer interconnection cable. The ALR-9780 is a 4-port reader, capable of connecting to four ultra high frequency (UHF) antennae. During the data collection process, the software used was Alien Gateway V2.15.08. To determine the optimal tag location for each product, RFID Tag Locator software V01.00.04 from Cape Systems (South Plainfield, NJ) was used. The results of the optimal tag location testing are presented in the next section.

Four Alien ALR-9610-AC circularly polarized antennae were used because they are less sensitive to tag orientation, and the read distance required was not large enough to require linear antennae (Figure 3).

The tags were an EPC Class 1 Gen 1 ALL-9340-02 "Squiggle™ 2" and an EPC Class 1 Gen 2 ALL-9440 "Gen2 Squiggle™". Each tag measured 4″ × 1/2″. These two tags types were chosen because they offered a comparison between Gen 1 and Gen 2 tag capabilities. Specifications for both tags claim the ability to work well on most packaging products (corrugated board, plastic, and paper), while the Gen 2 tag is claimed to perform well when used with package systems involving metal and/or water (Figure 4).

The conveyor (Buschman Conveyors (Cincinnati, OH) is 10′ long and 31.5″ wide. Conveyor speed was controlled by a converted Weslo treadmill (Colorado Springs, CO). A skate-wheel conveyor was positioned at

Figure 2. *ALR-9780 Reader.*

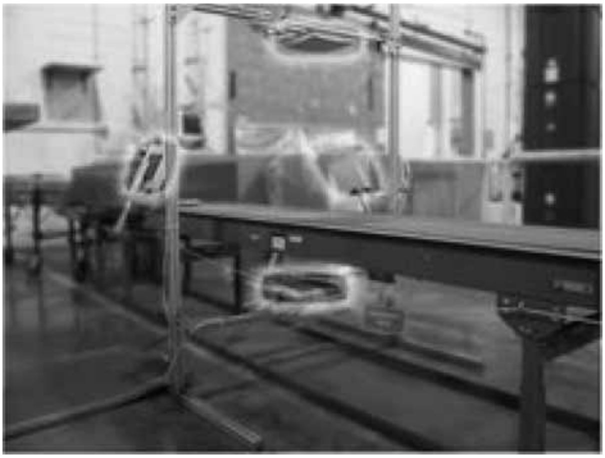


Figure 3. *ALR-9610-AC Antenna.*

the end of the Buschman conveyor to slow and stop the product. The speed of the conveyor was monitored by a Computak tachometer Model 8203 by Cole-Parmer Instrument Company (Vernon Hills, IL).

The antennae are placed on the left (1), right (3), top (2) (facing down towards the conveyor), and bottom (4) (facing up towards the conveyor) sides of the conveyor (Figure 5). The horizontal distance from the center of the conveyor belt to the center of the side antennae was 20.75″. The vertical distance from the top of the conveyor to the center of the side antennae was 8″. Both side antennae were angled 30 degrees down towards the conveyor. The vertical distance from the top of the conveyor belt to the top antenna was 30″, and to the bottom antennae was 12″.

(a) (b)

Figure 4. *(a) Back of Gen 1 Tag (top) and Gen 2 Tag (bottom). (b) Front of Gen 1 Tag (top) Gen 2 Tag (bottom).*

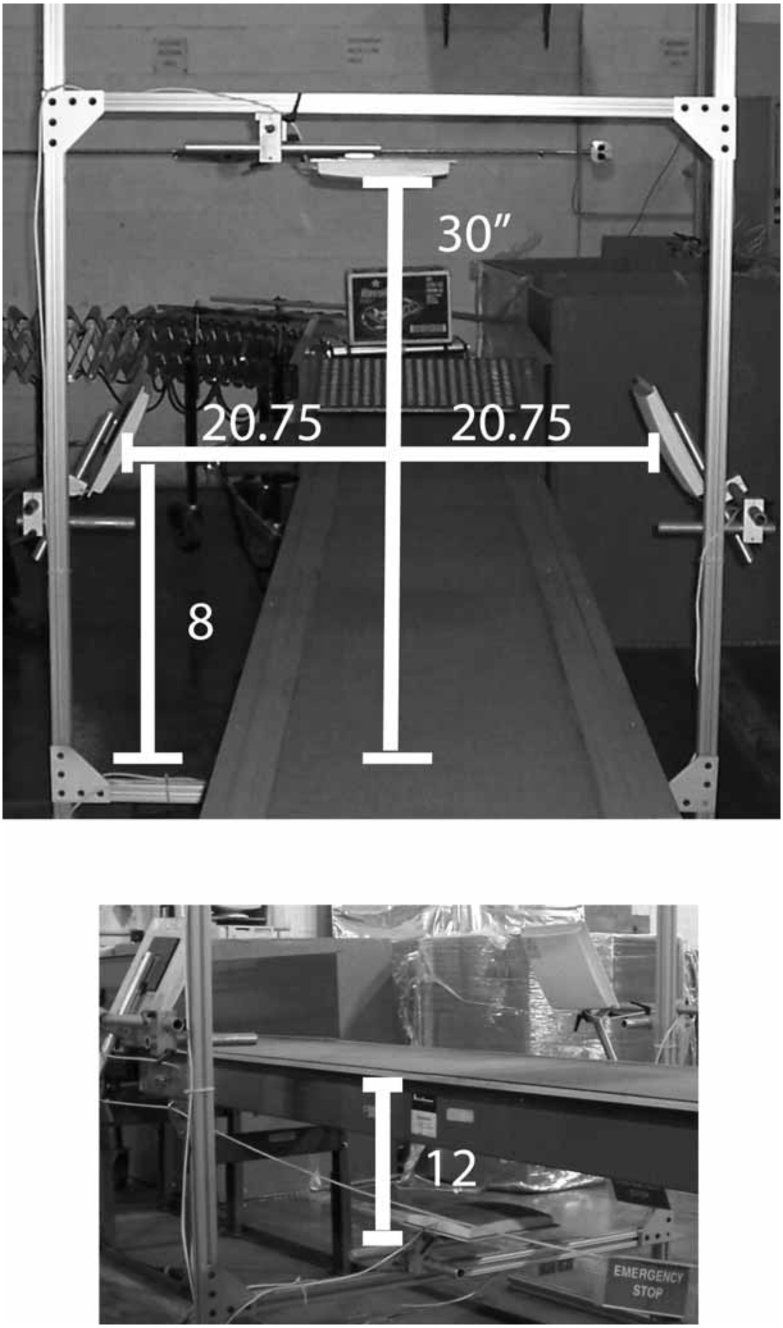
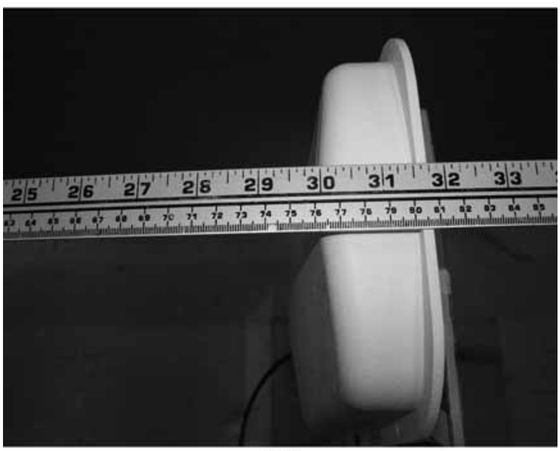


Figure 5. *Antennae Locations Surrounding Conveyor.*

Procedure for Determining Optimal Tag Location

Testing is conducted using one Alien ALR-9610-AC circularly polarized antenna mounted on a wooden stand 36″ from the center of the antenna to the floor. Each of the products tested is placed on top of a 30.5″ stand, composed of 3 empty corrugated boxes stacked on top of one another, and located at 90 degrees and 30″ away from the antenna (Figure 6). This corrugated stand provided adequate line of sight between the antenna and the tagged product, in addition to being a medium in which RF

(a)



(b)

Figure 6. *Case and Anntenna Set-up for Cape Systems RFID Tag Locator Software.*

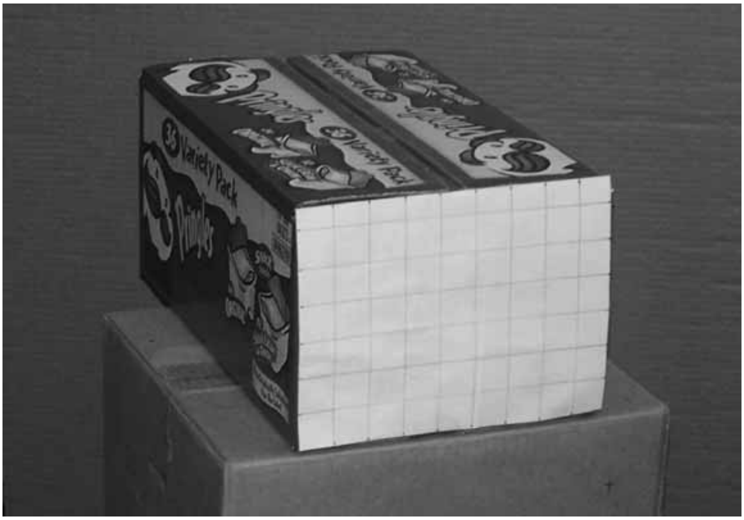


Figure 7. *Example Grid Placed on Front Face of Case.*

waves are neither absorbed nor reflected, thus ensuring the stand had no effect on the outcome of the test. With each product tested, the face of the case and the front of the antenna were kept 30″ apart, following the instructions for case testing provided in the Cape Systems user manual (version V01.00.04).

For each product, two sides of the case were selected to determine an optimal tag location: a front face of the case (representing the width of the case) and a side face of the case (representing the length of the case). Each face to be tested was equipped with a 1″ × 1″ 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 new trial run (Figure 7).

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, is selected. The software creates a 1″ × 1″ grid on each face of the case (Figure 8). The face representing the width of the case and the closest size tag (1″ × 4″) were selected from the on screen options. On the 3-dimensional on-screen image, an intersection was selected that allowed for 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.

The tag is placed on the package vertically, the antenna activated, and results are recorded at each grid intersection. When each intersection has been tested, the tag is moved to the length side of the case, and the test was repeated. After completion of both sides of the case, the tag is repositioned horizontally on the case, and both the width and length side of the case are tested again. Upon determining the optimal tag location, a pin was used to penetrate through the grid and mark the box. The grid was then removed from the package and the pin hole represented the place for which the center of the tag will be placed during conveyor testing.

Procedure for Testing RFID Tagged Case Loads on Conveyor

The product, package and case was tested in a warehouse (Figure 9). In addition, two other variables were tested: speed (600 and 300 feet per minute (fpm)) and tag type (a Generation 1 tag and a Generation 2 tag). Each test, which consists of 30 trials, begins with the activation of the RFID equipment through the Alien software. Next, the tagged case located outside of the antennae read field was placed on the moving conveyor belt operating at speed. The orientation of the case on the belt was such that the tag on the case is in the direct line of sight with one of the side antennae. The product travels down the conveyor, passed through

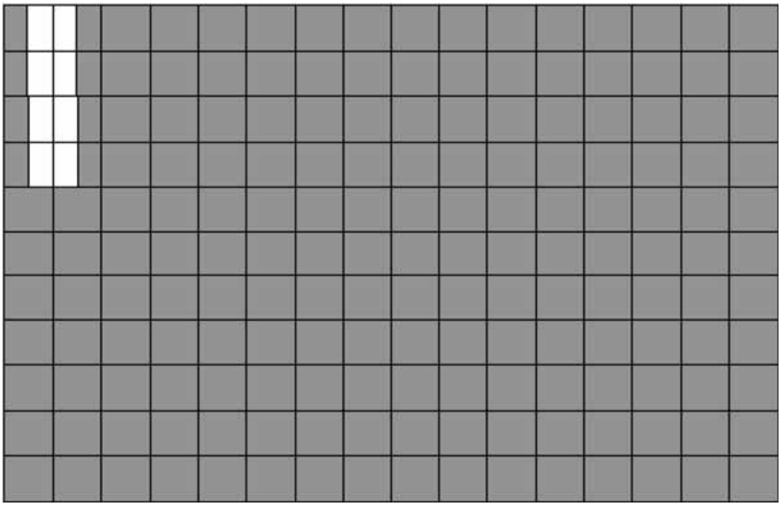


Figure 8. *Example Tag Location on Package Face.*

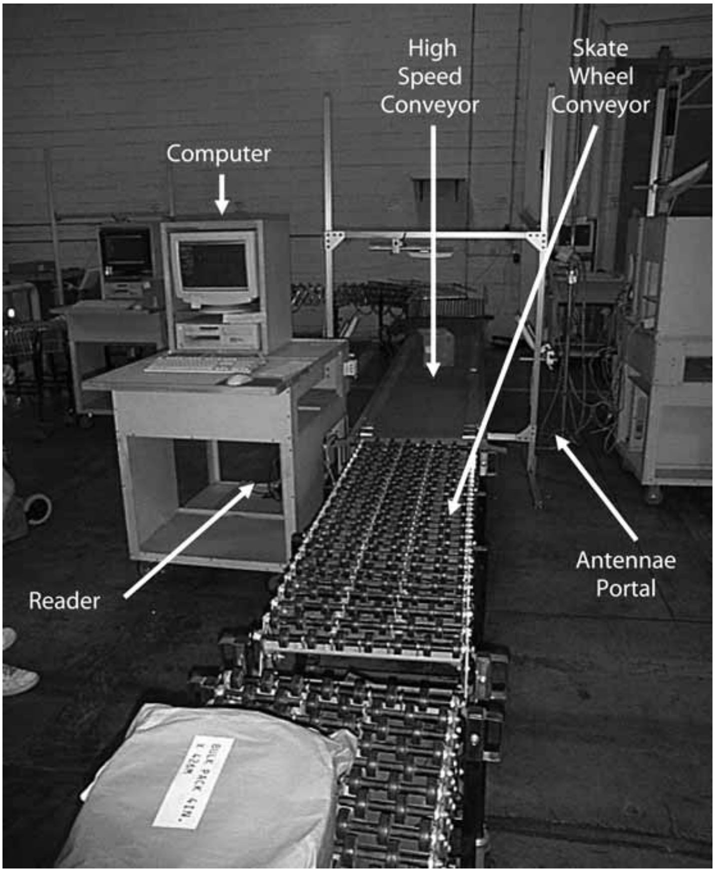


Figure 9. *Warehouse with Conveyor and RFID Set-up.*

the antenna portal read field, and eventually moved out of the read field when it was swept onto the skate wheel conveyor and brought to a halt. Each product undergoes 120 trials using two conveyor speeds and two tag types. Two types of results are recorded; whether the tag is detected or not, and the number of times the tag is detected. These results are stored in a Microsoft Excel file.

