2005

# The study of the effect of shock and vibration in the distribution cycle to the performance of RFID tags

Chalermlarp Rungkamol

# The Study of the Effect of Shock and Vibration in the Distribution Cycle to the Performance of RFID Tags

by

**Chalermlarp Rungkamol**

**A Thesis Project**

**Submitted to the**

**Department of Packaging Science**

**College of Applied Science and Technology**

**In partial fulfillment of the requirements for the degree of**

**Master of Science**

**Rochester Institute of Technology**

**2005**

Department of Packaging Science
College of Applied Science and Technology
Rochester Institute of Technology
Rochester, New York

**CERTIFICATE OF APPROVAL**

---

**M. S. DEGREE THESIS PROJECT**

---

The M.S. degree thesis project of **Chalermlarp Rungkamol**
has been examined and approved
by the thesis committee as satisfactory
for the requirements for the
**Master of Science Degree**

Deanna M. Jacobs

**Deanna M. Jacobs**
RIT, Packaging Science Graduate Program Chair

Karen L. Proctor

**Karen Proctor**
RIT, Packaging Science Undergraduate Program Chair

Daniel L. Goodwin

**Daniel L. Goodwin, PhD**
RIT, Packaging Science Professor

January 2005

**COPY RELEASE**

THE STUDY OF THE EFFECT OF SHOCK AND VIBRATION IN
THE DISTRIBUTION CYCLE TO THE PERFORMANCE OF RFID TAGS

I, **Chalermlarp Rungkamol**, hereby grant permission to the RIT Library of the Rochester Institute of Technology to reproduce my thesis in whole or in part. Any reproduction will not be for commercial use or profit.

Date: 02/01/05 Signature of Author: Chalermlarp Rungkamol

# ABSTRACT

The purpose of this research was to investigate the effect of shock and vibration during distribution on the performance of a Radio Frequency Identification (RFID) transponder. The RFID system selected for this study was a passive, ultra-high frequency system that complied with the requirements of Wal-Mart and the Department of Defense. The performance of an RFID tag was determined based on a transponder's read range. Two types of experiments were conducted in this research: test protocols used to identify the read range characteristics of the RFID transponder and a simulation of the product distribution cycle based on the ASTM D 4169-04 standard. The effect of shock and vibration on RFID tags was based on a comparison of the transponder's read range from a control experiment and the read range test. Test results demonstrated that there was no statistical difference between the two groups of data. The results indicated that the shock and vibration generated from the simulated product distribution did not have any effect on the performance of the RFID transponder.

## TABLE OF CONTENTS

# LIST OF TABLES

## LIST OF FIGURES AND CHARTS

# CHAPTER 1: INTRODUCTION

For many years, the concept of Automatic Identification (Auto-ID) has been applied in several businesses and industries to improve the effectiveness of data capture and the control of material and information flows. An example of the most popular Auto-ID technology used today is the barcode system. In recent years, there has been an emerging trend in technology that has the potential to improve the efficiency of data collecting process. This technology is Radio Frequency Identification (RFID). Unlike barcode technology, RFID collects product data via radio frequency transmission. Product identification can be done automatically without the need for line-of-sight and an operator to handle and scan the item (Clarke, n.d.).

Recognizing the potential of RFID technology to reduce the costs of supply chain and logistics, major retailers and organizations have planned to implement RFID into their distribution system. Wal-Mart and the Department of Defense (DoD) have announced projects to employ RFID technology into their distribution systems. They requested their major suppliers to put RFID tags on cases or pallets for product identification.

To meet the requirements of these retailers and to improve the efficiency of the supply chain, suppliers need to apply RFID technology in their distribution systems. However, the implementation of RFID involves great investment and risks. According to Byrnes (2003), large companies that plan to employ RFID, while being able to satisfy their customers and maintaining or increasing the market share, could suffer the loss of profit. In the cases of small and medium companies, they may not have enough resources to apply RFID technology.

Therefore, to successfully implement and obtain the maximum benefit of RFID, companies must understand the potential and limitations of RFID technology and be able to select the suitable RFID equipment to fit their applications. The performance evaluation of RFID devices is important. Tests of RFID equipment with products and packages in the distribution and warehouse environment are necessary to assure that these devices can effectively function in the operating field.

### *Background of the Problem*

The performance of an RFID system can be determined by the effective data transmission between two radio frequency devices: a reader and tags. Any errors regarding the data transfer will lead to the failure to capture product information. Since the data transmission is significant to the successful communication in the distribution system, the evaluation of RFID equipment's performance regarding the data transfer is necessary.

In recent years, there have been many research projects concerned with the performance of RFID readers and transponders in the distribution and warehouse environment. The purpose of these studies is to assure that RFID devices can reliably function under the conditions and environments required by major retailers, such as Wal-Mart, and the Department of Defense (DOD). One example of RFID research is the evaluation of read ranges and rates of several RFID transponders on different products and packages. Another example is the study of the effects of product and packaging materials (e.g., metals and liquid) on the RF transmission between a reader and tags.

Besides the research discussed above, another interesting area of study is the examination of the effect of shock and vibration from product distribution on RFID tag performance. Typically, shock and vibration are generated during distribution activities, e.g., product handling, palletizing, stacking, and transportation. These forces are generally applied to products, shipping containers, and RFID transponders labeled on cases or pallets during the distribution process. While there is a possibility for shock and vibration forces to damage or degrade the tag's ability to transmit data, it is important to investigate the robustness of the transponder to withstand the shock and vibration from the distribution cycle.

### *Problem Statement*

The success of product identification in the RFID system depends on the ability of RFID devices to effectively operate in the field. During distribution, shock and vibration from product handling and transportation may cause damage or decrease the performance of tags on the containers. The study of the effect of shock and vibration to RFID transponders is, therefore, necessary to assure that they can perform their specified function in the distribution environment.

### *Objective of the Research*

The objective of this thesis research is to determine whether there is any effect on the performance of RFID transponders by shock and vibration during product distribution.

### *Scope of the Research*

The scope of the research was limited to the testing of a passive RFID system operated at the ultra-high frequency range (865 to 956 MHz) on a selected product and a shipping container. The specifications of the RFID tags used for the experiments were based on the requirements of Wal-Mart and the DoD, i.e., the 96-bit, Electronic Product Code (EPC) Class 0 tag. The performance measure used to evaluate the RFID transponder was the read range – the distance between a reading antenna and a transponder – at which a tag could be successfully interrogated. The test schedules and procedures for the product distribution cycle simulation were based on the ASTM D 4169-04 standard. Details of test specimens and methods are provided in Chapter 3.

# CHAPTER 2: LITERATURE REVIEW AND BACKGROUND THEORIES

### *Electromagnetic Radiation and Radio Waves*

Electromagnetic radiation is the energy that travels in the form of electric and magnetic waves at the speed of light (Salt, 2002). Examples of electromagnetic radiation are radio waves, microwaves (or high frequency radio waves), visible light, and X-rays. Figure 2-1 presents an electromagnetic wave. The characteristics of electromagnetic waves vary by wavelengths and frequencies. The wavelength is defined as the distance between two adjacent wave crests. The inverse proportion of the wavelength is the frequency or the number of wave oscillations per unit time. Electromagnetic waves with high frequencies or short wavelengths have more radiated energy than the ones with low frequencies or long wavelengths. The bands of electromagnetic radiation with similar characteristics are presented in the electromagnetic spectrum shown in Figure 2-2.

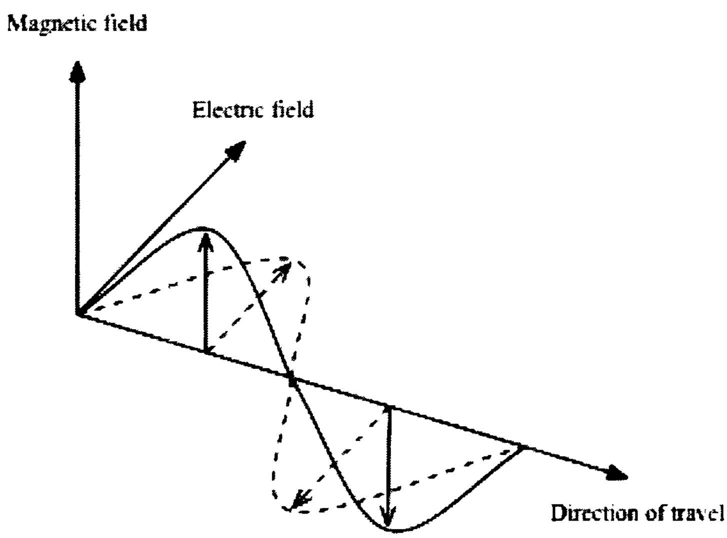



**Figure 2-1: Electromagnetic Wave**

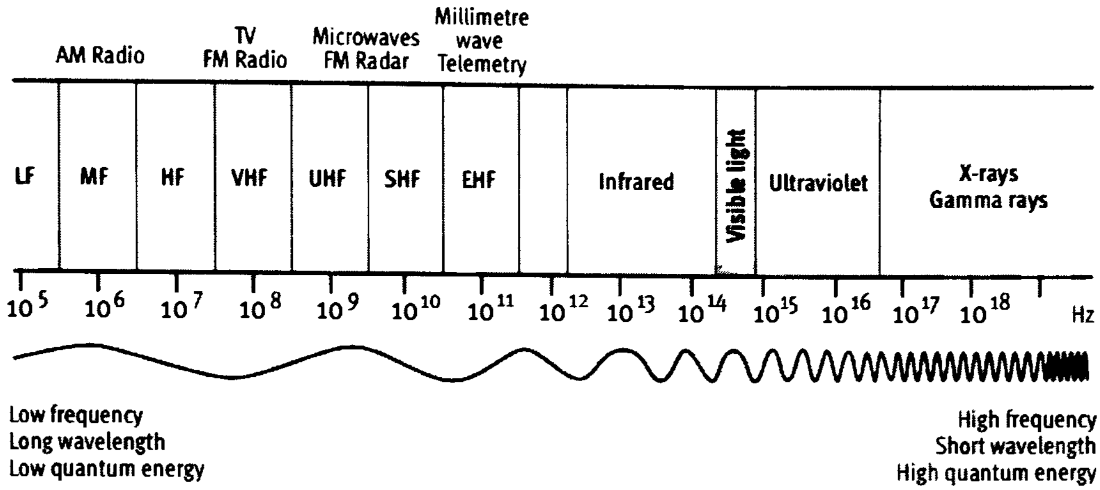



**Figure 2-2: Electromagnetic Spectrum (Hodges & Harrison, 2003)**

Radio waves are electromagnetic waves with a frequency range up to 3 THz (IEEE, 1997). Unlike light, radio waves are invisible. They have long wavelengths (> 0.1mm) and the ability to pass through materials, such as woods or plastics. Because of the wide frequency range, radio waves are grouped into different bands as shown in Table 2-1.