RESULTS

The Hotspot test determines whether a tag is in a good or bad location by measuring the level of attenuation at which a tag responds. The higher the attenuation value recorded when a tag responds, the lower the amount of power being delivered to the tag from the antenna. The range of power used by the software to detect the passive tag ranged from 15 dB to 0 dB, with 15 dB representing an optimal situation in which the antenna had to put out very little power to receive a signal back from the tag and 0 dB representing the tag not sending a response signal. As the tag is moved from intersection to intersection within the grid, attenuation values are recorded for each tag location. The value is then mapped to a certain color which appears on the screen at the intersection of interest (Figure 10). A tag attenuation response between 0–8 dB provides a color response ranging from bright red to bright white. A response between 8–15 dB provides a color response ranging from bright white moving to bright green. In general, a red response is a poor location to place a tag, a white response is an okay position to place a tag, and a green response is an excellent location to place a tag. The variance in color is due to a variety of interference possibilities due to packaging materials or product content.

Results for each of the seven products were recorded, testing two tag orientations on two adjoining faces of each case, a width and a length. From the data obtained, an optimal tag location and orientation was determined for each product. The results for the Hotspot test revealed similarities regarding each of the seven products. Although testing was performed with two tag orientations, the vertical tagging proved to be optimal for each product. Additionally, the width face, either end 5 or end 6 according to ASTM D 775, Standard Test Method for Drop Test for Loaded Boxes, of the case proved to be an equal or better tag location than length face of the case. To keep the testing consistent, the tag was placed on the width face of the case for each of the seven products.

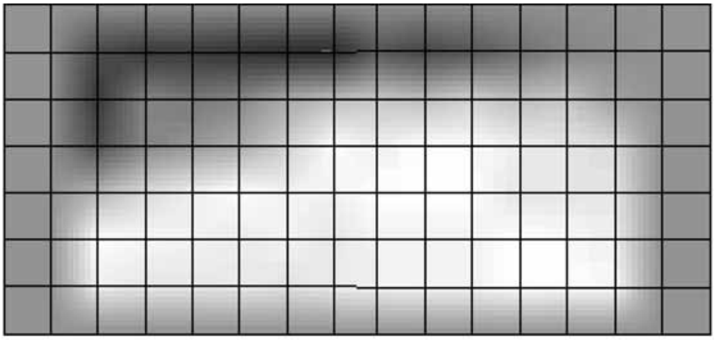


Figure 10. *Example RFID hotspot test outcome for one side of a case.*

Figure 11. *Tag Location on Ketchup Case.*

Product Effect Results from Hotspot Testing

For the case of ketchup the center of the tag was affixed on end 6 of the case, 8″ from uppermost left corner of the width face, and down 3″ from the top of the width face (Figure 11).

This location was determined to be optimal because it produced an attenuation level of 12 dB, which the software depicted as a bright green in that location (Figure 12).

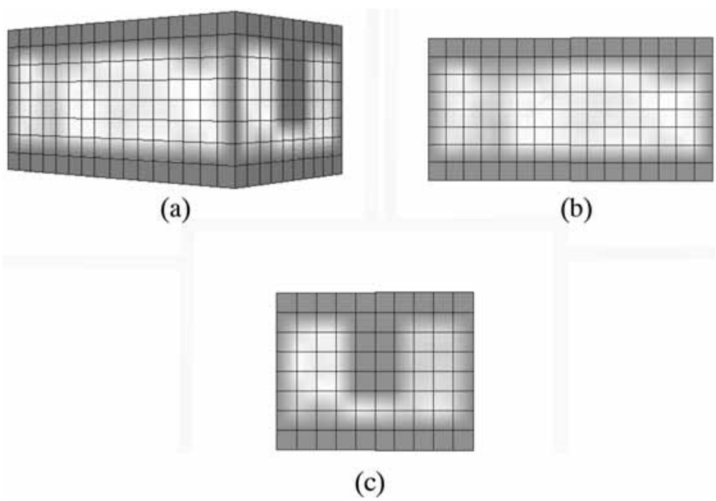


Figure 12. *Hotspot Test Output for Case of Ketchup, (a) Length and Width View of Case, (b) Length View of Case, (c) Width View of Case.*

Figure 13. *Tag Location on Motor Oil Case.*

For the case of motor oil the center of the tag was affixed on end 6 of the case, 1″ from uppermost left corner of the width face, and down 2″ from the top of the width face (Figure 13).

This location was determined to be optimal because it produced an attenuation level of 10 dB, which the software depicted as a very light green in that location (Figure 14).

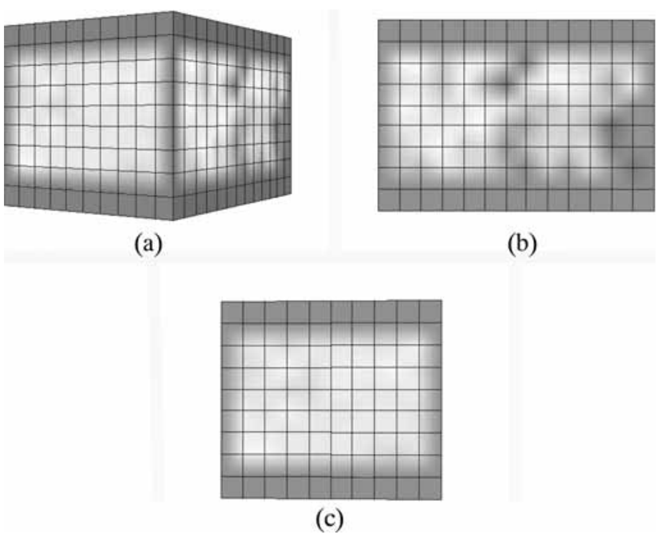


Figure 14. *Hotspot Test Output for Case of Motor Oil, (a) Length and Width View of Case, (b) Length View of Case, (c) Width View of Case.*

Figure 15. *Tag Location on Case of Chips in Plastic Tubs.*

Package Effect Results from Hotspot Testing

For the case of potato chips in plastic tubs the center of the tag was affixed on end 5 of the case, 4″ from uppermost left corner of the width face, and down 2″ from the top of the width face (Figure 15).

This location was determined to be optimal because it produced an attenuation level of 10 dB, which the software depicted as a very light green in that location (Figure 16).

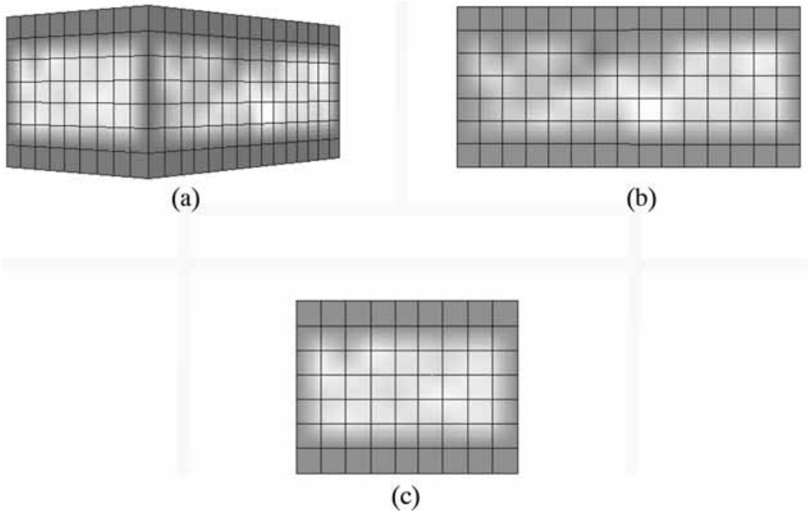


Figure 16. *Hotspot Test Output for Case of Potato Chips in Plastic Tubs, (a) Length and Width View of Case, (b) Length View of Case, (c) Width View of Case.*

Figure 17. *Tag Location on Case of Chips in MSWFC.*

For the case of potato chips in metalized spiral-wound fiberboard containers (MSWFC) the center of the tag was affixed on end 6 of the case, 4″ from uppermost left corner of the width face, and down 3″ from the top of the width face (Figure 17).

This location was determined to be optimal because it produced an attenuation level of 13 dB, which the software depicted as a bright green in that location (Figure 18).

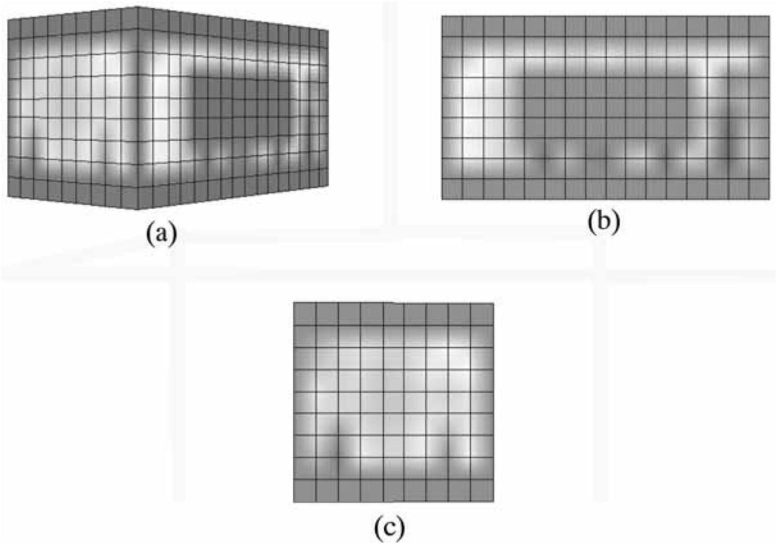


Figure 18. *Hotspot Test Output for Case of Potato Chips in MSWFC, (a) Length and Width View of Case, (b) Length View of Case, (c) Width View of Case.*

Figure 19. *Tag Location on Case of Cans.*

Package Shape Effect Results from Hotspot Testing

For the case of aluminum cans the center of the tag was affixed on end 6 of the case, 5″ from uppermost left corner of the width face, and down 2″ from the top of the width face (Figure 19).

This location was determined to be optimal because it produced an attenuation level of 4 dB, which the software depicted as a pinkish white in that location (Figure 20).

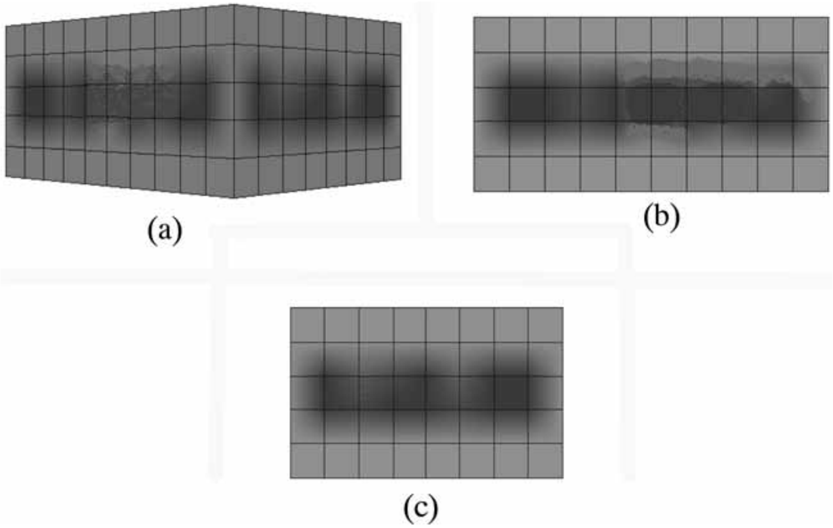


Figure 20. *Hotspot Test Output for Case of Cans, (a) Length and Width View of Case, (b) Length View of Case, (c) Width View of Case.*

Figure 21. *Tag Location for Tray of Bottles.*

For the tray of aluminum bottles the center of the tag was affixed on end 6 of the tray, 3″ from uppermost left corner of the width face, and down 6″ from the top of the width face (Figure 21).

This location was determined to be optimal because it produced an attenuation level of 8 dB, which the software depicted as a bright white in that location (Figure 22).

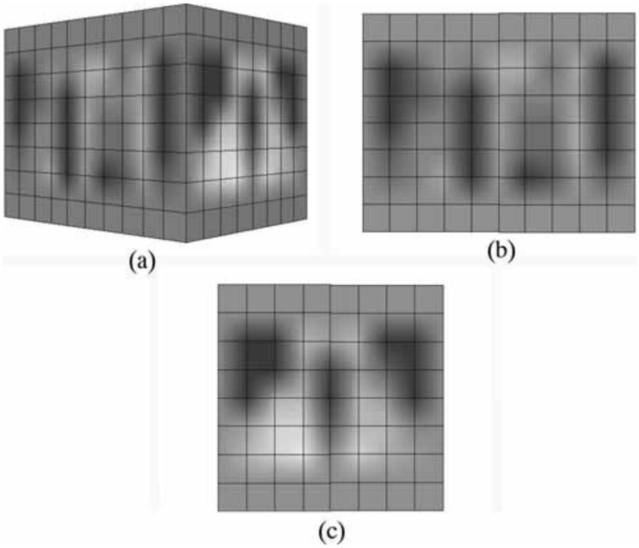


Figure 22. *Hotspot Test Output for Tray of Bottles, (a) Length and Width View of Case, (b) Length View of Case, (c) Width View of Case.*

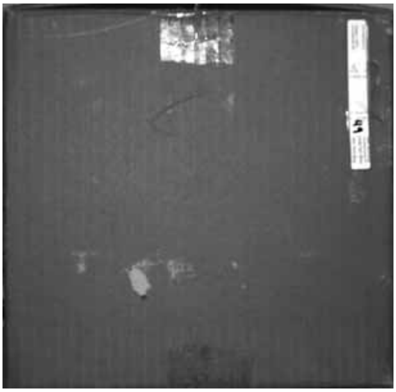


Figure 23. *Tag Location for Case of Tins.*

For the case of aluminum tins the center of the tag was affixed on end 6 of the case, 9″ from uppermost left corner of the width face, and down 2″ from the top of the width face (Figure 23).