As data carriers, radio waves contain information (e.g., speeches, music and pictures) in the encoded format by means of the amplitude[1] or frequency modulation. Amplitude Modulation (AM) is a technique to encode data by varying the amplitudes of radio signals at a constant frequency. Another method for data encoding is Frequency Modulation (FM), which employs the frequency variation of the constant-amplitude radio waves (Qualitative Reasoning Group, n.d.). Figures 2-3 and 2-4 show the varied amplitudes and frequencies of radio waves that represent the series of 0s and 1s data.

[1] The height of radio wave.

**Table 2-1: Radio Wave Bands (IEEE, 1997)**

| Band designation | Frequency | Wavelength |
|---|---|---|
| Ultra low frequency (ULF) | < 3 Hz | > 100,000 km |
| Extremely low frequency (ELF) | 3 Hz – 3 kHz | 100,000 – 100 km |
| Very low frequency (VLF) | 3 – 30 kHz | 100 – 10 km |
| Low frequency (LF) | 30 – 300 kHz | 10 – 1 km |
| Medium frequency (MF) | 300 kHz – 3 MHz | 1 km – 100 m |
| High frequency (HF) | 3 – 30 MHz | 100 – 10 m |
| Very high frequency (VHF) | 30 – 300 MHz | 10 – 1 m |
| Ultra high frequency (UHF) | 300 MHz – 3 GHz | 1 – 0.1 m |
| Super high frequency (SHF) | 3 – 30 GHz | 0.1 m – 1 cm |
| Extremely high frequency (EHF) | 30 – 300 GHz | 1 cm – 1 mm |
| Submillimeter | 300 GHz – 3 THz | 1 – 0.1 mm |

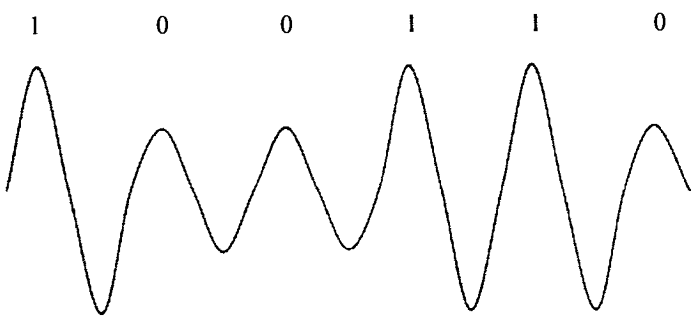



**Figure 2-3: Amplitude Modulation (AM) of Radio Wave**

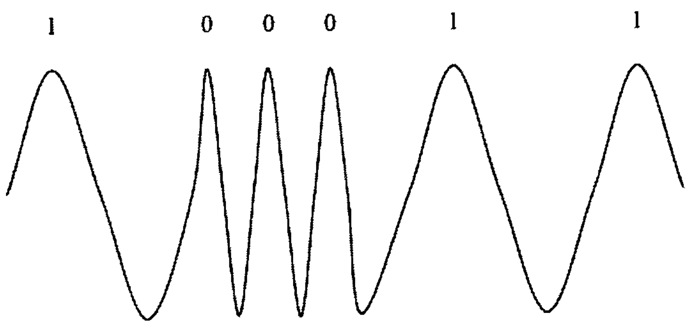



**Figure 2-4: Frequency Modulation (FM) of Radio Wave**

Typically, amplitude- or frequency-modulated radio waves are generated from a transmitter and sent out by a transmission antenna (NICT Okinawa, 2004). A receiver picks up the radio waves in the air through a reception antenna and demodulates or decodes the signals for use. A diagram of a radio system is presented in Figure 2-5.

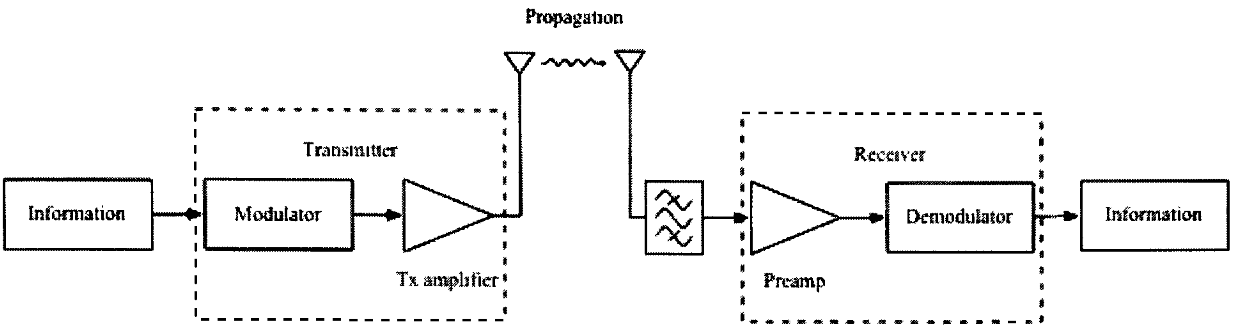



**Figure 2-5: Diagram of Radio System (Medina, 2000)**

***History of RFID***

The history of RFID can be traced back to the 1800s when Michael Faraday and James Clerk Maxwell proposed their works that led to the understanding of electromagnetic energy, which is the fundamental underpinning of RFID technology. However, the concept of RFID was not originated until World War II. The RFID-related technology, Identification, Friend or Foe (IFF), was developed and used by the British military to distinguish Allied aircraft from those of the enemy (Scharfeld, 2001).

In 1948, Harry Stockman published the first work about RFID, "*Communication by Means of Reflected Power*" (Landt, 2001). However, his idea could not be implemented at that time because items such as transistors, integrated circuits, microprocessors, and communication networks had not yet been developed.

The 1950s saw the beginning of RFID explorations. Several RFID research publications during this period were the result of radio and radar developments in the previous two decades

(Landt, 2001). Example of works from the 1950s are F.L. Vernon's, *"Application of the Microwave Homodyne"*, and D.B. Harris', *"Radio Transmission Systems with Modulatable Passive Responder"*. RFID research continued to grow in the 1960s. R.F. Harrington proposed the RFID-related theory, *"Field Measurements Using Active Scatterers"* and *"Theory of Loaded Scatterers"* in 1963 and 1964.

The first commercial RFID device was created in the late 1960s. The U.S. companies Sensormatic and Checkpoint developed the 1-bit Electronic Article Surveillance (EAS) for anti-theft application (Landt, 2001). Advance developments in RFID began in the 1970s. The government, academic institutes, and companies were interested in working on RFID projects. Animal tracking, vehicle tracking, and factory automation were early RFID applications that were developed (Landt, 2001). In 1978, the Port Authority of New York and New Jersey did a pilot test of RFID for toll collection, while the first implanted RF animal tag was developed in 1979.

The full implementation of RFID applications began in the 1980s. In the United States, RFID applications were designed to enhance transportation and personnel security access, while RFID developments in Europe focused on animal, business, and industrial applications (Landt, 2001). The deployment of RFID technology significantly increased in the 1990s when electronic toll collection systems (e.g., E-Z Pass) were widely implemented on U.S. highways.

At the beginning of the 21$^{st}$ century, performance improvement, as well as cost and size reduction, has continuously increased a number of RFID applications. RFID systems are now used in the airline industry for tagging individual baggage. Factories and warehouses employ RFID to track items and improve logistics and inventory control. In 2003, Wal-Mart requested its top 100 suppliers to attach RFID tags on their shipping containers and pallets by January 2005 (RFID Journal, 2003).

***RFID: Definition and Components***

RFID is a technique used to identify individual items and capture information by employing electromagnetic radiation at radio frequencies. By utilizing radio waves, RFID does not require contact or line-of-sight to transmit data and, therefore, overcomes the limitations of other Auto-ID technologies, such as barcode (Sabetti, 1998). Moreover, RFID is a fully automatic system that discards the need to manually handle identification activities, such as scanning items. The Association of Automatic Identification and Mobility (AIM) defined RFID as

> Systems that read or write data to RF (Radio Frequency) tags that are present in a radio frequency field projected from RF reading/writing equipment. Data may be contained in one or more bits for the purpose of providing identification and other information relevant to the object to which the tag is attached. It incorporates the use of electromagnetic or electrostatic coupling in the radio frequency portion of the spectrum to communicate to or from a tag through a variety of modulation and encodation schemes.

RFID systems consist of three basic components: reading/writing equipment or a reader, an antenna, and a tag or a transponder. Typically, a reader sends radio signals through antenna(s) to activate and request data from a transponder that locates in a read range. Then, a transponder, as a data carrier, responses by transmitting information back to a reader. Finally, a reader retrieves the tag data in the encoded format, decodes the data, and transfers the data to a host computer. Figure 2-6 shows the configuration of an RFID system.

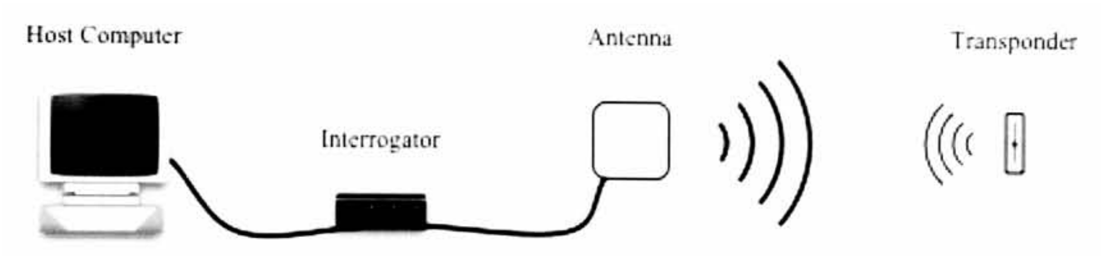



**Figure 2-6: RFID System Configuration**

A reader, also known as an interrogator, is defined as a set of electronics that reads and, depending on design and technology, modifies data stored in a transponder (Ames, 1990). Its main function is to supply *"the means of communication with transponders and data transfer"* (Medina, 2000). Another function of a reader is to manage and control its communication with multiple tags. A regular interrogator has an anti-collision protocol to prevent the interference of radio signal from several transponders and allow multiple-tag readings in the interrogation zone (Finkenzeller, 2003).