At no point during the Hotspot test was there ever a dB level greater than 0 recorded, therefore the tag location was determined by using a location on the case that had been a traditional tag location in previous research testing, the upper right hand corner of the case (Figure 24).

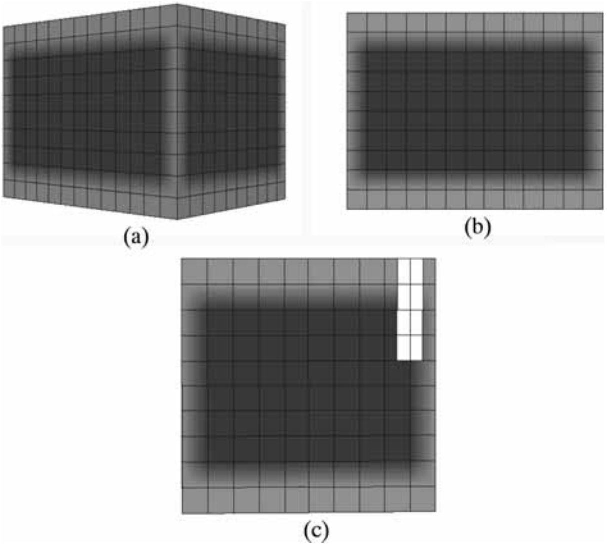


Figure 24. *Hotspot Test Output for Case of Tins, (a) Length and Width View of Case, (b) Length View of Case, (c) Width View of Case.*

CONCLUSIONS AND RECOMMENDATIONS

The testing methods described herein have been used for testing the influence of conveyor operation on RFID read rates. It is apparent that the variables that a number of variables (conveyor speed, product type, package type, and package shape) can be studied with this system and that both individual and combined effects can be determined with the appropriate statistical analysis.

With the knowledge that conveyor speeds can potentially have a drastic effect on RFID tag readability, it is crucial that suppliers meeting RFID mandates communicate with their retailers regarding their distribution center and conveyor speed operations. Armed with this information suppliers can guarantee their tagged product will be detected at retailer RFID checkpoints, ensuring payment for their product. With retailers having knowledge of the tagged product's location, they are less likely to incur a situation in which a product is out of stock, and through this, retailers are able to increase product sales.

Although the effects of package, product and type of tag on read rates have been relatively well documented, the effect of conveyor speed, and its potential interaction with these variables has not been researched in detail. The outcome of this, and our future research will provide RFID users, whether they are implementing the technology into their own supply chain or merely meeting the mandates of retailers, with valuable information to consider when working with RFID tagged product on conveyors.

REFERENCES

1. RFIDJournal, "Glossary of Terms", 2006.
2. EPCglobal, "Frequently Asked Questions", http://www.epcglobalinc.org/about/faqs.html, 2003, (1/4/2005).
3. MIT, "Technology Guide", http://archive.epcglobalinc.org/new_media/brochures/Technology_Guide.pdf, 2002, (12/12/2004).
4. EPCglobal, "EPCglobal Ratifies Royalty-Free UHF Generation 2 Standard", http://www.epcglobalinc.org/news/pr_detail_epcinc.cfm?release_id=183, 2005, (1/4/2005).
5. Collins, J., "What's Next for Gen 2?" http://216.121.131.129/article/articleprint/1301/-1/1/, 2004 A, (1/5/2005).
6. Matrics, "Understanding The Wal-Mart Initiative", http://rfid.bluestarinc.com/resources/Understanding_The_Wal-Mart_Initiative.pdf#search='Matrics%2C%20Understanding%20WalMart%20Initiative', 2004, (4/1/06).
7. SmartCode, http://smartcodecorp.com/newsroom/16-12-04.asp, 2004, (1/5/2005).
8. Ferguson, R.B., *New Wave for RFID; EPC's UHF Gen 2 works in dense reader envioronments., in eWeek.* 2005. p. 30.

9. Diorio, C., “Gen 2ùThe Tough Questions”, http://www.rfidjournal.com/article/articleview/1783/1/82/, 2005, (6/9/2006).
10. Collins, J., “Hiccups Expected for Gen 2”, http://216.121.131.129/article/articleprint/1289/-1/1/, 2004 B, (1/4/2005).
11. BusinessWire, “Intermec Applauds Ratification of EPCglobal UHF Generation 2 Air Interface Protocol”, http://tmcnet.com/usubmit/2004/Dec/1102596.htm, 2004, (1/4/2005).
12. Kleist, R., *RFID Labeling.* 1 ed. 2004, Irvine: Printronix. 211.
13. SymbolTech, *Class 0 Tag Information*, J. Falls, Editor. 2006.
14. AlienTechnology, “Alien Squiggle Family of EPC RFID Tags”, http://www.alientechnology.com/products/documents/alien_squiggle_family.pdf, 2006, (06/08/06).
15. RFidGazette, “"RFID regulations by FCC”, http://www.rfidgazette.org/2005/12/rfid_regulation.html, 2005, (5/22/06).
16. Quirk Jr., R., “Don’t get Behind the Regulatory Eight Ball”, http://www.rfidjournal.com/article/articleview/1484/1/133/, 2005, (5/22/06).
17. Wikipedia, “Wal-Mart”, http://en.wikipedia.org/wiki/Wal-Mart, 2006, (2/18/06).
18. IDTechEx, “RFID progress at Wal-Mart”, http://www.idtechex.com/products/en/articles/00000161.asp, 2005, (3/31/06).
19. Roberti, M., “Wal-Mart Begins RFID Rollout”, http://www.rfidjournal.com/article/articleview/926/1/1, 2004, (3/25/2006).
20. Johnson, J., “What RFID did for Wal-Mart”, http://www.dcvelocity.com/articles/20060101/rfidwatch.cfm, 1/7/06, (2/20/06).
21. O’Connor, M., “Wal-Mart Specifies Gen 1 Sunset, Forklift Pilot”, http://www.rfidjournal.com/article/articleview/2271/1/1/, 2006, (4/15/06).
22. Crawforth, T., *The Effect Of Antennae Configuration, Product and Tag Type on Readability of Passive UHF RFID Transponders*, in *The School of Packaging.* 2005, Michigan State University: East Lansing. p. 60.
23. Intermec, “Nut grower Paramount Farms speeds load processing time by 60 percent with Intermec RFID”, http://yahoo.knowledgestorm.com/shared/write/collateral/CST/12482_17163_61327_ParamountFarms_cs_web.pdf, 2004, (1/20/2005).
24. Williams, D., “The Strategic Implications of Wal-Mart’s Mandate”, http://www.directionsmag.com/article.php?article_id=629&trv=1, 2004, (3/18/2006).
25. Defense, D.o., *United States Department of Defense Suppliers’ Passive RFID Information Guide (Version 8.0).* 2005. p. 27.
26. MSNBC, “Thompson resigns with grim warning”, http://www.msnbc.msn.com/id/6644980, 2004, (4/4/06).
27. DCVelocity, “FDA turns its gaze on the food chain”, http://www.dcvelocity.com/articles/jan2005/news.cfm, 2005, (1/24/2005).
28. Wessel, R., “Orion Pharma Tests Item-Level Tagging”, http://www.rfidjournal.com/article/articleview/2179/1/1/, 2006, (3/19/2006).
29. Wasserman, E., “Purdue Pharma to Run Pedigree Pilot”, http://www.rfidjournal.com/article/articleview/1626/1/1, 2005, (3/19/2006).
30. O’Connor, M., “Pfizer Using RFID to Fight Fake Viagra”, http://www.rfidjournal.com/article/articleview/2075/1/1/, 2006, (3/19/2006).
31. Roberti, M., “RFID in Europe: A Special Case”, http://www.rfidjournal.com/article/articleview/1688/1/2/, 2005, (05/05/2006).
32. Collins, J., “Tesco CTO Describes Europe’s Hurdles”, http://www.rfidjournal.com/article/articleview/1502/1/20/, 2005, (4/23/06).
33. Collins, J., “Tesco Revises RFID Plans”, http://www.rfidjournal.com/article/articleview/2243/1/9/, 2006, (4/23/06).
34. Collins, J., “Marks and Spencer to Extend Trial to 53 Stores”, http://www.rfidjournal.com/article/articleview/1412/1/20/, 2005, (04/24/06).
35. Collins, J., “Metro Group Reaps Gains From RFID”, http://www.rfidjournal.com/article/articleview/1355/1/20/, 2005, (5/1/2006).

36. Roberti, M., “What Metro Knows About RFID”, http://www.rfidjournal.com/article/articleview/2200/1/2/, 2006, (5/1/2006).
37. O’Connor, M., “NEC to Sell Gen 2 Readers in Japan”, http://www.rfidjournal.com/article/articleview/2287/1/1/, 2006, (5/1/2006).
38. Konomi, S.i., “RFID in Japan: RFID Jeans in Future Department Store”, http://ubiks.net/local/blog/jmt/archives3/004744.html, 2006, (5/10/2006).
39. EPCglobal, “EPCglobal Korea Provides Support to the Flourishing RFID Market”, http://www.epcglobalinc.org/thesource/2005_04/html/member_showcase.html, 2005.
40. O’Connor, M., “Sun to Build Korean RFID Test Center”, http://www.rfidjournal.com/article/articleview/1473/1/26/, 2005, (05/10/06).
41. RFIDjournal, “RFID News Roundup- Singapore Expands RFID UHF Spectrum”, http://www.rfidjournal.com/article/articleview/2241/2/1/, 2006.
42. ChinaRFIDNews, “RFID Standards Battle in China”, http://www.chinarfidnews.com/index.php/2006/04/17/chinese-rfid-developing-with-government-guidance/, 2006, (5/10/2006).
43. ChinaRFIDNews, “Chinese RFID: Developing With Government Guidance”, http://www.chinarfidnews.com/index.php/2006/04/17/chinese-rfid-developing-with-government-guidance/, 2006, (5/10/2006).
44. ChinaRFIDNews, “China Retailer Pilots RFID Program”, http://www.chinarfidnews.com/index.php/2006/04/28/chinese-retailer-pilots-rfid-program/, 2006, (5/10/2006).
45. OnlineDictionary, “Conveyor”, http://dictionary.reference.com/search?q=Conveyor, 2006, (3/23/06).
46. Apple, J., *Material Handling Systems Design*. 1972, John Wiley & Sons: New York. p. 656.

Listeria Monocytogenes Attachment and Biofilm Formation on Aluminum Packaging Surfaces

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ABSTRACT: The impact of topographical features of packaging aluminum surface on *Listeria monocytogenes* adhesion and early stages of biofilm formation has been studied. Observations made by both fluorescence and scanning probe microscopy illustrate that, in the developmental process of the biofilm a number of stages are involved whereby the cells attain different spatial arrangements determined by the surface topography. Based on the morphological analysis of bacteria adhesion process, we were able to distinguish between several types of surface constraints by their lengthscales and an impact on the foodborne pathogens' colonization behavior. Proposed theoretical model enables to estimate the critical size of a surface confine that does not impose limitations on nutrient access to the bacteria. The data obtained allow better understanding of the mechanisms of surface colonization by foodborne pathogens and evaluating the bioavailability of engineered metal surfaces.

INTRODUCTION

CONTAMINATION by microorganisms is the major cause of foodborne illnesses with significant economic loss. There are more than 30 pathogenic bacteria commonly associated with foodborne illnesses that cause microbial spoilage of foods. These pathogenic microorganisms tend to colonize surfaces (Wong, 1998) of processing equipment and packages, forming biofilms. Aluminum is the one of the most used materials for packaging applications in food industry. Packaging is an indispensable element in the food manufacturing process that often considered a critical control point in HACCP plan, since improperly treated packaging materials can themselves be a source of contamination. Accidental contamination may occur at any step in food distribution chain between foodstuff processing and its consuming.

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All "real-life" surfaces have substantial non-uniformity, with the surface irregularities (patterns) size ranging from nanometers to hundreds of microns. Although a number of studies have investigated the influence of the surface topography on biofilm formation by various microorganisms, including foodborne pathogens (Silverstein and Donatucci, 2003; Edwards and Rutenberg, 2001; Bower and Daeschel, 1999; Scheuerman *et al.*, 1998; Weincek and Fletcher, 1997), most published results are devoted to the biofilm development in flow-through systems. It is difficult to separate the effects of surface patterns and those of the liquid flow on bacteria adhesion in such systems.

An ability to adhere to a surface provides an important survival mechanism for microorganisms (Bower *et al.*, 1996). The process of microorganism's attachment to the material surface is very complex, and the nature of both the microbial cell surface and the supporting substrate is important (Blake *et al.*, 1988). For example, an electropolished stainless steel substratum showed significantly lower bacterial cells adhesion rate and delay in biofilm formation, compared with the sandblasted one (Arnold and Bailey, 2000). Planktonic microbial cells are delivered by diffusion and motility from a bulk medium to the surface, where a fraction of those cells adheres to the surface. The dynamics of bacterial adhesion is a unique characteristic of the specific microorganism; there may even be differences among the phenotypes and strains of the same bacterium (Kalmokoff *et al.*, 2001).

Bacterial colonization of surfaces is influenced by two factors: first, well-developed surface has higher adsorption capacity, and therefore the preconditioning organic film necessary for bacteria attachment is more likely to be formed on such surface. On the other hand, surface topography influences bacterial attachment and proliferation, limiting the directions of colony growth, and nutrient access.

In this work we attempt to investigate the effect of surface morphology of the metal packaging surface on bacterial attachment and biofilm development processes. Batch-type non-flow environment has been used to examine the process of surface colonization. The authors suggest that this type of the experimental setup better represents natural environment (as it exists on the packaging surface) for foodborne pathogens growth than the flow-through systems. In this case, biofilm initiation in the studied system is driven by the physiological responses of bacteria, and not by the flow regime. Furthermore, bacteria are spreading over the surface by their motility, not affected by the convection or shear stress forces that inevitably are present in flow-through systems.