An antenna is a conductive element to couple or radiate electromagnetic energy (AIM, 2001). Antennas are connected to a reader or integrated into a transponder to transmit and receive data via radio frequencies. There are various shapes and sizes of antennas for different RFID systems. At the low (125 – 134 kHz) and high frequency (13.56 MHz), one usually employs coiled antennas to create electromagnetic coupling[2] between a reader and a tag (RFID Journal, n.d.). Dipole (linear) antennas emit radio signals from and to RFID devices at the ultra-high frequency (865 – 956 MHz and 2.45 GHz). Other designs of antenna (e.g., the Yagi-Uda antenna)_ are also used to improve the RF transmission at the UHF.

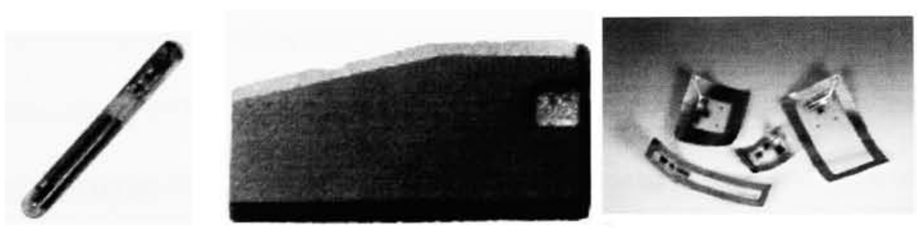
[2] A means of data or energy transfer by applying a magnetic field (AIM, 2001).

Loop Antenna Dipole Antenna

**Figure 2-7: RFID Antennas**

A transponder, i.e., a transmitter/responder, is an electronic, data-carrying device that gathers radio signals from and transfers data to a reader. A typical transponder consists of a microchip for storing data and a coupling element (e.g., a coiled antenna) for radio frequency communication (Sarma & Engels, 2002). Housing or film layers are also used to cover transponders for protection from abuse and harsh environments.

Transponders come in various physical forms depending on applications. For example, glass transponders have been designed to inject under the skin for animal identification (Finkenzeller, 2003). Plastic housing tags are suitable for applications in automated factories that require mechanical protection. A smart label is a self-adhesive, paper or plastic transponder that is attached to baggage, parcels or packages for identification purposes.



Glass Transponder Plastic Housing Transponder Smart Labels

**Figure 2-8: RFID Transponders (Texas Instruments, 2004)**

### *Types of RFID Transponder*

RFID transponders can be categorized based on the power sources of the tags. Three types of RFID tags are discussed below:

1) **Active transponder**. An active tag employs a built-in battery as a power source for operation. It has the advantage of a farther read range when compared to a non-battery (passive tag) transponder. Because of the integrated power supply, the read range of an active transponder can be up to 300 feet (Medina, 2000). However, internal batteries also increase the cost of active tags. The typical unit price of an active tag ranges from $5 to $100 according to Harrop (2001). Therefore, active transponders are suitable for high-value items that require long range operation, such as vehicle tracking.
2) **Passive transponder**. A passive transponder balances the read range with the cost. Without a built-in battery, a passive tag derives electromagnetic energy from a reader to power itself and transmit radio signals back to an interrogator (AIM, 2001). The read ranges of passive transponders are from 4 inches up to 15 feet (Medina, 2000). Typical passive tags cost from 20 cents to several U.S. dollars (RFID Journal, n.d.). An example of a passive tag is a smart label used for tracking a shipping container.
3) **Semi-active or semi-passive transponder**. A semi-active tag applies energy from internal and external power supplies. A built-in battery is used to power the tag's circuitry and memory, while a semi-active tag draws radio energy from a reader for signal broadcast (RFID Journal, n.d.). The radio energy from a reader can also be used to recharge batteries in some semi-active tags. This helps to decrease the size of batteries and keep the cost down. Semi-active tags can be used for tracking high-valued assets or reusable containers in supply chains.

### *Operating Frequencies*

Operating frequencies are the communication channel between a reader and a transponder in an RFID system.. Frequencies used in RFID systems can range from 100 kHz to 5.8 GHz (Finkenzeller, 2003). However, to avoid interference with other radio frequency devices such as television, radio, and mobile radio services, there is a limitation regarding the number of operating frequencies. According to Hodges & Harrison (2003), the frequencies currently used in RFID systems are low frequency (125-134 kHz), high frequency (13.56 MHz), and UHF (865-956 MHz & 2.45 GHz). Table 2-2 summarizes the characteristics and applications of RFID systems at different frequencies.

**Table 2-2: RFID Frequency Bands and Applications (AIM, 2004)**

| Frequency Band | Characteristics | Typical Applications |
|---|---|---|
| Low frequency<br>(125-134 kHz) | Short to medium read range<br>Inexpensive<br>Low reading speed | Access control<br>Animal identification<br>Inventory control<br>Car immobilizer |
| High frequency<br>(13.56 MHz) | Short to medium read range<br>Potentially inexpensive<br>Medium reading speed | Access control<br>Smart cards<br>Item tracking & inventory control |
| Ultra-high frequency<br>(865-956 MHz & 2.45 GHz) | Long read range<br>Expensive<br>High reading speed | Item tracking & inventory control<br>Railroad car monitoring<br>Toll collection systems |

### *Anti-collision Protocol*

The operation of RFID system depends on the communication between an interrogator and a transponder. Usually a single reader has to operate with numerous tags in the read zone. The problem occurs when a number of tags access (transmit data to) a reader simultaneously. The interference or collision of signals from several tags confuses the reader and leads to failure to read data. To avoid this problem, an anti-collision protocol is programmed in a reader to distinguish an individual transponder from the others and to prevent the colliding of tag signals.

According to Finkenzeller (2003), there are several methods of anti-collision used in RFID systems: space division multiple access (SDMA), frequency domain multiple access (FDMA), and time domain multiple access (TDMA).

SDMA separates a reader's interrogation zone into small areas that cover only a single or a few transponders. An interrogator is designed to read tags in each divided area one after the other with decreased opportunity for signal interference.

FDMA employs a range of frequencies (e.g., 915 – 918MHz) to carry data from several tags to a single reader. Transponders are differentiated by multiple frequency channels used to respond to an interrogator. The use of several frequencies helps to avoid data collision during transmission.

TDMA is a technique that allows a single reader to work with one tag at a time. There are two types of TDMA: transponder-driven and interrogator-driven procedures (Finkenzeller, 2003). An example of a transponder-driven procedure is a system where the transponder is programmed to switch off after successful data reading. An interrogator-driven procedure relies on a reader to select and read an individual tag based on its unique serial number.

### *The Physics of RFID: Near-field and Far-field Theories*

RFID systems can be distinguished based on two operating principles: the near-field and the far-field theories. At the low (125-134 kHz) and high (13.56 MHz) frequency bands, where the wavelengths of radio waves are relatively long compared to the read range, RFID systems employ the near-field theory for operations (Hodges & Harrison, 2003). The near-field theory applies the coupling of magnetic or electric fields for data communication. Generally, magnetic couplings (usually known as inductive couplings) are more popularly used than electric or capacitive couplings (Scharfeld, 2001).

In the inductive coupled system, electric current is passed through the coiled (loop) antenna of a reader or a read/write device (RWD) to create a magnetic field. A magnetic field induces the voltage of a tag or label antenna and, thus, generates electric current to supply power and transfer data to a transponder (AIM, 2000). Figure 2-9 illustrates the principle of the near-field RFID system.

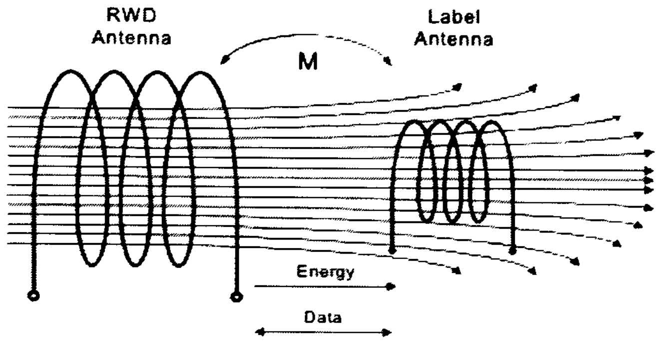



**Figure 2-9: The Near-field (Inductive Coupling) RFID System (AIM, 2000)**

At the UHF range (865 – 956 MHz), where the wavelengths are relatively short compared to the read range, RFID systems operate based on the far-field theory. In the far-field system (see Figure 2-10), a reader communicates to a transponder through the propagation of radio waves (AIM, 2001). Basically, a reader emits electromagnetic energy to a transponder in the interrogation zone. The transponder (in the case of a passive system) absorbs part of the electromagnetic energy for its power supply and reflects radio waves back to a reader for data transmission. This process is known as *backscatter* (RFID Journal, n.d.). The propagation of radio waves is discussed in detail in the next section.

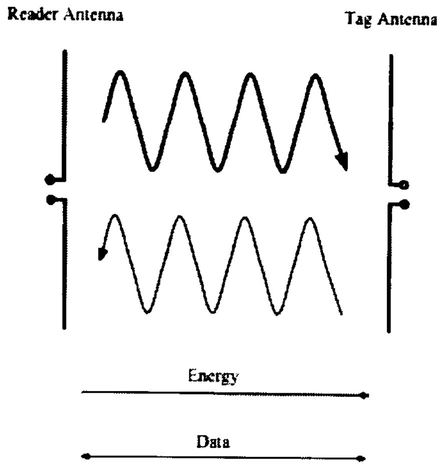



**Figure 2-10: The Far-field RFID System**

***The Physics of RFID: Radio Wave Propagation***

The definition of radio wave propagation is *"the transfer of energy by electromagnetic radiation at radio frequencies"* (IEEE, 1997). Radio wave propagation is important as a means of communication for RFID systems in the UHF range (AIM, 2000). Radio waves are propagated between a reader and transponders for data transfer. The efficiency of radio wave propagation depends on various factors such as the energy of the radio wave, the design of the antenna, the environment through which the radio wave propagates, and the radio signal interference and noise.

The power of a radio wave significantly determines the operating range of an RFID system, especially for passive systems where energy is required to power tags. Distributed in all directions, a radio wave loses its power as it travels away from a transmitter (Hodges & Harrison, 2003). The relationship between the energy of radio wave and the distance from the transmission source is an inverse square or $1/d^2$, where d is the distance from a transmitter (AIM, 2000). This means that the power of radio wave will be reduced to one-fourth of its value when it travels from distance d to 2d as presented in Figure 2-11.

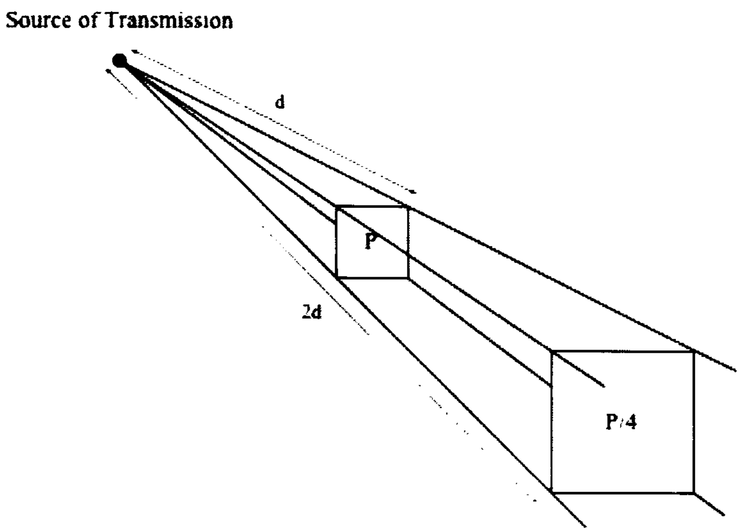



**Figure 2-11: The Power of Radio Wave at Distances from Transmission Source (Hodges & Harrison, 2003)**

Another important factor that affects radio wave propagation is the design of antenna. The amount of radio energy received depends on the size of antenna (AIM, 2000). Typically, to achieve resonance and improve reception characteristics, the length of antenna (i.e., a dipole) is designed at half of a wavelength of any operating frequency (Scharfeld, 2001). For example, at 900 MHz, the length of the half-wave dipole antenna is about 0.17 m or 6.6 in. The shorter antenna receives less radio energy compared to the half-wave dipole. However, it can also help to reduce the noise signal.

The orientation of antennas is also important to the range of radio wave propagation. A typical antenna, i.e., a single dipole, does not uniformly emit radio energy in all directions (Finkenzeller, 2003). Therefore, different orientations between two antennas can alter the radio transmission range. In the case of single dipole antennas, reader and tag antennas must be oriented in parallel to each other for the maximum reading range. The control of antenna orientation may not be practical in all applications. As a result, a dual dipole antenna is designed to solve the problem of orientation by covering the low radiation area of a single dipole.

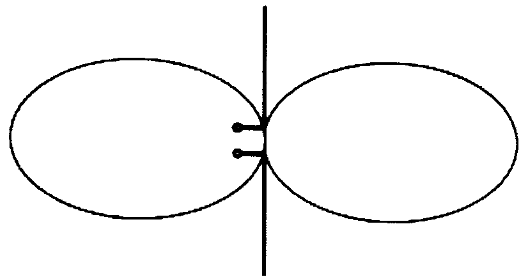


**Figure 2-12: Radiation Pattern of Single Dipole Antenna (Finkenzeller, 2003)**

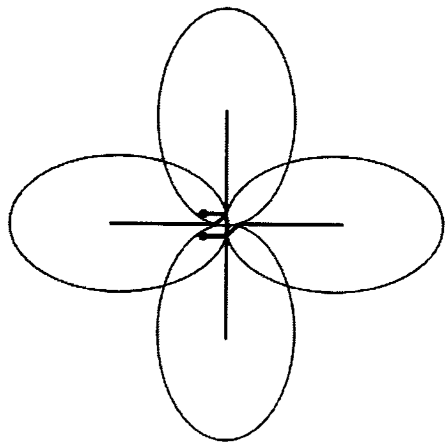


**Figure 2-13: Radiation Pattern of Dual Dipole Antenna**

Substances or materials along the traveling path of radio waves are significant to the propagation of radio waves. Due to the nature of electromagnetic radiation, a radio wave that passes through mediums besides a vacuum will lose some energy to the medium substance (e.g., water) by absorption (AIM, 2000). This absorption of energy is known as *attenuation*. In addition, at the UHF frequency, a radio wave is reflected by a conductive or partially conductive surface such as metal or concrete. In an environment with a lot of conductive materials, the reflection of radio waves can be a problem since these materials may obstruct the radio transmission between a reader and a transponder. However, there are other types of materials that do not absorb or reflect radio frequency. These materials are transparent or friendly to radio frequencies. Table 2-3 lists examples of substances or materials that influence radio frequency propagation.

**Table 2-3: Substances or Materials that Affect Radio Frequency Propagation**

| Effects on Radio Frequency (RF) | Examples of Substances or Materials |
|---|---|
| RF Transparent or RF Friendly | Woods, paper, plastics |
| RF Absorbing | Water |
| RF Reflecting | Metals and concrete |

Signal interference and noise decrease the performance of radio wave propagation, and are generated from both internal and external sources (Medina, 2000). Internal noise comes from the RFID equipment, such as the antenna, transmission lines, and receiver. External noise comes from natural and man-made sources. The occurrences of natural noise are due to the weather (e.g., thunderstorms) or other sources in space (e.g., the sun and stars). Man-made noise is produced from electrical and electronic devices, such as radio frequency equipment and mobile phones.

***RFID Standards***

In recent years, competition among RFID suppliers, differing viewpoints on market needs, and the requirement to conform to regulations and legislation in several parts of the world have driven the development of RFID technologies in different directions (Hodges & Harrison, 2003). While the need for interoperable devices for RFID applications has increased, the absence of standardization has obstructed the extensive use of this technology. To solve this problem, there have recently been attempts to develop RFID standards for the industry, such as the creation of the EPC and the ISO/IEC standards.

***Electronic Product Code (EPC)***

EPC is *"an identification scheme for universally identifying physical objects via Radio Frequency Identification (RFID) tags and other means"* (EPCglobal, 2004). The EPC data standards have been developed to define the length and position of data stored in an RFID tag. EPC was originally created by the Auto-ID Center[3] and is now under the management and control of EPCglobal Inc., a joint venture between EAN International and the Uniform Code Council.

The structure of an EPC number includes the header, filter value, and domain identifier (EPCglobal, 2004). The header is a binary number that indicates the length, type, structure, version, and generation of the EPC (EPCglobal, 2003). The filter value is optionally used to enhance the EPC tag reading. The domain identifier consists of a manager number that represents the company's identity, an object class to use as a unique product identifier, and a serial number to identify the specific item. Both the header and the domain identifier represent different coding schemes based on several EAN-UCC standards, e.g., Seriallized Global Trade Identification Number (SGTIN), Serial Shipping Container Code (SSCC), and Global Returnable Asset Identifier (GRAI). Figure 2-14 and Table 2-4 show the structure and an example of standard EPC tag data.

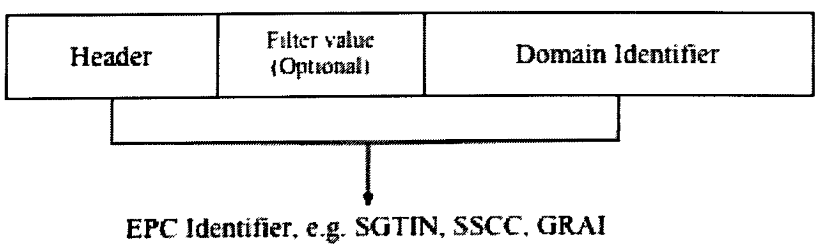



**Figure 2-14: The EPC Tag Data Structure (EPCglobal, 2004)**

[3] An RFID research center with its headquarters at the Massachusetts Institute of Technology (M.I.T.), now known as Auto-ID labs.

**Table 2-4: The EPC 96-bit SGTIN Data Structure (EPCglobal, 2004)**

| | Header | Filter Value | Partition | Company Prefix | Item Reference | Serial Number |
|---|---|---|---|---|---|---|
| SGTIN-96 | 8 | 3 | 3 | 20 – 40 | 24 – 4 | 38 |
| | 00110000 (Binary) | 8 (Decimal) | 8 (Decimal) | 999,999 – 999,999,999,999 (Decimal) | 9,999,999 – 9 (Decimal) | 274,877,906.943 (Decimal) |

The specifications of EPC are classified based on the number of bits (which indicate the capacity to store data, e.g., 64, 96 or 128 bits) and operating frequencies (e.g., 13.56 and 900s MHz). The EPC tags are also divided by classes that specify the read/write ability of the transponder. The EPC Class 0 tag is a read-only transponder that can only be programmed during manufacture (Blue & Powel, n.d.). The EPC Class 1 tag allows the user to write data in a transponder once (Write Once, Read Many or WORM), while the EPC Class 2 tag is a rewritable transponder.

The current generation of EPC used in the industry is the version 1 standard. However, the EPC Generation 2 is now under development and expected to be released by the end of 2004 (O'Connor, 2004).

***ISO/IEC Standards***

The International Standards Organization (ISO) and the International Electrotechnical Commission (IEC) are currently developing standards for automatic identification and data capture techniques (Hodges & Harrison, 2003). The ISO/IEC JT 1/SC 31/WG 4 (Joint technical committee 1, subcommittee 31, workgroup 4) is responsible for standards regarding RFID for item management. The ISO/IEC standards developed by this committee are summarized in Table 2-5. Other standards regarding conformance and test methods of RFID tags and devices (e.g., ISO/IEC 18046 and 18047) are issued by the JT 1/SC 31/ WG 3 committee.