MATERIALS AND METHODS

Preparation of Aluminum Samples

Aluminum coupons made from food-grade aluminum foil (alloy 1100, McMaster, Inc.) of 12.8 mm in diameter were cut out of an aluminum foil, washed in ethanol, then grinded with an ultrafine-grade Sandblast sandpaper (50, 15, 6, 1 μm) and BAS (BioAnalytical Systems, Inc.) electrode polishing kit, according to the standard procedure. All coupons were rinsed with distilled water after polishing, then ultrasonically treated for 10 minutes in acetone (FS30 sonicator, Fisher Scientific) and annealed by heating in an oven at 150°C for three hours.

Model Microorganism

Listeria monocytogenes is a widespread and virulent foodborne pathogen that can adapt to, survive in and multiply in an amazingly wide range of extreme environments. *L. monocytogenes* strain 10403 (D. Portnoy, University of California, Berkeley) has been cultured in BHI broth. The culture was incubated at 30°C for 18 hours to obtain cell concentration of 10^9 cfu/mL, the resulting concentration was verified by measuring optical density of the culture). Serial dilutions in BHI broth were then made to obtain six final cell concentrations ranging from 10^3 to 10^8 cfu/mL. These were used for the cell adhesion study; for all other experiments the concentration of 10^8 cfu/mL has been used. At least 3 replicate experiments were conducted for each measurement. The cells used in different experiments were always subcultured from the same, "original" culture.

Cell Adhesion and Biofilm Formation Assay

For adhesion experiments, 4.5 mL of BHI broth and 0.5 mL of bacterial culture were transferred into a 24-well plate. Aluminum coupons were immersed into the bacteria-inoculated medium and removed one at a time at various time intervals (ranged from 30 s to 2000 s) for further cell enumeration and microscopy analysis.

Enumeration of Cells

After removing from the culture, each coupon has been washed with peptone water, and then transferred to 0.0055% Acridine Orange (AO) solution for 30 sec. After staining, coupons were viewed and photographed with an Olympus BH2-RFCA fluorescent microscope, at 400× magnification; cell counting was accomplished by the custom-designed MATLAB image analysis program (MathWorks, Inc.). To observe biofilm morphology and cell attachment, a scanning probe microscope Q Scope 250 was used.

RESULTS

Adhesion Kinetics of *L. monocytogenes*

Our adhesion study indicates that cells initially adhere to the substratum randomly, with substantial amount of space between the cells. Cell population density increases with time, leaving less space between the cells. As time progresses, cell groups develop branched structures, corresponding to the diffusion-limited kinetics of microbial growth. Cell colonies grow towards the regions of the highest nutrient concentration and the smallest number of cells. After two hours clustering of cells becomes more pronounced and a distinct polysaccharide film, which is an extracellular polymeric substance (EPS) associated with biofilm formation (Characklis, 1990; Christensen, 1989), is observed to surround each cluster (see Figure 1). At this stage microbial colonies also appear to be uniting with each other, thereby forming a microbial web structure all over the surface.

The authors suggest that cell adhesion is virtually not influenced by cell growth during the initial period of cell culture contact with the surface, when the time of contact does not exceed the characteristic time of bacteria reproduction. For *L. monocytogenes* the characteristic doubling time is ~20 min.

Digital analysis of obtained data allows us to determine the kinetics of bacterial adhesion. Figure 2 illustrates experimentally obtained adhesion kinetics of *L. monocytogenes* to the aluminum surface. The plot shows that available surface area is quickly filled with individual bacteria. For the first 1000 seconds their adhesion rate essentially follows the first order kinetics, i.e. the number of cells adhered to the surface per

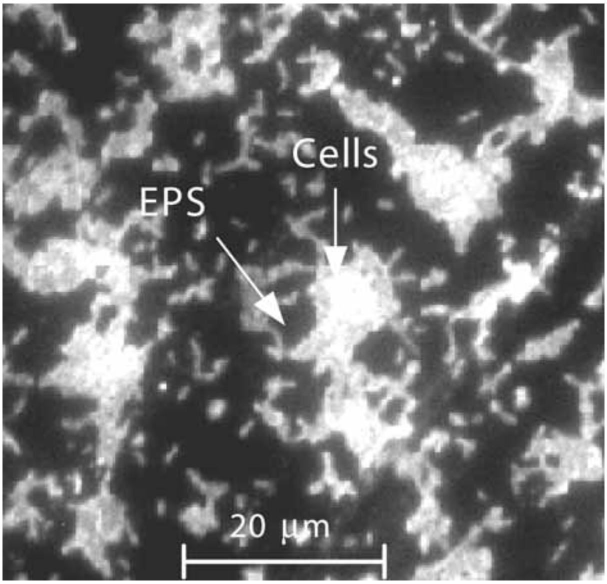


Figure 1. *Bacterial colony formation on an aluminum surface after 210 min of contact time.*

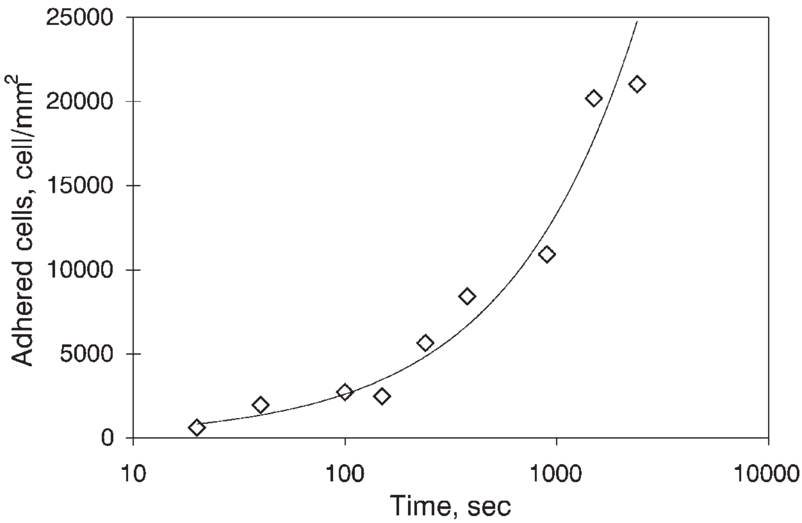


Figure 2. *Cell adhesion kinetics as a function of the contact time.*

time unit increases linearly. Adsorption takes place only at specific surface sites, and the saturation coverage corresponds to complete occupancy of these sites.

Dependence of Bacteria Attachment on the Bulk Population Density

The higher the concentration of planktonic cells in the solution, the more competition there exists, therefore more cells start to approach the surface presumably in search of more protective environment. The dependence of a number of bacteria attached to the surface on bacteria concentration in the inoculum size has been determined by enumeration of bacteria attached to the aluminum surface after 20 minutes of contact (see Figure 3). It was found that at concentrations less than 10^5 cfu/mL the number of attached cells is virtually independent on the bacterial concentration. However, for bacterial loads higher than 10^5 cfu/mL, a strong correlation between the two parameters was observed. In the latter case, the number of attached bacteria changes as a power of the inoculum concentration.

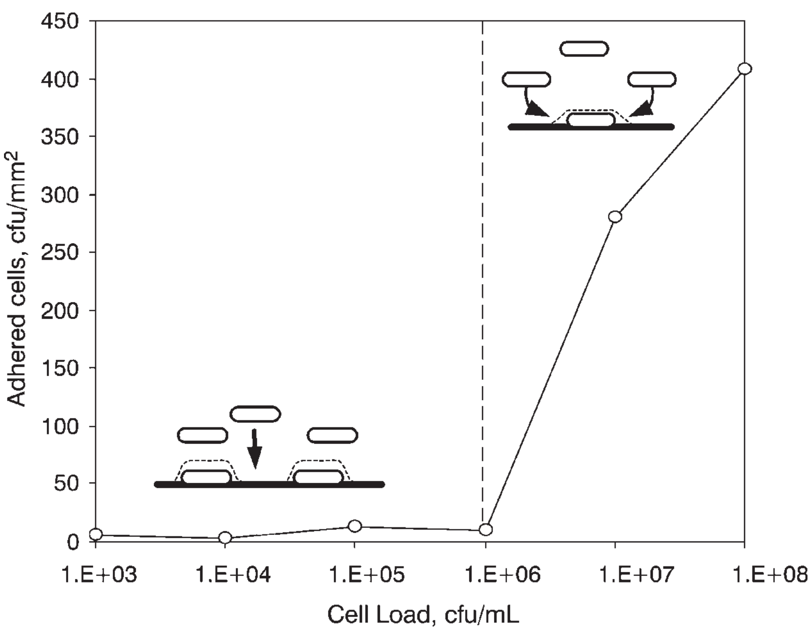


Figure 3. *Cell adhesion as a function of bacterial concentration (contact time t = 5 min).*

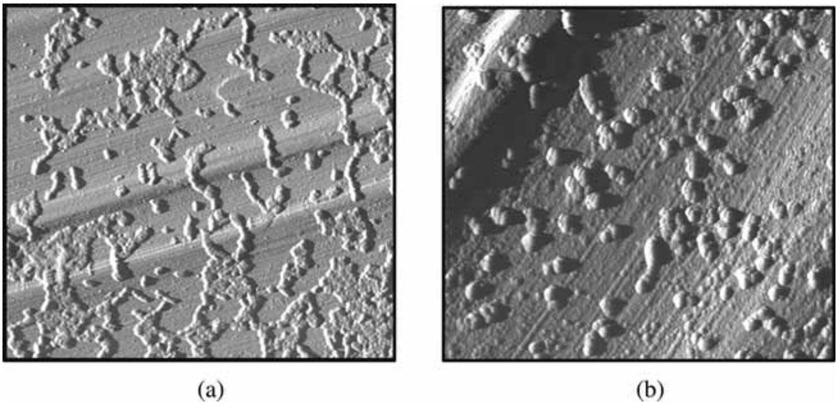


Figure 4. *Listeria biofilm formation on untreated aluminum surface (a), and on aluminum surface pre-treated with hydrogen peroxide (b). Scan size: 25×25 μm.*

Effect of Surface Properties on Bacterial Attachment

A surface pre-treated with a sanitizing agent is not favorable for biofilm formation; we used an aluminum surface pre-treated in hot hydrogen peroxide (50°C, 30 min) as the model adverse surface. As follows from our observations [see Figure 4(b)], bacteria cannot form continuous biofilm on this surface. Since bacterial attachment to such unfavorable surface is difficult, the cells start to grow on top of the previously adhered bacteria. Contrary to the non-treated metal surfaces [see Figure 4(a)], *L. monocytogenes* develop 3-D structured colonies on the pre-treated surface during the initial steps of biofilm formation. Therefore, treatment of a surface with a sanitizing agent not only decreases the amount of bacteria adhered to the surface, but also prevents continuous biofilm formation.

Effect of Surface Patterns on *L. Monocytogenes* Attachment and Growth

Surface patterns affect microorganisms' proliferation influencing the nutrient transport to the surface. The effects of size, shape and morphology of surface constraints on *Listeria* adhesion and growth were studied by direct observations of irreversibly adhered *L. monocytogenes* cells on the pre-patterned aluminum surfaces by fluorescence and scanning probe microscopy. Two geometric parameters can be used to characterize and distinguish between surface patterns: confine aspect ratio $K = H/W$, where W, H are the width and the depth of the confine respectively, and characteristic bacterium size a. Surface elements can be divided into three groups based on their geometry: plain surface elements ($H \leq a$, $W >> a$); wide constraints or low-profile obstacles ($W > 50a$, $K \leq 1$); and narrow confines ($W \sim 10 - 15a$, $K >> 1$). The majority of "real-life" surfaces can be represented by a combination of these morphological surface units.

We found that there is a critical size of the surface pattern, which triggers bacteria behavior on the surface; it can be estimated as $W \sim 15a$. Comparing cell adhesion in the narrow ($W < 10a$) and wide ($W > 20a$) grooves, it has been observed that *Listeria* cells preferentially adhere in the corners of narrow grooves, and to the center of wide ones.

A successful strategy of bacteria growth is to find the balance between the maximum security/protection for the existing cells and unrestricted nutrient access to them. Narrow confines with high aspect ratio are characterized by the diffusion-limited nutrient supply; hence bacteria settled in these confines will eventually experience starvation stress. Microorganisms were observed to attach in the corners of narrow grooves first [Figure 5(a)], maximizing the surface area available for subsequent adhesion, and developing more compact and protective EPS "umbrella". This highly adaptive surface colonization strategy is likely to exist only in motile microorganisms, which corresponds with the observations of Scheurman (Scheuerman et al., 1998) that only motile organisms can be found on the bottom of narrow grooves. Further biofilm development in a narrow confine consists of two steps: colony spreading over the confine base, and development of 3-D pillar structures in the middle of the groove [Figure 5(b)].

The mechanism of pillar development might be explained as follows. To survive in a deep surface confine bacteria either have to build a 2-D biofilm over its walls, or to develop 3-D structure. However, it is difficult for bacteria to adhere to vertical walls of the confine, since the number of cells settled on its base is not sufficient to produce enough EPS film to cover walls of the constraint. Therefore, newborn cells prefer to grow on top of the existing colony, erecting the next biofilm layer and developing 3-D structure. This way they are getting better access to the energy source.

On the contrary, wide and relatively shallow constraints allow unrestricted nutrient access to the whole surface. Cells adhere preferably in

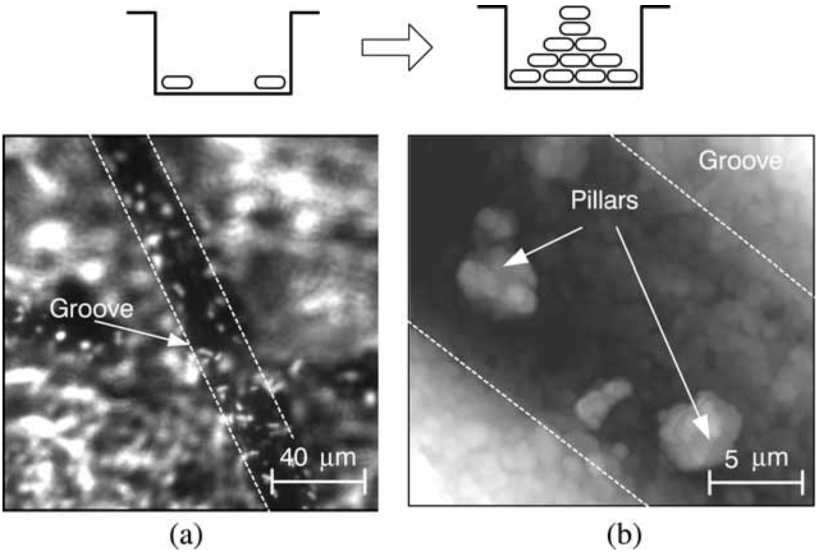


Figure 5. *Biofilm development in a narrow groove: (a) bacteria attach in the corners; (b) 3-D cell pillars grow in the constraint with a high aspect ratio.*

the center of these grooves, initiating colonies equidistant from the sidewalls [see Figure 6(a)]. As the cells grow and the population density increases, bacteria fill the bottom of the wide surface constraints, spreading towards the walls and eventually growing over the edges, merging with colonies outside the obstacle [Figure 6(b)].