**Table 2-5: ISO/IEC RFID Related Standards (High Tech Aid, 2004)**

| Standard Number | Title | Status |
|---|---|---|
| ISO/IEC 15434 | Transfer Syntax for High Capacity ADC Media | Published - To be amended for second edition |
| ISO/IEC 15459-1 | Unique identifier for transport units – Part 1: Technical Standard | Published - To be amended for second edition |
| ISO/IEC 15459-2 | Unique identifier for transport units – Part 2: Procedural Standard | Published - To be amended for second edition |
| ISO/IEC 15459-3 | Unique identifier for transport units – Part 3: Unique Item Identification for Supply Chain Management | Published |
| ISO/IEC 15961 | RFID for Item Management – Data Protocol: Application interface | Published |
| ISO/IEC 15962 | RFID for Item Management – Protocol: Data encoding rules and logical memory functions | Published |
| ISO/IEC 15963 | RFID for Item Management – Unique Identification of RF Tag | Published |
| ISO/IEC 18000 | RFID for Item Management – Air Interface<br>• 18000-1 Part 1 – Generic Parameters for the Air Interface for Globally Accepted Frequencies<br>• 18000-2 Part 2 – Parameters for Air Interface Communications below 135 kHz<br>• 18000-3 Part 3 – Parameters for Air Interface Communications at 13.56 MHz | Published |
| ISO/IEC 18000 (cont.) | • 18000-4 Part 4 – Parameters for Air Interface Communications at 2.45 GHz<br>• 18000-5 Part 5 – Parameters for Air Interface Communications at 5.8 GHz (Withdraw)<br>• 18000-6 Part 6 – Parameters for Air Interface Communications at 860 to 930 MHz<br>• 18000-7 Part 7 – Parameters for Air Interface Communications at 433 MHz | Published |
| ISO/IEC 18001 | RFID for Item Management – Application Requirements Profiles (ARP) | Published |
| ISO/IEC 18046 | RFID Tag and Interrogator Performance Test Methods | FDIS ballot passed, waiting for ISO to publish |
| ISO/IEC 18047 | RFID Device Conformance Test Methods, split to mirror ISO/IEC 18000<br>• 18047-1 Part 1 – Not available<br>• 18047-2 Part 2 – Parameters for Air Interface Communications below 135 kHz<br>• 18047-3 Part 3 – Parameters for Air Interface Communications at 13.56 MHz<br>• 18047-4 Part 4 – Parameters for Air Interface Communications at 2.45 GHz<br>• 18047-5 Part 5 – Not available<br>• 18047-6 Part 6 – Parameters for Air Interface Communications at 860 to 930 MHz<br>• 18047-7 Part 7 – Parameters for Air Interface Communications at 433 MHz | • Part 2 – Working draft (in committee)<br>• Part 3 – Published<br>• Part 4 – Approved, waiting for ISO to publish<br>• Part 6 – Working Draft (in committee)<br>• Part 7 – PDTR ballot passed waiting for BRM |
| ISO/IEC 19762 | Information Technology AIDC Techniques – Harmonized Vocabulary | Sent to ISO for FDIS ballot (2 month ballot) |
| ISO/IEC 24710 | Information Technology AIDC Techniques – RFID for Item Management – ISO 18000 Air Interface Communications – Elementary Tag license plate functionality for ISO 1800 air interface definitions | DTR ballot closes 2005-01-06 |

*Standards and Procedures for the Distribution Cycle Simulation*

There are two standards developed to simulate the distribution or transport environments for the shipping container test. These standards are the ASTM D 4169-04 and the ISTA 3 series. The ASTM D 4169-04 or the standard practice for performance testing of shipping containers and systems is the standard for evaluating the capability of shipping containers to withstand the distribution environment. It consists of a list of test schedules representing different activities in the distribution process, e.g., product handling, warehouse stacking, and transportation. Different test schedules are selected from a list to create the test sequence for the distribution cycle simulation. An example of a simple distribution cycle is warehousing composed of test schedule A for product handling and schedule B for warehouse stacking.

The intensity of each test schedule is determined from the assurance level. Assurance level I indicates a high intensity of the test with a low probability to occur. The second-level assurance represents medium test intensity and a medium probability of occurrence. Assurance level III has a low intensity test level with a high probability of occurrence. Table 2-6 lists the categories of test schedules in the ASTM D 4169-04 standard.

**Table 2-6: A Category of the ASTM D 4169-04 Test Schedules (ASTM, 2004)**

| Schedule | Test Schedule | Hazard Element |
|---|---|---|
| A | Handling – manual and mechanical | Drop, impact, stability |
| B | Warehouse Stacking | Compression |
| C | Vehicle Stacking | Compression |
| D | Stacked Vibration | Vibration |
| E | Vehicle Vibration | Vibration |
| F | Loose Load Vibration | Repetitive shock |
| G | Rail Switching | Longitudinal shock |
| H | Environmental Hazard | Cyclic exposure |

Another standard procedure for distribution cycle simulation is the ISTA 3 series or general simulation performance tests. The ISTA 3 series is developed to simulate the damage-producing forces and conditions of transport environments (ISTA, 2003). It consists of several procedures designed for various types of distribution cycles. Each procedure contains a sequence of atmospheric conditioning, shock, compression, or vibration tests to evaluate the protective performance of packaged-products. Table 2-7 summarizes a list of procedures in the ISTA 3 series.

**Table 2-7: A List of ISTA 3 Series Procedures**

| Procedure or Project | Description |
|---|---|
| Project 3A | Packaged-Products for Parcel Delivery System Shipments 70 kg (150 lb) or Less |
| Procedure 3C | Packaged-Products 150 lb (68 kg) or Less for Parcel Delivery System Shipments |
| Procedure 3D | Small Packaged-Products Bagged for Parcel Delivery System Shipment |
| Procedure 3E | Unitized Loads of Same Product |
| Procedure 3F | Packaged Products for Distribution Center to Retail Outlet Shipment 100 lb (45 kg) |
| Procedure 3G | Thermal Controlled Transport Packaging for Parcel Delivery System Shipment (now Procedure 7D) |
| Procedure 3H | Performance Test for Products or Packaged-Products in Mechanically Handled Bulk Transport Containers |
| Procedure 3J | Reusable Intermediate Bulk Containers (now Procedure 7C) |

# CHAPTER 3: METHODOLOGY

The objective of this thesis research was to prove whether there was any effect of shock and vibration from distribution on the performance of an RFID transponder. The comparison between the RFID tag's reading performance after applying the distribution test and the performance from a control experiment helped to determine the effect of the distribution cycle. As indicators for a tag's reading performance, read ranges of RFID transponders were measured in the control experiment for reference. A series of shock and vibration tests based on the ASTM D 4169-04 were applied to RFID tags and shipping containers to simulate the transportation and handling activities during the product distribution cycle. After the distribution tests, tags' read ranges were measured and compared to data from the control experiment. A diagram of the RFID test is presented in Figure 3-1.

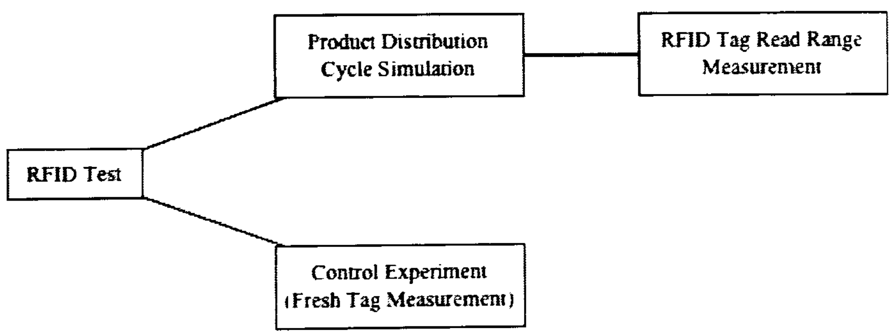



**Figure 3-1: Diagram of RFID Test**

This chapter describes the methods and equipment used in this thesis research project. It includes descriptions of the test specimens, equipment, test parameters, test configuration and protocols, as well as statistical analysis.

### *Test Specimen: RFID Transponder*

RFID transponders selected for the test were the 4" × 4" Dual Dipole tags fabricated by Matrics. The specification of the Matrics Dual Dipole tag was the passive, UHF (860 – 960 MHz), 96 bits + 16 bit CRC Read Only, EPCglobal Class 0, Version 1 (Matrics, 2004). The selected tags were designed for corrugated container application and complied with the specification requirements of both Wal-Mart[4] and the Department of Defense[5]. The physical structure of the 4" × 4" Dual Dipole tag label was composed of a microchip and 8.5 mil-thick paper stock printed with conductive ink to form antennas. Adhesive was applied to the tag label for conveniently adhering it to a corrugated container. The design of the dual dipole antenna helped to improve the orientation of tag readings. The reading distance of this RFID tag was up to 25 feet. Figure 3-2 presents the picture of Matrics 4" × 4" Dual Dipole tag.

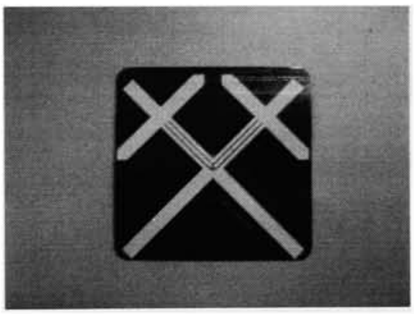


Figure 3-2: The Matrics 4" × 4" Dual Dipole Tag

### *Test Specimen: Test Product and Shipping Container*

Test products used in this research were food-storage plastic bags donated from Pactiv Corporation. The bags were fabricated from polyethylene. The primary package of the products was a 0.0175 inch-thick paperboard, folding carton composed of 25 units of product. The

[4] The UHF (868 – 956 MHz), 96-bit EPCglobal Class 0, 0+, or 1, RFID tags (RFID Journal, 2003)
[5] The UHF (860 – 960 MHz), 64- or 96-bit EPCglobal Class 0 or 1, RFID tags (Department of Defense, 2004)

product's shipping container was a single wall, C-flute, 26 lbs/in ECT, RSC[6] style, glue jointed, corrugated with a dimension of 9 4/7" × 13 4/7" × 11 5/8". The container holds 9 boxes of product. The total weight of a shipping container including product was 8.5 lbs. All product and packaging materials (i.e., paper and plastic) were radio frequency friendly. Test products, including their primary packages and shipping containers, were incorporated with RFID tags for read range measurement and product distribution cycle tests. Figure 3-3 shows the test product and shipping container.


**Figure 3-3: Test Product and Shipping Container**

***RFID Test Equipment***

A description of the equipment and tools for the RFID tag's read range measurement is as follows:

1) RFID Reader. The AR 400 reader was the UHF band (902 – 928 MHz), multi-protocol reader that can operate with various EPCglobal compliant tags, i.e., Class 0, 0+ and 1. It was designed for industrial use in plant or warehouse for item identification and visibility. The AR 400 reader had a maximum dynamic read range of 25 feet with the read rate up to 1,000 tags per second (Symbol Technologies, 2004). It also had multi-

[6] Regular Slotted Carton

ports, which can connect up to 4 read points (4 transmit and 4 receive). The reader can connect to a host computer for data transfer through multiple interfaces such as an I/O interface (DB15 connector), Ethernet interface (RJ45), RS422/485 interface, and RS232 interface (DB9 connector). The AR 400 reader is shown in Figure 3-4.

**Figure 3-4: The AR-400 Reader**

2) Read Antenna. The Matrics dual directional panel antenna was operated at 900 – 928 MHz (Matrics, 2004). Its dual directional design helped to cover more radiation area than the design of a single directional antenna. The dimensions of the antenna were 8.8" × 8.1" × 1.6". The dual directional panel antenna was connected to a reader via the LMR 240 cable. Typically, one read point required two antennas for transmitting and receiving radio signals. Figure 3-5 shows pictures of the Matrics antennas.
3) Personal Computer. A personal computer was used as a host computer to manage and control the AR-400 reader and RFID data. The minimum requirements for the host computer were a Microsoft Windows 95/98/2000 or Windows NT 4.0 operating system,

200 MHz Pentium II processor, 32 MB of RAM, UART[7] 16550A, and 20 MB HD space for evaluation software installation (Matrics, 2004).

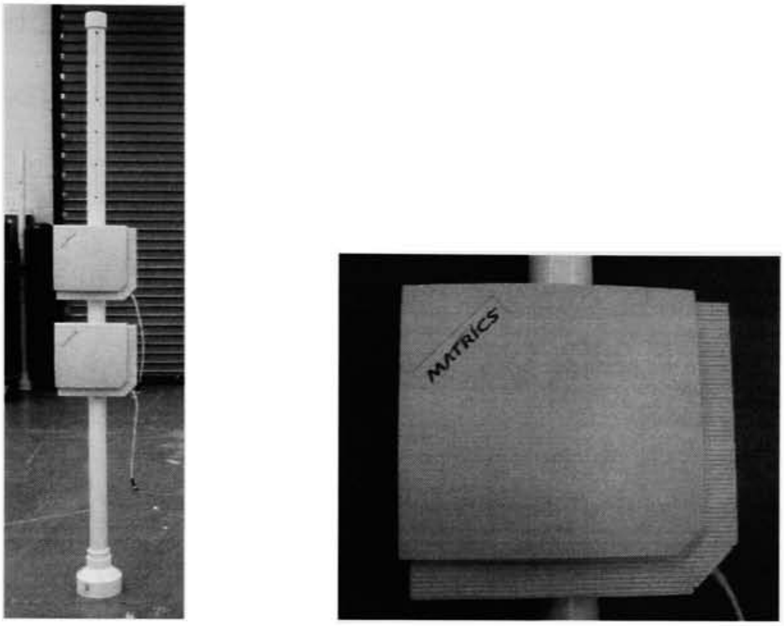



**Figure 3-5: The Dual Directional Panel Antenna**

4) RFID Evaluation Software. The Matrics Tag Tracker software was the evaluation software installed to a host computer and used to control RFID tag reading. The software displayed the item data when a reader detected transponders. It also recorded tag activities (i.e., the arrival and departure time) when RFID transponders entered or left the interrogation zone. Figure 3-6 illustrates the user interface of the evaluation software.
5) Thermometer/Hygrometer. A thermometer/hygrometer measured temperature and relative humidity of the environment during the tests.

[7] Universal Asynchronous Receiver/Transmitter, a computer component to manage serial port communications (Hyperdictionary, n.d.)

6) Cart. A cart carried RFID tags and shipping containers during the read range measurement. It was mainly made of wood (RF friendly) with a minimal portion of metal.

7) Tape Measure. A tape measure was used to measure the distance between the RFID transponder and the reading antennas.

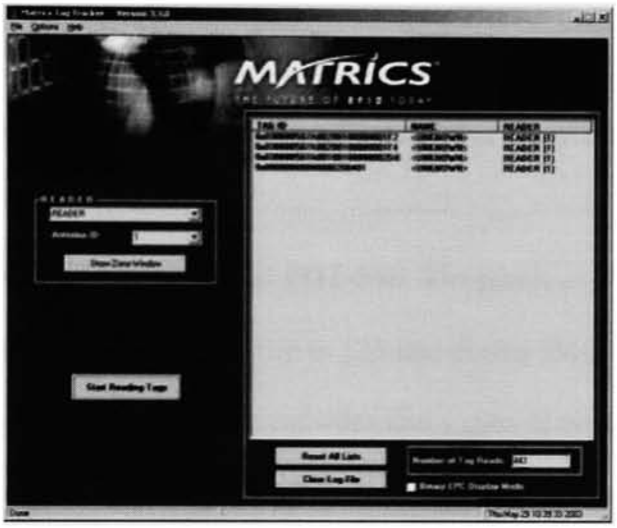



**Figure 3-6: The User Interface of Matrics Tag Tracker**

***Equipment for the Distribution Cycle Test***

1) Lansmont Vibration Test System: Model 7000-10 (Figure 3-7). The Lansmont vibration test system was the electro hydraulic machine used to simulate vibration during product distribution. Depending on the data programmed to the machine, the system can simulate the vibration of truck, air, or sea transportation based on ASTM standards. The machine can produce sinusoidal or random vibration from 3 to 300 Hz.

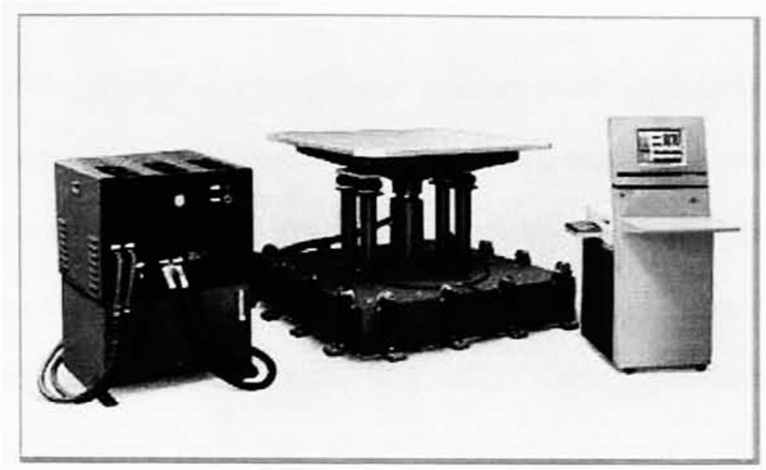


**Figure 3-7: Lansmont Vibration Test System (Lansmont, n.d.)**

2) Lansmont Precision Drop Tester: Model PDT-56E. The precision drop tester was used to simulate the drop of a single container (up to 125 lbs) during the distribution cycle. It was designed to perform a drop test at different sides and angles of container. The drop height was adjustable from 12" to 60". Figure 3-8 shows the Lansmont precision drop tester.

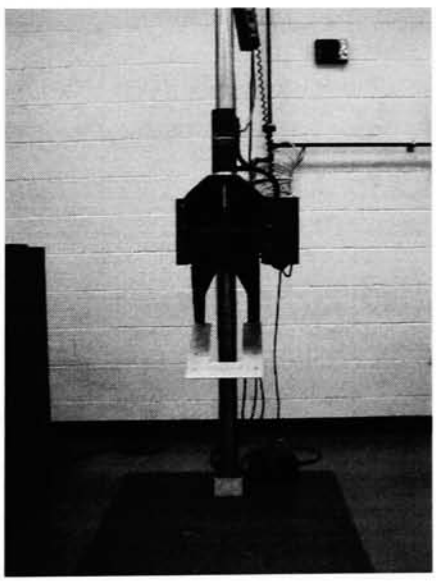


**Figure 3-8: Lansmont Precision Drop Tester**

*Test Parameters*

The test parameter selected as a performance measure in this research was the read range of an RFID tag. "Read range" was defined as the distance that a reader could reliably communicate with a transponder (RFID Journal, n.d.). Because of the non-uniform radiation pattern of an antenna, read range varies depending on the transponder's position to a read point (see Figure 3-9). Describing a tag's read range using a single value (a or b) without referring to its position will cause confusion. As a result, the tag's read range must be defined by using three values in a 3D space (x, y, z) and a read point as a reference (Zeller, 2001). In Figure 3-10, x represented the distance between a transponder and a reading antenna, while y and z were the horizontal and vertical deviation of the tag's location from an antenna. In this research, the tag's read ranges at several positions from a reading antenna were measured to determine the radiation pattern between a read point and the transponder.