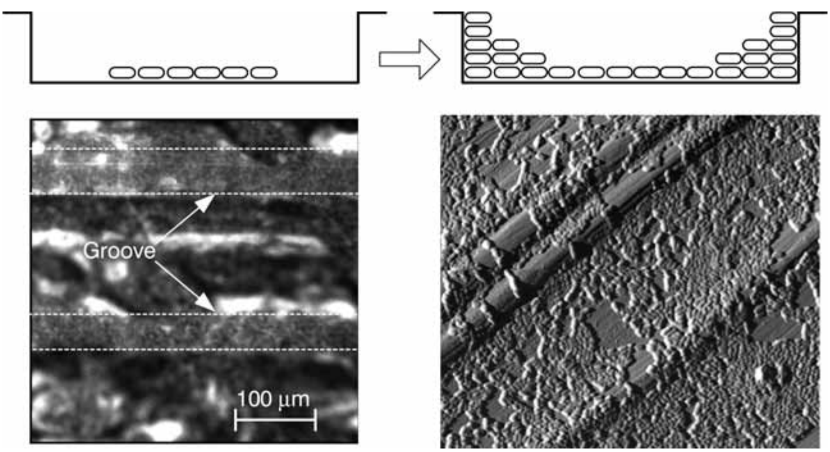


Figure 6. *Biofilm development in a wide groove: (a) cells attach to the center, and (b) spreading over the confine base.*

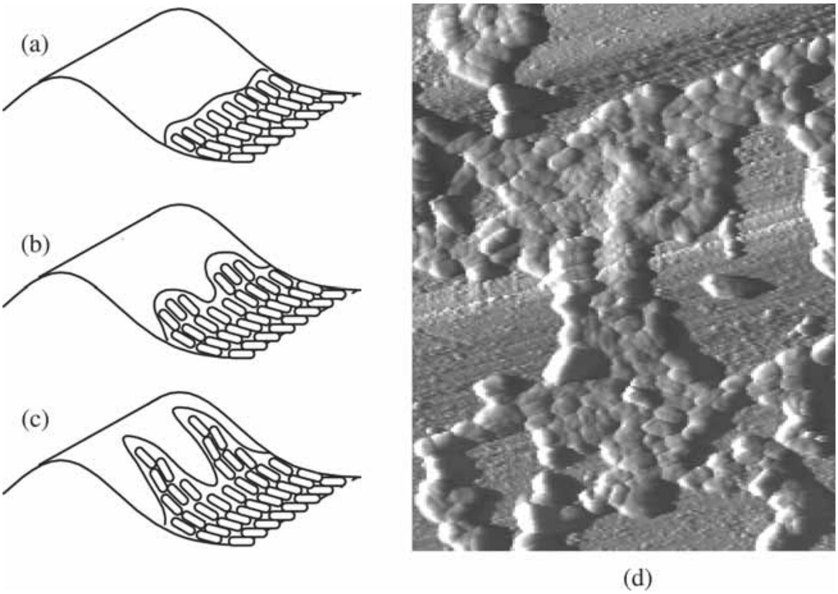


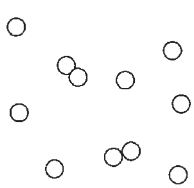
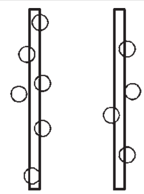
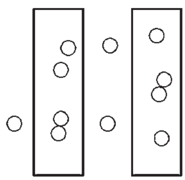
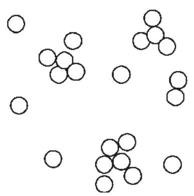
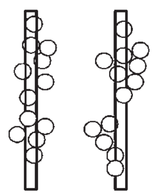
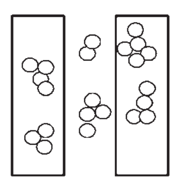
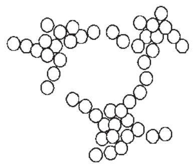
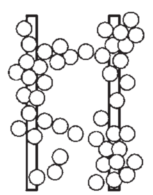
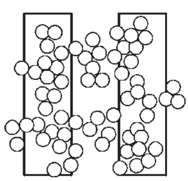
Figure 7. *Suggested mechanism of biofilm surmounting a shallow obstacle: (a) cell accumulation in the depression; (b) perturbation of a biofilm frontline; (c) development of finger-type cell structures; (d) experimentally observed "bridge".*

Based on our experimental data, we propose the following three-step mechanism of obstacle surmounting by proliferating bacteria, depicted in Figure 7. First, growing biofilm reaches the sidewalls with continuous smooth colony front line [Figure 7(a)]. The bacteria slow their proliferation there, building the precursor EPS film. Then the biofilm front line loses its stability due to the difference in the reproduction/adhesion rates between various cell groups, advancing some of them [Figure 7(b)]. Advanced groups have better nutrient access and continue to grow faster. Finally, instability of the biofilm front line transforms into the finger-type wave front [Figure 7(c)]; further finger elongation leads to the formation of bridges over the low-profile obstacle between the inside and outside colonies.

Bacterial Colonization of Rough Surfaces

From our experiments we have found that surface roughness influences the process of biofilm formation only at the initial stages but not at the stage of matured biofilm. As follows from our experimental data, the biofilm development processes are similar for all surface topographies, differing by the spatial organization of bacterial colonies during the early stages of biofilm formation. The bacterial spatial organizations and the steps of biofilm formation on patterned surfaces with different sizes of patterns are schematically represented in Table 1, where circles sketch bacterial cells and rectangles represent surface constraints. A smooth, plain surface is characterized by an initially homogeneous distribution of adhered cells and low clusters occurrence. Further colony proliferation leads to the development of a web-type hierarchical cell structure. The presence of micro-patterns on the surface impacts cell behavior and changes the patterns they form. Cell deposition and cluster formation dominantly occur in the constraint vicinity. During the biofilm growth stage cells cover the constraints spreading along them. The degrees of

Table 1. Biofilm formation on patterned surfaces.

	Surface		
Stage	**Smooth/Plain**	**Macro-patterned 6–15 μm grooves**	**Micro-patterned 50–100 μm grooves**
Random bacteria attachment			
Colony formation			
Mature biofilm			

freedom for a colony are limited by geometry and distribution of the constraints. The two colonies usually become connected by bridges between the two neighbor constraints [Figure 7(d)]. Wide constraints (or macro-patterned surfaces) allow uniform initial cell adhesion, similar to the plain surface. However, the freedom of colony spreading is limited by the constraints. Bacteria can build bridges and proliferate over the obstacles, but taking into account the mechanism explained earlier it should require longer time.

DISCUSSION

Bacterial attachment determines surface colonization during the initial contact of metal (aluminum) surface with bacterial culture. As the biofilm grows and spreads over the surface, planktonic and sessile (surface) cell populations begin competing for the nutrient supply. Bacteria on the surface are more stable and stress-resistant (Cloete, 2003; Mah and O'Toole, 2001), but their planktonic competitors probably have greater growth rate. It is difficult to predict the result of this competition, but it is clear that surface topography should play a major role in the survival strategies of sessile bacterial population.

As we believe, surface patterns impact microorganisms' proliferation and biofilm development often restricting free nutrient access to the growing bacterial population. The extent of these limitations can be examined in terms of nutrient diffusion transport. Let us consider a model surface (similar to our experimental surface) with a confine (see Figure 8) immersed into the solution with an initial nutrient concentration C_{n0}. Nutrient consumption at the confine bottom is performed by the bacterial population, and the metabolic products are diffusing out of the confine. This nutrient consumption results in an external nutrient diffusion flux to the confine from the bulk solution.

To examine possible limits of nutrient transport due to the surface topography we will consider two problems: external nutrient transport to the confine from the bulk medium, and internal diffusion transport of nutrients inside the confine. The analysis of the internal nutrient transport allows estimating a critical confine depth (H_{cr}) at which bacteria settled on the bottom start to experience nutrient deficiency. A critical size (W_{cr}) of confine opening (footprint) can be obtained from the mass balance between the bulk and the confine.

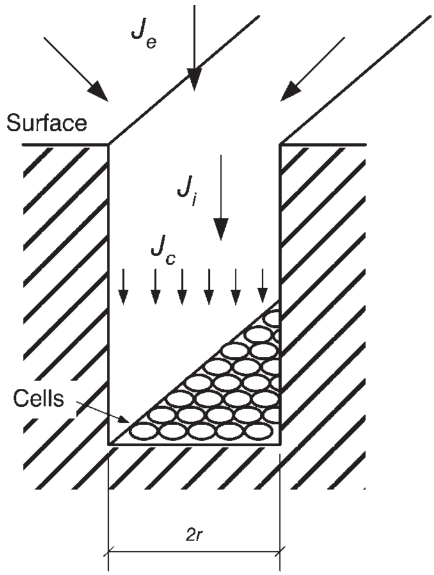


Figure 8. *Model representation of the surface confine.*

The governing diffusion equation for the internal transport problem can be written as:

$$J_i = D_n \frac{dC_n}{dx} \tag{1}$$

where C_n, D_n are the concentration and diffusivity of the nutrient.

Boundary conditions (BCs) for can be obtained by examining the physical limits of an idealized confine. Boundary condition at the confine bottom describes the balance between nutrient concentration at the confine entrance (mouth) and the equilibrium nutrient concentration in the bulk. The second BC reflects the fact that there is a flux of the nutrient at the confine bottom due to bacteria metabolic activity:

$$C_n = C_{n0}\big|_{x=0}$$
$$\frac{dC_n}{dx} = J_c\big|_{x=H} \tag{2}$$

The number of the microorganisms settled on the confine bottom is

$C_c = S/a^2$, where S is the footprint of the confine, and a is the average bacteria size. The total amount of nutrient required to support this population is $C_n \sim C_c\gamma$, where γ is the biomass yield coefficient (Bazin, 1982). Finally, nutrient flux due to its consumption by the bacteria can be determined from the amount of nutrient that is required to double cell biomass per division time:

$$J_c = \frac{\mu}{a^2\gamma} \tag{3}$$

where μ is the bacteria specific growth rate.

Linearizing as

$$D_n \frac{dC_n}{dx} \approx D_n \frac{C_n\big|_{x=0} - C_n\big|_{x=L}}{H}$$

where $C_n\big|_{x=0,H}$ are the nutrient concentration at the confine mouth and its bottom respectively, the maximum nutrient flux in the confine $(C_n\big|_{x=H} \to 0)$ can be estimated as following:

$$J_{i\,\max} = \frac{D_n C_{n0}}{H} \tag{4}$$

Combining equations and we can estimate the critical depth of the surface constraint, which allows yet unrestricted development of bacterial population:

$$H_{cr} = \frac{D_n C_{n0}}{\gamma\mu} = \frac{D_n C_{c\max}}{\mu} \tag{5}$$

where C_{cmax} is the maximum carrying capacity of a medium with given nutrient concentration (experimentally determined C_{cmax} value for BHI is approx. 10^9 cfu/mL). Performed calculations indicate that the critical depth of the surface constraint is ~10 μm, which corresponds well with our experimental observations.

For the external transport problem, diffusion-controlled nutrient flux towards the confine opening can be expressed as:

$$J_e = -D_n \frac{\partial C_n}{\partial r} \tag{6}$$

where r is the confine radius (half width, $W/2$), and the boundary conditions for are:

$$C_n\big|_{x=\infty} = C_{n0}$$

$$C_n\big|_{x=r} = 0$$

Solving over the hemispherical domain $r = [r_0, \infty)$:

$$J_e = -\frac{D_n C_{n0}}{r} - \frac{D_n C_{n0}}{\sqrt{\pi D t}} \tag{7}$$

Using nutrient mass balance as suggested earlier, the critical radius of the confine can be estimated equating expressions and:

$$r_{cr} = \frac{H_{cr}\sqrt{\pi D_n t}}{\sqrt{\pi D_n t} - H_{cr}} \xrightarrow[t=\infty]{} H_{cr} \tag{8}$$

Therefore, in all surface constraints with the critical width (W_{cr}) less than ~20 µm and the confine ratio greater than 1, growing bacterial cells will experience nutrient deficiency. One of possible responses of bacterial population to this starvation stress is to change its spatial organization, e.g. by building 3-D pillar structures as was observed in our experiments (see Figure 5).

CONCLUSION

The dynamics of *L. monocytogenes* biofilm formation on an aluminum packaging surface has been investigated in this work. The analysis of bacteria adhesion process allowed us to distinguish several types of surface constraints by their lengthscales and an impact onto the bacteria behavior during the initial cell attachment and biofilm formation process.

Surface topography was found to greatly affect the behavior and morphology of bacterial cells within colonies during the initial stages of biofilm development. In an effort to maximize their survival rate, bacteria form clusters of unique shapes, ranging from 2-D single layer colonies to 3-D pillar-like structures within grooves. Hence, it is possible to control initial colony shape by varying the characteristics of surface constraints. Coupled with surface topography, starvation may play an important role in the attachment of bacteria to the surface, which is directly supported by our observations of bacterial behavior in the surface confines with limited nutrient access.

In general, surface topography of the packaging material impacts microbial population in several ways: a well-developed (patterned) surface has higher adsorption capacity; at the same time the presence of highly inclined regions (constraints) makes cell attachment more difficult. As follows from the obtained data, initial biofilm formation on rough surfaces occurs in two dimensions. If nutrient access is limited by the configuration of surface constraints and/or diffusion transport, bacteria can develop 3-D structures. On the other hand, if the tested surface is plain and smooth, bacteria always spread over it as a single-layer (2-D) colony. Maturing of the biofilm and corresponding total surface coverage lead to the development of three-dimensional structures, which have been previously described in the literature (Wimpenny and Colasanti, 1997; Zaiat *et al.*, 1997; Wentland *et al.*, 1996) and also observed in our experiments.

REFERENCES

Arnold, J. and Bailey, G. (2000) Surface Finishes on Stainless Steel Reduce Bacterial Attachment and Early Biofilm Formation: Scanning Electron and Atomic Force Microscopy Study. *Poultry Science.* 79: 1839–1845.

Bazin, M. (1982) *Microbial population dynamics.* Boca Raton, FL: CRC Press.

Blake, R., Nortonb, W. and Howardb, G. (1988) Adherence and growth of a Bacillus species on an insoluble polyester polyurethane. *International Biodeterioration & Biodegradation.* 42: 63–73.

Bower, C.K. and Daeschel, M.A. (1999) Resistance responses of microorganisms in food environments. *International Journal of Food Microbiology.* 50: 33–44.

Bower, C.K., McGuire, J. and Daeschel, M.A. (1996) The adhesion and detachment of bacteria and spores on food-contact surfaces. *Trends in Food Science & Technology.* 7: 152–157.

Characklis, W. (1990) *Biofilms.* New York: John Wiley and Sons, Inc.

Christensen, B.E. (1989) The role of extracellular polysaccharides in biofilms. *Journal of Biotechnology.* 10: 181–202.

Cloete, T.E. (2003) Resistance mechanisms of bacteria to antimicrobial compounds. *International Biodeterioration & Biodegradation.* 51: 277–282.

Edwards, K.J. and Rutenberg, A.D. (2001) Microbial response to surface microtopography: the role of metabolism in localized mineral dissolution. *Chemical Geology.* 180: 19–32.

Kalmokoff, M.L., Austin, J.W., Wan, X.D., Sanders, G., Banerjee, S. and Farber, J.M. (2001) Adsorption, attachment and biofilm formation among isolates of Listeria monocytogenes using model conditions. *Journal of Applied Microbiology.* 91: 725–734.

Mah, T.-F.C. and O'Toole, G.A. (2001) Mechanisms of biofilm resistance to antimicrobial agents. *Trends in Microbiology.* 9: 34–39.

Scheuerman, T., Camper, A. and Hamilton, M. (1998) Effects of Substratum Topography on Bacterial Adhesion. *Journal of Colloid and Interface Science.* 208: 23–33.

Silverstein, A. and Donatucci, C.F. (2003) Bacterial biofilms and implantable prosthetic devices. *International Journal of Impotence Research.* 15: S150–S154.

Weincek, K.M. and Fletcher, M. (1997) Effects of substratum wettability and molecular topography on the initial adhesion of bacteria to chemically defined substrata. *Biofouling.* 11: 293–311.

Wentland, E., Stewart, P., Huang, C. and McFeters, G. (1996) Spatial variations in growth rate within Klebsiella pneumoniae colonies and biofilm. *Biotechnol. Progress.* 12: 316–321.

Wimpenny, J.W.T. and Colasanti, R. (1997) A unifying hypothesis for the structure of microbial biofilms based on cellular automaton models. *FEMS Microbiology Ecology.* 22: 1–16.

Wong, A.L. (1998) Biofilms in Food Processing Environments. *J Dairy Sci.* 81: 2765–2770.

Zaiat, M., Vieira, L. and Foresti, E. (1997) Intrinsic kinetic parameters of substrate utilization by immobilized anaerobic sludge. *Biotechnology & Bioengineering.* 53: 220–225.

Fragility Assessment using the Simultaneous Input and Response Monitoring (SIRM) Technique

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ABSTRACT: A protective package can be thought of as that device which provides a benign interface between a fragile product and a potentially harmful environment. The potentially harmful input from the environment can be described in terms of physical forces such as shock, vibration, compression or similar inputs. It is the job of the packaging engineer to determine what level of input is likely when the product is shipped from the point of manufacture to its ultimate destination, and to provide the protection necessary. This includes the assessment of basic product ruggedness and the judgments about the relative values of product ruggedness and packaging and distribution costs.

The Simultaneous Input and Response Monitoring (SIRM) technique is a combination of the Damage Boundary and Shock Response Specturm methods to design protective packaging. This approach has been used to design protective package systems for over the past 15 years. In general, it has resulted in a more economical package system design than would have been the case using only the traditional Damage Boundary approach.

INTRODUCTION—THE CONCEPT OF A PROTECTIVE PACKAGE

An optimum protective package system consists of a product of known (and reasonable) ruggedness combined with a package that together provide sufficient resistance to damage from those inputs likely to be encountered in the distribution environment without undue or unreasonable costs, as illustrated in Figure 1.

Since the product and package must work together as a system to achieve this, it is obvious that a tradeoff can be made between the amount

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of ruggedness built into the product and the amount of protection designed into the package. The exact tradeoffs between product ruggedness and package protection should be a matter of economic analysis between product designers and packaging and logistics personnel. In an ideal world this tradeoff would have its goal the minimum total delivered cost of the product. This concept is illustrated in Figure 2.

Perhaps the most severe physical input that a protective package must mitigate is the shock input associated with drops or other mishandling of a packaged product. In this case, the job of the package system is to transform the relatively high peak G short duration input typical of dropping a package onto a rigid surface into a long duration low G shock pulse which is below the fragility level of the product (Figure 3).

The package normally performs this transformation by means of a cushion system which deflects in response to the deceleration produced by the impact of the product on the cushion system. The cushion can deflect in compression, in shear, in torsion or any other spring mode, although generally the compressive mode is used in packaging design work. All cushion systems work in this same way, namely, they trade peak deceleration for duration.

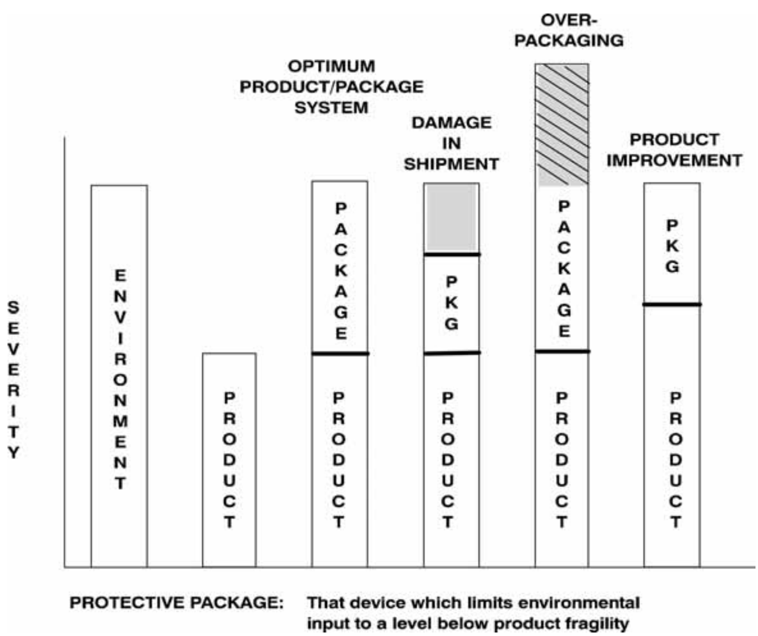


Figure 1. *Protective Package Model from [1].*

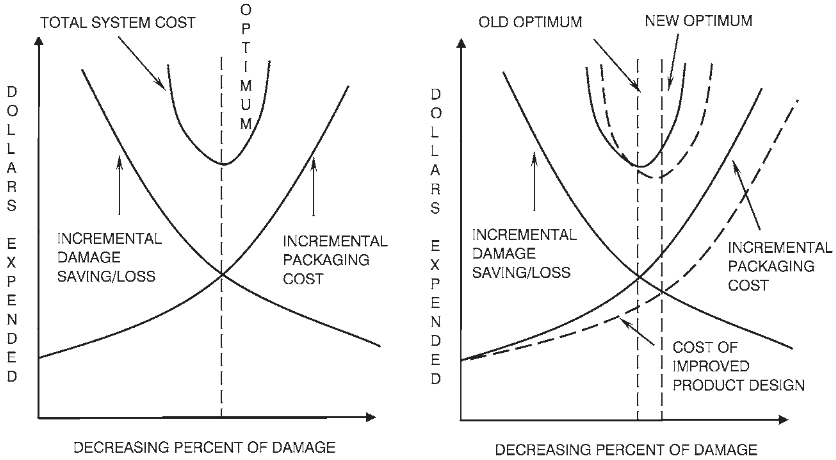


Figure 2. *Optimum Package Cost Model from [2].*

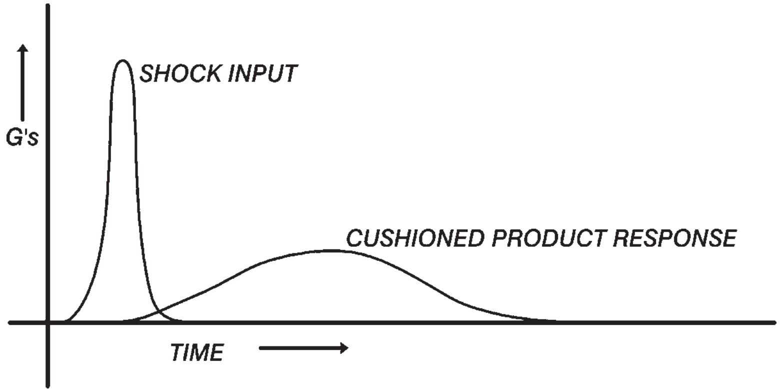


Figure 3. *Shock Trade-off in a Protective Package from [3].*

A BRIEF HISTORY OF PROTECTIVE PACKAGE DEVELOPMENT

Initially cushions were modeled as mechanical springs and were designed to protect against the maximum potential energy delivered by an impact. This energy was determined from knowing the mass of the product and the likely drop height. The stress-strain curve for a particular cushion would give the proper thickness and area of cushion necessary to reduce the energy at impact to below what was *believed* to be a safe value for the product. Cushion materials were assigned “cushion factors” to aid in this process.

During the 1950’s considerable attention was focused on the general area of shock testing as well as the equipment and techniques useful to describe the phenomenon of shock response. The Firestone Aerospace Division was active in designing and testing cushion systems (primarily rubber airbags) for military applications. One of the big drawbacks was the lack of reliable fragility information on the fragility of military hardware. Another was the inadequate sophistication of equipment used to determine shock fragility.

In the early 1960’s several companies, including Monterey Research Laboratories, were formed for the express purpose of building reliable shock test equipment geared to the military and aerospace testing markets. In the mid-1960’s Dr. James Goff, then at Michigan State University, suggested that this equipment and test approach could be used for commercial and industrial products and that significant amounts of money could be saved with efficient package designs using this approach.

To determine its feasibility and to simplify the procedure, Dr. Robert Newton at the Naval Postgraduate School in Monterey, California, was asked to suggest a test procedure which would utilize shock response spectrum analysis for commercial products with an eye towards improving the packaging procedure for these products. The result of his effort was the now famous Damage Boundary theory for product fragility testing [4,5].

Goff then ran a lengthy series of tests on a wide variety of consumer products during the late 1960’s. Equipment to run this testing was leased from Monterey Research Laboratories and the results were published in [6]. The results showed that the theory was indeed workable and did provide an accurate means of assessing product fragility.

The Damage Boundary Theory was simplified and put in an easy to follow step-by-step procedure and expanded to incorporate vibration analysis, compression, altitude (reduced pressure), temperature and humidity extremes, electrostatic discharge, etc. Standard test protocols were incorporated by the ASTM and other standard writing bodies to assist in the incorporation of the theory and lend credibility to the process. Laboratory equipment was developed and marketed to allow easy use of the theory and practice. These tools became standard fare for protective packaging engineers just as the computer age was exploding and the tech-hungry world demanded wide spread distribution of this notoriously fragile hardware.

Demand for packaging expertise resulted in the rapid increase in the number of university level programs geared to packaging. As of the early 2000's, there were about a dozen degreed programs in the United States and about half that number overseas. Professional organizations dedicated to the packaging function have flourished worldwide with aggregate membership in the neighborhood of 50,000. The globalization of the production and distribution of goods in the past decade further showed our enormous reliance on packaging expertise because the logistics of global distribution is impossible without efficient packaging. Similarly, our reliance on supply chain engineering to squeeze out the last penny of distribution costs is not possible without efficient and effective packaging.

OVERVIEW OF ENGINEERING FOR PRODUCT PROTECTION

As in all engineering disciplines, it is important to first define the problem, after which the engineer will set to work on searching out all possible solutions. The solutions are then ranked according to feasibility and each of them tested. The best solution is picked and the implementation is carried out in an orderly fashion.

Similarly, the packaging engineer designs a protective package system by first defining the environment through which the package must perform its job. The engineer then determines product sensitivity to physical inputs likely to cause damage. Tradeoffs between packaging costs and product improvements are examined at this point. Once the product has been finalized, the package system is designed after reviewing all potential materials and systems suitable for the application. The prototype package is tested according to a relevant specification and evaluated as either feasible for the job or requiring some modifications and retesting.

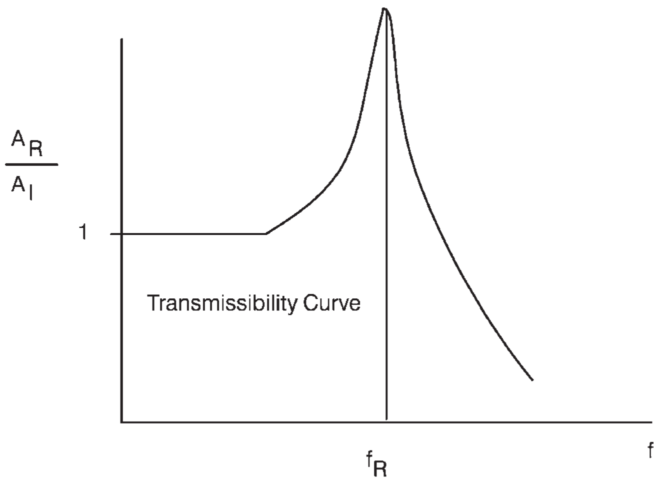
Product Fragility Analysis—Vibration

Determining vibration sensitivity of most products is a function of locating the resonant frequencies of critical components in each of the product's major axes. As a general rule, product damage during distribution will not occur due to non resonant inertia loading (vibration from distribution vehicles). The reason for this is that the acceleration levels of most vehicles are relatively low when compared to the critical acceleration sensitivity for most products. It is only when a component is excited by vibration at or near its resonant frequency that damage is likely to occur.