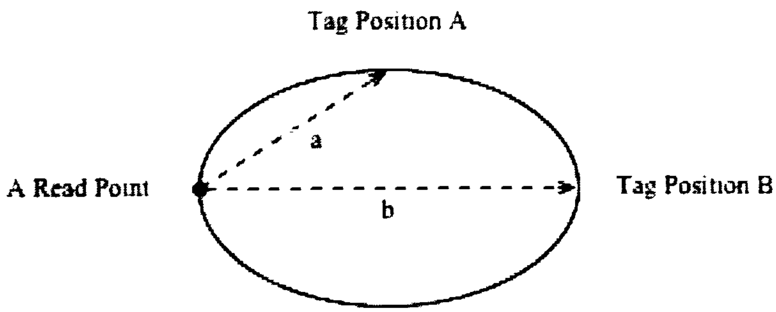



**Figure 3-9: Read Ranges of RFID Tag at Different Positions**

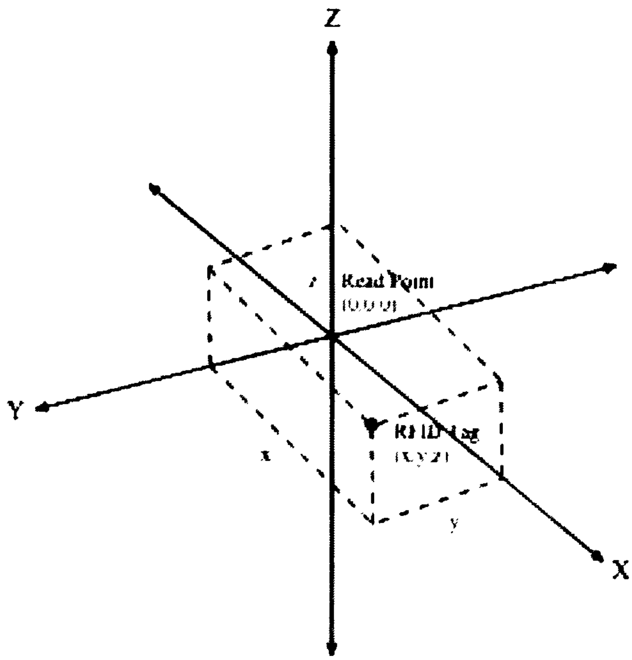



**Figure 3-10: RFID Tag Read Range Measurement**

Another parameter for the test was tag speed. Since most tag reading activities occurred when tags were delivered on a forklift or on a conveyor to the read point, read ranges of RFID transponders should also be measured while tags are moving at a specific speed. According to Rommel (2004), Wal-Mart specified its conveyor speed at 600 feet/min, which was the speed of moving a tag on a conveyor. However, because of human limitation during testing (tags were manually moved), the tag speed used for the read range measurement was 500 feet/min. Read ranges of a moving tag at 500 feet/min were measured and compared to read ranges of a non-moving tag to identify the effect of tag speed.

### *Sample Sizes*

Sample sizes were chosen for the distribution cycle test and the tag's read range measurement. For the distribution cycle test, sample size was determined based on the recommendation of an expert in transport packaging. Because of the limited number of testing specimens (i.e., products and shipping containers), the minimum sample size suggested for the test was 5 (Goodwin, 2004). Therefore, the number of transponders used for the tests was also 5.

The number of tests (or sample sizes) for each tag's read range measurement was considered from previous RFID research and work of experts in the field. Medina (2000) used 30 samples for each tag reading test in his doctoral dissertation, *"A Test Protocol to Characterize the Effect of Active Interference on the Performance of Radio Frequency Identification Systems"*. Zeller (2001) suggested using test sizes of 10, 20, and 30 in his draft of an RFID test plan for ISO/IEC 18046. While the test of multiple tags (5 tags) and several measuring points increased the complexity of the read range measurement, to simplify the experiment, the number of tests selected for this research was 10.

### *Data Structure*

The data structure in the RFID transponders was the Generation 1, EPC class 0 programmed from the manufacturer(i.e. Matrics). A sample of data structure is shown in Table 3-1. The first part of the data structure was the header that defined the length (e.g., 64 or 96 bits), type (e.g., SGTIN, GRAI), and structure of the EPC tag. The second part was the EPC manager number or manufacturer's identifier. The object class or product's SKU number was represented in the third part of the data structure. The final part indicated the tag's serial number.

**Table 3-1: Data Structure of Matrics RFID Transponder**

| Header | EPC Manager Number | Object Class | Serial Number |
|---|---|---|---|
| 0300 | 80507A | 802001 | 000009A52B |

***Test Configuration***

The test configuration for the tag's read range measurement is presented in Figures 3-11 and 3-12. Two reading antennas (one transmitted and one received radio signals) were combined and functioned as a read point. The middle point between two antennas was used as a reference point (0,0,0) for the read range measurement. As shown in Figure 3-11, transponder's read ranges were measured at five different positions: (x,0,0), (x,48,0), (x,-48,0), (x,0,23), and (x,0,-23). The distance x represented the maximum read range between a read point and a transponder in the X-axis. The orientation of both reading antennas and RFID tag during the read range measurement was 90 degrees.

***Transponder's Position on the Shipping Container***

According to AIM (2004), the recommendation for tag location on the transport package was between 1" to 17" above the bottom of container, but not closer to 1" from the top of the package. The placement of the transponder was also at least 0.75" from each vertical edge of the container. However, the position of the transponder selected for the distribution cycle test was 0.5" above the bottom and 0.5" from the glue joint of a container (see Figure 3-13). This location was considered the area most affected by shocks and vibrations during distribution (Goodwin, 2004). It was selected to simulate the worst-case scenario for the tests.

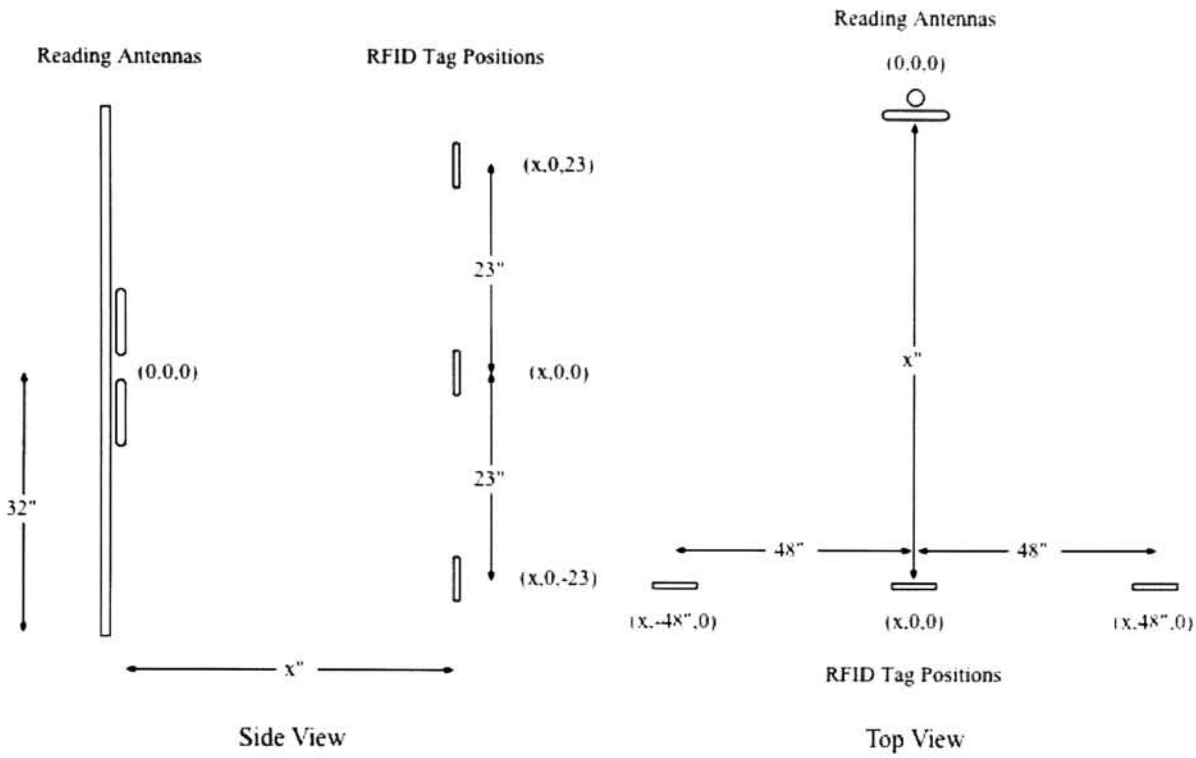



**Figure 3-11: Test Configuration for RFID Tag's Read Range Measurement**

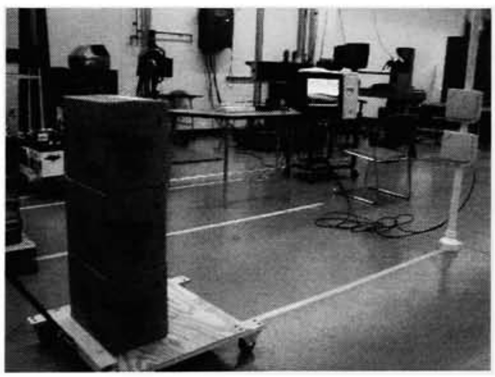


**Figure 3-12: Read Range Measurement of RFID Tag**


**Figure 3-13: Position of Transponder on the Shipping Case**

*Test Protocols*

There were two types of tests conducted for this thesis research: the read range measurement of RFID transponders and the distribution cycle test of tags and shipping containers. The RFID tag's read range measurement was performed twice for the control experiment and the read range test (after applying the distribution cycle simulation).

**Test Protocol for the RFID Tag's Read Range Measurement**

1) There were two read range measurement tests for nonmoving and moving transponders (see Figure 3-14). Both tests were performed in the dynamic packaging laboratory, where the distribution testing machines were located. To minimize the radio interference in the room, all equipment was turned off during the tests. Temperature and relative humidity in the lab were also recorded during the experiment.