Product vibration sensitivity is determined by performing a Resonant Frequency Search Test [7] and is run by fixturing a product to the table of a suitable vibration test machine and subjecting it to a low level acceleration input over the frequency range of the distribution environment, typically 2 to 300 Hz. The acceleration response/input ratio is plotted as a function of frequency. This ratio reaches a maximum at the component resonant or natural frequency. The test usually involves monitoring sufficient components in each axis of the product to characterize its overall vibration sensitivity.

The result of this test is a series of Resonant Frequency Plots, such as that shown in Figure 4. This plot describes the natural frequency and the maximum amplification (transmissibility) of a component monitored during the test. At frequencies below the resonant frequency the response of the component is roughly equal to the input, that is the response/input ratio is nearly 1. At frequencies greater than the resonant frequency, the response acceleration is lower than the input. In this region, the component acts as its own isolator and results in a condition known as attenuation.

At and near the component resonant frequency, the response acceleration can be very much greater than the input, causing component fatigue and ultimate failure in a relatively short time. The purpose of vibration sensitivity testing is to identify those critical frequencies likely to cause damage to the product so that they can be filtered out by the protective package system.



A_R = Response accelerationof the product or component

A_I = Input acceleration

f = Input frequency

f_R = Resonant frequency of the product or component

Figure 4. *Resonant Frequency Plot.*

The importance of vibration testing cannot be overemphasized. Any product that is shipped is subjected to vibration because of the vehicle in which it is riding. The probability of this input is 100%. Not only is vibration input a certainty, but its damage effects can be severe. This is particularly true if a package system amplifies vibration input at the exact frequency where the product is most sensitive. This can result in a rapid buildup of acceleration levels, leading to product failure in a very short period of time. Thus it is possible for an improperly designed package system to actually destroy the product it is designed to protect. Without adequate vibration data on the product and the package, it is impossible to know that this situation exists prior to actually shipping the package.

The amplification ratio at resonance, sometimes referred to as “Q”, is a measure of the damping built into the spring/mass system (or critical component) under study. At one extreme a totally undamped system would have infinite response at its resonant frequency, see Figure 6. On the other extreme, a component with critical damping would exhibit hardly any amplification at all, even at its resonant frequency. Most real systems are somewhere between these two extremes. Figure 5 shows the effect of damping on transmissibility of various components.

Note that components with high transmissibilities are likely candidates for fatigue damage. The exact mechanism of this damage will vary from component to component. However, the end result is always the same, namely, product failure.

Either sinusoidal or random vibration can be used to determine product resonance. In theory, all spring-mass systems respond at their natural frequency and therefore the type or level of excitation is not significant. As a practical matter, random vibration is widely used during this type of analysis because of its ability to excite all residences simultaneously. Both the constructive and destructive interferences of spring-mass systems within a given product are accounted for during the actual test. In addition, random vibration is a much quicker test to run resulting in greater laboratory efficiency.

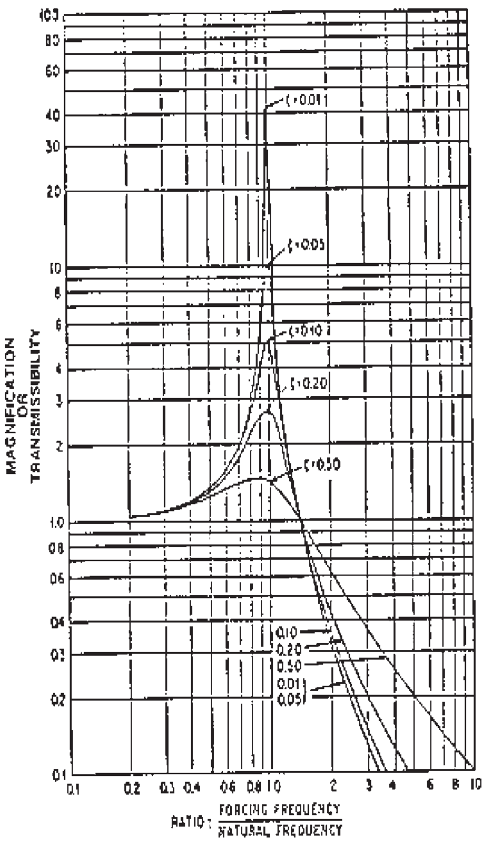
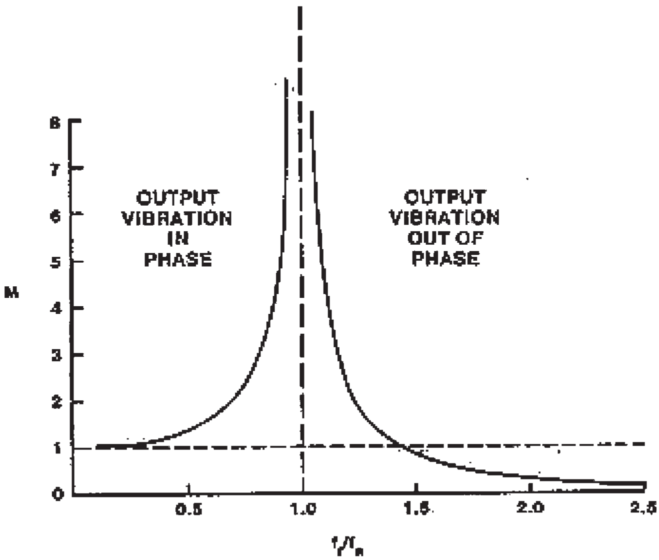


Figure 5. *Transmissibility and System Damping.*



The Absolute Value of the Magnification
Factor Shown as a Function of the Frequency Ratio

Figure 6. *Transmissibility of an Undamped System.*

Product Fragility Testing—Shock

The concept of product fragility is misunderstood by many people. Product fragility is just another product characteristic similar to size, weight, shape and color. These characteristics are determined by measurements and in a similar way, product fragility can be "measured" with shock inputs. This measurement takes the form of a Damage Boundary Curve as described in [8].

The Damage Boundary is the principal tool used to determine the shock sensitivity of a product. The Damage Boundary Plot, shown in Figure 7, defines an area bounded by Peak Acceleration on the vertical axis and Velocity Change (related to pulse energy content) on the horizontal axis. Any shock pulse experienced by the product which can be plotted inside this boundary will cause damage to the product whether or not it is packaged.

Implicit in the concept of a Damage Boundary test is the fact that "damage" to the product has been defined a priori. However, damage may show up in ways and places that are totally unsuspected by the engineer prior to the test. At one extreme, damage may be catastrophic failure, yet, there are many less severe damage modes which can make a product unacceptable to the customer. In some cases damage can be determined by looking at the product. In others, it involves running sophisticated functional checks. Once the determination of damage has been made, the definition must remain constant throughout the test and must be consistent with what is deemed unacceptable to the customer.

The Damage Boundary Test is initiated by determining the critical velocity change sensitivity of the product. To accomplish this, the product is fixtured securely to the table of a shock test machine and subjected to a short duration (2 msec) half sine shock pulse. It is crucial that the duration of the shock pulse be very short in relation to the natural period of critical components within the product. This so-called “velocity shock” input is stepped with increasing velocity change levels until damage occurs. The last non-failure input defines the critical velocity change for the product in that orientation. All three orientations are tested for products that can be hand-carried.

After the velocity change sensitivity for the product has been deter-

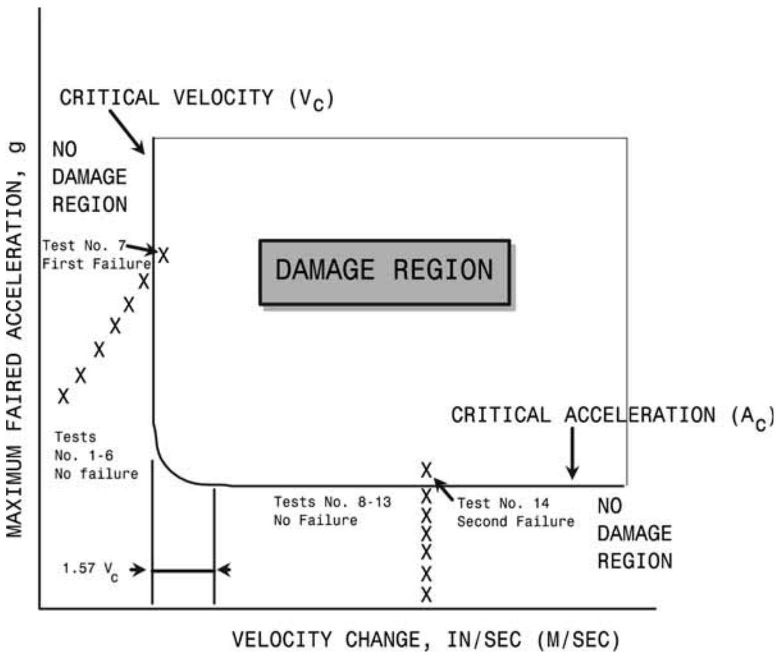


Figure 7. *Damage Boundary Plot from [8].*

mined, it is necessary to determine the product's acceleration sensitivity. This is accomplished by fastening a fresh product to the table of a shock test machine and subjecting it to a low acceleration level pulse with a velocity change double that which produced damage in the Critical Velocity Change test. Alternately, the velocity change can be that anticipated from the design drop height determined from environmental studies. Note that a trapezoidal shock pulse is specified for this test because of its broad spectral content.

The product is fastened to the table of a shock test machine and subjected to a shock input. The product is then examined for damage using the previously defined damage criteria. If none has occurred, it is subjected to a higher acceleration level pulse with approximately the same velocity change. Again, the product is examined for damage and if none has occurred, receives a shock pulse with a slightly higher acceleration level. This process continues until the damage point is reached or the test is terminated. The last non-failure shock input defines the critical acceleration level for the product in that orientation. All three orientations are tested for products that can be hand-carried.

The Damage Boundary can then be plotted by drawing a horizontal line through the critical acceleration level and a vertical level through the critical velocity change point. The intersection of these two lines (the knee of the curve) is a smooth line as shown in Figure 7. A rectangular intersection can be used as a conservative approximation for the damage region.

The Damage Boundary tells us that any shock pulses which can be plotted inside the damage region will cause damage to the product in that orientation. That is, any shock pulse with a combination of velocity change and acceleration which can be plotted inside the damage region is likely to damage the product.

It also means that velocity change can theoretically be infinite without product damage, as long as the acceleration level is below the critical threshold. Conversely, the plot shows that acceleration levels can be very high without product damage as long as the velocity change is below the critical velocity change threshold. This last point is very significant for product ruggedization and for the possible elimination of protective packaging altogether. Sadly, it is this step velocity test which is most often eliminated when time or test specimens become tight. This testing can yield a wealth of information which definitely makes it worthwhile to run.

Critical velocity change is related to equivalent freefall drop height by the formula:

$$\Delta V = (1 + e)x\sqrt{2gh}$$

where:

e = the coefficient of restitution of the impact surfaces (V_R/V_I)
g = the gravitational constant (9.8 m/s^2)
h = the equivalent freefall drop height

From this formula the designer can estimate how high the unpackaged product can fall onto a surface before damage occurs in that axis. If this drop height is likely to be exceeded in the distribution environment, then the product must be cushioned. The performance requirements of the cushion are that no more than the critical acceleration be transmitted to the product.

The Damage Boundary has proven to be a significant tool for determining product fragility and packaging requirements. However, in the 25 years that it has been in widespread use, some significant problems have developed. These include the following:

1. Since this testing is normally done in the prototype stage of the product, the actual test specimens tend to be different and normally less rugged than actual production samples. Often the test results are accepted as a good conservative estimate of the product fragility. The overly expensive package that results is viewed as an opportunity for cost reduction in the future. Normally these cost reductions never occur.
2. There is a tradeoff between the size of the “steps” used in both velocity and acceleration inputs and the number of cycles inflicted on the test specimen. On one extreme the engineer can specify a very small step in both the velocity and acceleration increments and thus achieve a relatively precise number for the critical velocity and critical acceleration values. However, this normally means that a large number of shock inputs must be absorbed by the product prior to failure. The effect of these shock inputs, normally considered low cycle fatigue, is unknown but certainly will contribute to early product failure.

   On the other hand, increasing the size of the velocity change and acceleration steps means fewer shock inputs must be withstood by the product, but the inaccuracy that results is significant due to the large steps between inputs. For example, if the acceleration step was 20 G's and the product failed at 80 G's, then the last non-failure input is 60 G's. The entire area between 60 and 80 G's is unknown; thus, to be on the conservative side the designer may select a 60 G level as the critical acceleration for the product in that axis.

3. The effect of fixturing the product to the shock table is a large unknown. Traditionally products have been fastened to the table and the shock input was allowed to transmit through the structure of the product in an unknown fashion. Engineers know that the best approach is to employ a specialized fixture which secures the product in a fashion similar to how a package might secure the product. However, this is rarely done due to the cost and time associated with designing and building an elaborate fixture.
4. The use of the trapezoidal pulse to determine critical acceleration results in a large conservative bias in the Damage Boundary. Figure 8 shows the Damage Boundary for various types of acceleration waveforms. It can be seen that the trapezoidal pulse produces the most conservative critical acceleration estimate. Most package cushion materials will transmit acceleration in approximately a half sine wave. It follows then that a 60 G half sine pulse has a much lower velocity change (energy content) than a 60 G trapezoidal pulse.

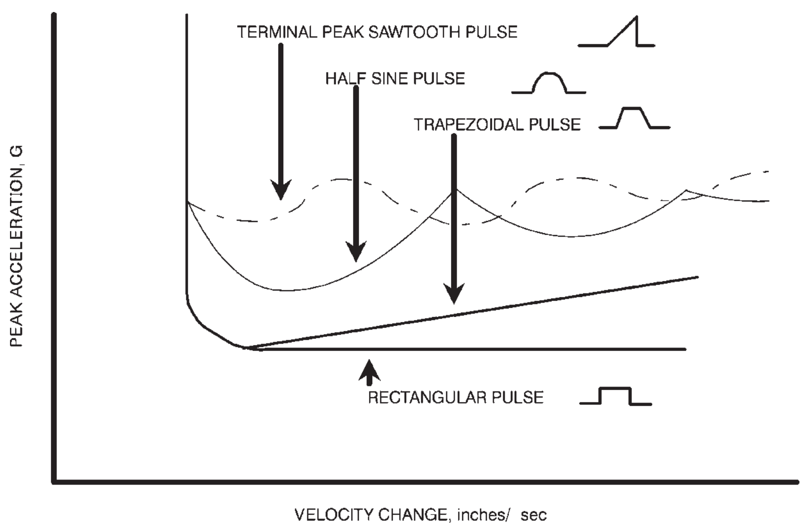


Figure 8. *Theoretical damage boundary plots for various waveforms.*

5. It is important to remember that the critical velocity change and critical acceleration numbers generated from the Damage Boundary test are measurements taken from accelerometers mounted on the table of a shock test machine. When the package is designed and tested, a response accelerometer is placed on the product, normally on a rigid component or structure of the product. However, it is likely that even the rigid component has some compliance from the exterior of the product and thus, the number being generated during a *package response test* should be compared to a number generated at that same location of the product during the *product fragility test*. This has been called simultaneous input and response measurement and is dealt with more thoroughly later on. The use of input only measurements for fragility analysis results in a conservative estimate of the product response, and therefore, an overly conservative—and often expensive— package system.
6. The Damage Boundary test works only for "cushion-able" products. If the product is such that a cushion between the product and the environment is impossible or impractical, then the Damage Boundary test has little or no meaning. It is only when the designer is able to place a protective medium (a mechanical filter) between the product and the environment that the critical acceleration number becomes meaningful.

SHOCK RESPONSE SPECTRUM AND FOURIER ANALYSIS

Many of the problems associated with performing a Damage Boundary test and the resulting package drop test can be resolved through the use of Shock Response Spectrum (SRS) analysis. It is interesting to note that the Damage Boundary theory was originally a simplification of SRS and was put forth as a way to bring this powerful analytical tool to those who neither understood nor had the analytical capability of dealing with shock response spectrum.

The SRS was devised in the early 1930's as a method for determining the resistance of buildings to earthquakes. Rather than being concerned with the diverse characteristics of the shock input pulse, it was proposed that the civil engineer use a method of describing the response of structures to those pulses. They would then no longer be concerned with the complex shape of a pulse, but only with its effect. This can be done analytically or experimentally before a building is fabricated (or a product is designed). SRS quickly became the analytical tool of choice for a wide variety of complex structures, not just buildings and bridges.

The easiest way to visualize the SRS is that the amplitude vs. time "picture" of the transient shock pulse (time domain) is converted into an amplitude vs. frequency picture or spectrum (frequency domain). A similar analysis is true for the Fourier spectrum. A relationship exists between SRS and Fourier spectrum analysis. In general, SRS analysis is used to analyze transients rather than periodic signals. Fourier analysis is used on either. Both of these methods provide great power in understanding and working with mechanical shock and especially the response of spring-mass systems to mechanical shock.

The SRS is best understood by studying a single degree of freedom system (SDOF) spring-mass model shown in Figure 9, consisting of a mass supported on a spring with some degree of damping associated with it.

The model assumes that the mass is a rigid body and that the spring constant, k, is measurable. For the standard SDOF system, the following equations apply:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} = 3.13\sqrt{\frac{K}{W}} = \frac{3.13}{\sqrt{\Delta x}}$$

where:

f_n = natural frequency of the spring-mass system
k = spring constant
M = mass
Δx = static deflection of the spring under the mass

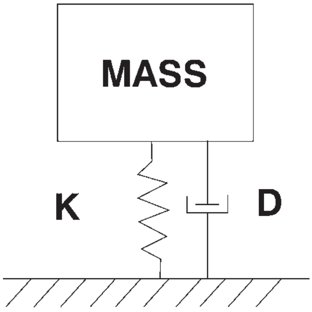


Figure 9. *Single Degree of Freedom Spring-Mass Model.*

There are three different types of springs which we will encounter in the analysis of these systems:

1. *Linear Springs:* force vs. deflection characteristics are linear throughout the entire working range of the spring.
2. *Hardening Spring (tangent elasticity):* Some springs are non linear with a hardening characteristic, that is the slope of the curve representing force vs. deflection increases with increasing deflection. Rubber in compression exhibits this behavior. Note that for small deflections the linear and the hardening springs may be characterized in a similar fashion. Also note that most commercially available cushion systems behave in this fashion.
3. *Softening Spring (hyperbolic tangent elasticity):* A non linear spring may also have a softening characteristic. This occurs when the slope representing the force vs. deflection decreases with increasing deflection. This characteristic is rarely observed in real systems.

Non-linear springs are dealt with mathematically by assuming that their characteristics are linear over a small deflection range.

The effect of damping on an SDOF system are the same as discussed earlier; see Figure 5. For more complete analysis, see [9].

GENERATING A SHOCK RESPONSE SPECTRUM FROM A SINGLE DEGREE OF FREEDOM SYSTEM

To demonstrate the concept, we placed a simple spring mass system on the table of a shock test machine and subjected it to a series of increasing duration (decreasing frequency) trapezoidal shock pulses. Both the input (shock test machine) and the response of the mass were monitored with accelerometers. The results were plotted on a graph with the vertical axis measuring magnification and the horizontal axis measuring normalized frequency. (For this analysis, the y axis is normalized; that is, it is made non-dimensional.)

The primary spectrum from this test is shown in Figure 10. Note that residual spectra normally exists after the response has subsided (while the system is ringing). For clarity the residual spectra were not plotted for this exercise. For some pulses at some frequencies, the residual spectra can be higher than the primary spectrum. This so-called “maximax” spectrum is an envelope of either spectrum, primary or residual, which-

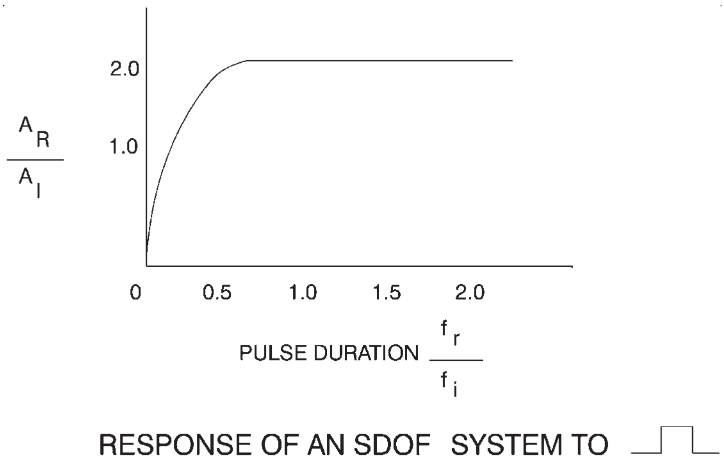


Figure 10. *SRS of a Single Degree of Freedom Spring-Mass System.*

ever is greater. The shock response spectrum shown in Figure 10 is the basis from which the Damage Boundary is plotted.

We are now able to analyze the maximum response of a real system using shock response spectrum analysis. The response of the system is monitored with an accelerometer mounted on an appropriate area of the product. The product is then dropped from the design drop height onto a cushioned surface and the shock response spectrum is captured and analyzed. If no damage occurs, the stiffness of the cushion is increased, normally by decreasing its thickness and the test is repeated. This process continues until damage occurs. The spectrum of the last non-failure input is used to determine packaging parameters such as maximum peak transmitted acceleration through the cushion material.

Normally, a prototype package is designed and built using this parameter. The system is tested by placing the accelerometer in the same location as before and dropping the packaged product from the "design" drop height. The passing criterion is that the response spectrum should be less than that which produced damage in the earlier test.

The advantages of this approach are as follows:

1. The approach is valid for a wide variety of different types of cushioned shock inputs.
2. The effect of shock pulse filtering is totally eliminated.
3. There is no need for an expensive shock test machine, only an accurate method of dropping the product onto a cushioned surface.

The disadvantages include:

1. The complex nature of the analytical technique.
2. The need for a potentially expensive shock spectrum analyzer.
3. The practical reality of the test set-up is such that repeatability is impossible.

A COMPROMISE APPROACH

A possible compromise between the complex but accurate nature of the SRS analysis and the simplified but less accurate Damage Boundary may be found by measuring both the input and the response during a fragility test. This has been referred to as Simultaneous Input and Response Monitoring (SIRM) in the time domain. The SIRM technique is an attempt to determine the differences between package input and product response. More significantly, it is an attempt to determine the exact nature of the response of a measured component (called a “reference location”) within the product to a known input. Even though this seems like a fairly academic question and one that should be easily resolved, packaging engineers often struggle with this issue. The use of the SIRM technique may offer more help to resolve it.

To use this technique, it is necessary to generate fragility data using both an input and response accelerometer. This deviates from the recommended practice for Damage Boundary testing in which only the input pulse is monitored and the last non-failure acceleration input is considered to be the fragility limit of the product. Using the SIRM approach, both the input of the shock test machine and the response of a reference location would be recorded. This is shown schematically in Figure 11.

To use the data, a protective package would be designed using the input data as the fragility limit of the product, as is the current recommended procedure. However, when testing the protective package (i.e., drop testing), the passing criteria is the response of the product at the reference location. For example, if, during the product fragility test, the product fails at an input of 50 G’s and exhibits a response at the reference location of 80 G’s (not uncommon), then the design criteria for the package should be 50G’s (the shock input) but the acceptance criteria for the package drop test should be 80 G’s as measured at the reference location.

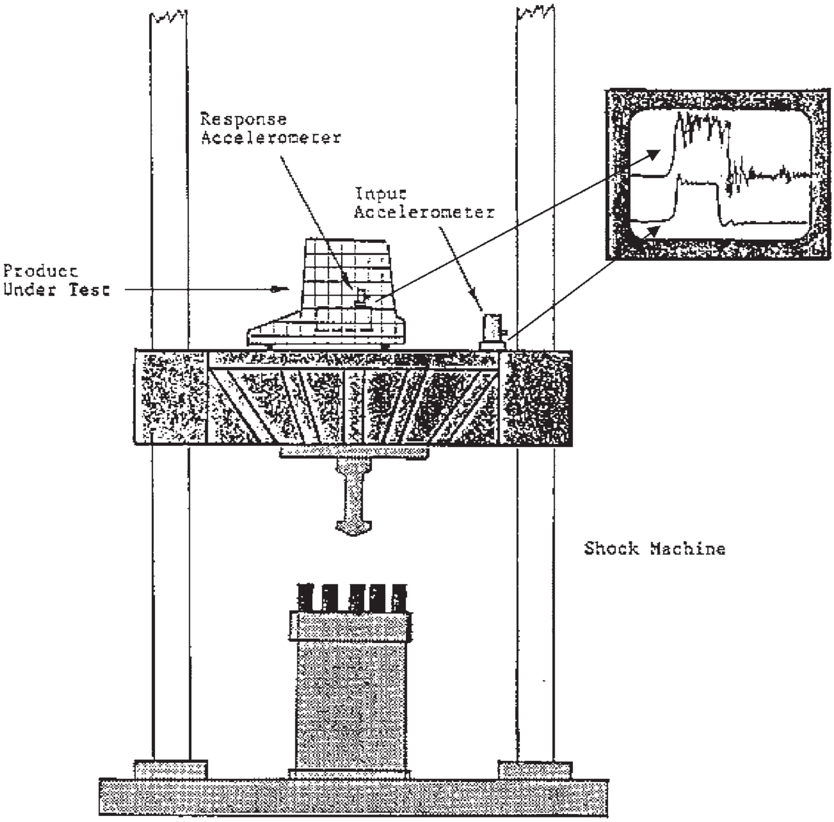


Figure 11. *Test Setup for Input-Response Measurement (SIRM) During Damage Boundary Testing.*

The reason for this should be clear: the 50 G input to the product results in an 80 G response at the reference location. Similarly, during the package drop test, an 80 G response measured at the reference location must be generated by a 50 G input. Bear in mind that one cannot measure the shock input during a package drop test, only the product response to that input.

When the product is placed in the protective package system for package drop testing, the acceleration response is monitored at the same reference location as during the Damage Boundary testing. The high frequency ringing and other responses typical of this type of testing will make the data look very noisy and difficult to interpret. Proper filtering techniques are helpful in a situation like this.

CONCLUSIONS

This approach has been used by the author in designing protective package systems for computer related products over the past 15 years. In general, it has resulted in a more economical package system design than would have been the case using only the traditional Damage Boundary approach.

In most cases the SIRM technique should resolve the issue of package input vs. product response during a package drop test. This should result in significant cost savings for many over designed package systems, especially for high technology products.

Another significant advantage is that the natural frequency characteristics of both the product and the package can be evaluated using the SIRM technique. It should be emphasized that this results only in an estimate of the natural frequencies involved in the product and package system and that accurate response data should be obtained from vibration transmissibility tests.

The astute packaging engineer will recognize that this approach amounts to using the shock response spectrum analysis in the time domain rather than the frequency domain. Clearly there are some tradeoffs in this approach but there are some significant advantages as well, not the least of which is introducing SRS analysis to the packaging engineer. Hopefully in the future this will lead to more accurate and sophisticated testing of both product and the package systems.

REFERENCES

1. Personal communication, Lansmont Corporation, 2006.
2. Personal communication, R. M. Fiedler & Associates, 2006.
3. Personal communication, Westpak, Inc. 2007.
4. Burgess, GJ. Product fragility and damage boundary theory. Packaging Technology and Science, Volume 1, Issue 1 , Pages 5–10, 2006.
5. Designing Product, Package and Unit Load for Greater Shipping Efficiency, International Safe Transport Association, 2006.
6. Goff, J. Product fragility testing using the damage boundary theory. Technical Report Number 17, School of Packaging, Michigan State University, 1969.
7. Standard Test Methods for Vibration (Vertical Linear Motion) Test of Products. ASTM standard D3580. 1999.
8. Standard Test Methods for Mechanical-Shock Fragility of Products, Using Shock Machines. ASTM standard D3332. 1999.
9. Shock and Vibration Handbook. New York:McGraw Hill. 2002.

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

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

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