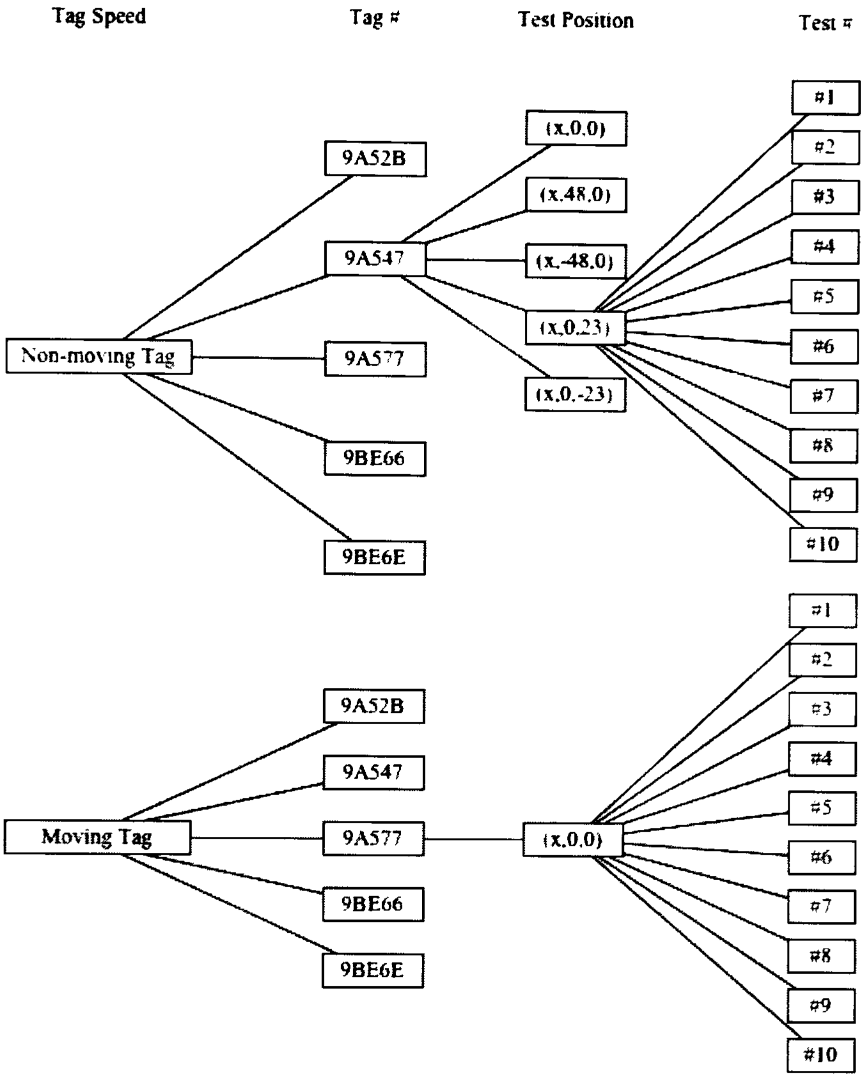



**Figure 3-14: Diagram of RFID Tag's Read Range Measurement Test**

2) For the non-moving tag test, a transponder was placed at one of the five positions shown in Figure 3-11. It was slowly moved (close to 0 feet/min) on a cart toward a read point. A transponder was stopped when tag data was read (tag data was constantly displayed on a computer screen). The distance x between a read point and a tag was measured and recorded. This procedure was repeated 10 times per testing position per tag.

3) For the moving tag test, a transponder was measured at the (x,0,0) position. It was moved on a cart toward a read point at a speed of 500 feet/min. A digital video camera was used to record a moving tag during the test. The voice signal was also recorded to indicate when tag data was read. Information from a video camera was used to determine a read range of the test transponder. This process was repeated 10 times per tag.

**Test Protocol for the Distribution Cycle Test**

The distribution cycle for the test was referred to a general product distribution from a manufacturer to a retailer. Typically, products are loaded and shipped in unitized pallets from a manufacturer to distribution centers around the country. At each distribution center, products are unloaded, mixed with other goods, and loaded into pallets for shipping to retail stores. In this thesis research, a series of distribution tests were developed to simulate activities during product shipment from a distribution center to a retail store (the distribution cycle of products on mixed pallets).

The standard and procedure selected to develop the test protocol was based on the recommendation of experts in the field. According to Proctor (2005), ASTM D 4169-04 standard was used to simulate the distribution cycle. Figure 3-15 shows a diagram of the distribution cycle test. The distribution cycle selected for the test was to simulate the handling and motor freight transportation (truck load, TL) of containers in the non-unitized or mixed pallet. The test sequence was referred to distribution cycle number 5 in Table 1 of the D 4169-04 standard. Table 3-2 summarizes the test sequence for the distribution cycle number 5.

**Table 3-2: Test Sequence for the Distribution Cycle Number 5**

| Sequence | Test Schedule | Test Method | Assurance Level |
|---|---|---|---|
| 1 | Schedule A – Manual Handling | D 5276 | II |
| 2 | Schedule D – Stacked Vibration | D 4728 Method A or B (Random Test for Truck) | II |
| 3 | Schedule E – Vehicle Vibration | D 4728 Method A or B (Random Test for Truck) | II |
| 4 | Schedule A – Manual Handling | D 5276 | II |

The test sequence in Table 3-2 was composed of schedule A, D, E, and A. Assurance level II was selected for the intermediate test intensity and the moderate probability of occurrence. The manual handling test in schedule A simulated hazard from throwing or dropping a shipping container during loading, unloading, or palletizing activity. Schedule D and E generated the vertical vibration environment during truck transportation. The dynamic compression stress from vehicle stacking to a shipping container and a transponder was also applied in schedule D. The compression stress (L) used in this test was 72 lbs[8]. The details of the test protocol for each schedule were in the ASTM D 4169-04 standards.

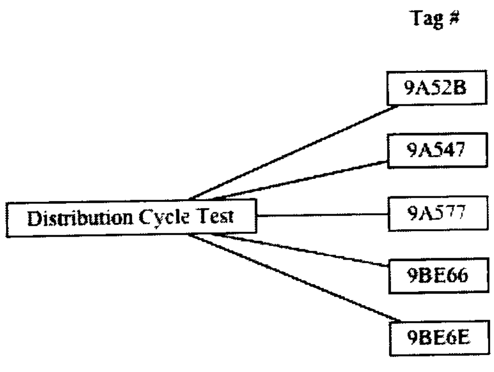



**Figure 3-15: Diagram of Distribution Cycle Test**

[8] See Appendix A for the calculation of compression strength for stacked vibration test

*Statistical Analysis*

The researcher's t distribution was selected to represent the distribution of the RFID tag's read range data. The following are the tests of hypothesis concerning the difference between the mean of the tag's read range ($\mu_1$) from the control experiment and the mean of the tag's read range after the distribution cycle test ($\mu_2$) (Mendenhall, Beaver, & Beaver, 2003).

Null hypothesis: $H_0$: $\mu_1 - \mu_2 = D_0$ (where $D_0 = 0$)

Alternative hypothesis: $H_a$: $\mu_1 - \mu_2 \neq D_0$ (two-tailed test)

Test statistic:
$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \qquad \text{equation 3-1}$$

where
$$s^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{(n_1 + n_2 - 2)} \qquad \text{equation 3-2}$$

Rejection Region: Reject $H_0$ if $t > t_{\alpha/2}$ or $t < -t_{\alpha/2}$

The $\bar{x}_1$, $s_1^2$, $n_1$ were the sample average, variance, and sample size of the tag's read range from the control experiment, while the $\bar{x}_2$, $s_2^2$, $n_2$ were the sample average, variance, and sample size of the tag's read range after the distribution cycle test. The values $t$ and $t_{\alpha/2}$ were based on the degree of freedom of $(n_1 + n_2 - 2)$. The assumptions for the researcher's t distribution depended on the random selection of samples from the normal distribution populations and the equality of variances ($\sigma_1^2$ and $\sigma_2^2$) from both tags' read range tests.

# CHAPTER 4: RESULTS, ANALYSIS, AND DISCUSSION

This chapter addresses the test results, statistical analysis, and discussion of the non-moving and moving tag data from the read range measurement and the control experiment.

***Read Range Measurement of Non-moving Tags***

**Table 4-1: A Summary of Tag's Read Ranges from the Control Experiment (in)**

| Tag Serial Number | Test Position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (x,0,0) | | (x,48,0) | | (x,-48,0) | | (x,0,23) | | (x,0,-23) | |
| | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ |
| 9A52B | 135.13 | 1.40 | 86.49 | 1.09 | 87.10 | 1.87 | 111.59 | 1.71 | 138.43 | 1.65 |
| 9A547 | 130.82 | 2.08 | 81.22 | 2.05 | 82.57 | 1.63 | 112.54 | 1.03 | 130.79 | 1.38 |
| 9A577 | 137.71 | 1.67 | 81.18 | 1.90 | 84.94 | 1.14 | 115.06 | 2.05 | 139.70 | 2.09 |
| 9BE66 | 132.38 | 1.27 | 82.06 | 1.92 | 83.11 | 2.77 | 115.06 | 1.51 | 131.74 | 1.83 |
| 9BE6E | 134.49 | 1.71 | 84.68 | 2.02 | 85.16 | 1.77 | 115.79 | 1.71 | 139.16 | 1.76 |
| Total | 134.11 | 2.87 | 83.13 | 2.76 | 84.58 | 2.45 | 114.01 | 2.28 | 135.96 | 4.26 |

**Table 4-2: A Summary of Tag's Read Range from the Read Range Test (in)**

| Tag Serial Number | Test Position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (x,0,0) | | (x,48,0) | | (x,-48,0) | | (x,0,23) | | (x,0,-23) | |
| | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ |
| 9A52B | 134.22 | 1.89 | 87.16 | 1.41 | 87.78 | 1.66 | 111.69 | 1.00 | 139.60 | 1.21 |
| 9A547 | 131.84 | 1.29 | 82.78 | 1.81 | 81.23 | 1.63 | 113.24 | 0.77 | 130.78 | 1.46 |
| 9A577 | 136.91 | 1.41 | 82.18 | 2.20 | 85.44 | 0.77 | 115.43 | 1.95 | 138.99 | 0.70 |
| 9BE66 | 132.33 | 1.56 | 83.46 | 1.67 | 84.98 | 0.83 | 116.35 | 1.32 | 131.08 | 0.89 |
| 9BE6E | 133.11 | 1.41 | 85.43 | 1.55 | 86.50 | 1.11 | 117.03 | 2.27 | 139.08 | 1.84 |
| Total | 133.68 | 2.34 | 84.20 | 2.50 | 85.19 | 2.53 | 114.75 | 2.51 | 135.90 | 4.29 |

Table 4-1 and 4-2 present the averages ($\bar{x}$) and standard deviations ($s$) of non-moving tag's read ranges from the control experiment and the read range test. The tests were performed at 68.70° F and 35.11% humidity for controlled tags and 68.63° F and 34.98% humidity for tested tags. According to the data in Tables 4-1 and 4-2, read ranges of transponders varied at different test positions. The RFID tag had a high read range at (x.0,0) and (x,0,-23) positions (130s inch range). Read range decreased when changing test position horizontally or vertically[9] from a read point (0,0,0).

The decrease of read ranges was symmetric when the test position was horizontally moved (either right or left) from a read point. The values of the tags' read ranges at (x,48,0) and (x,-48,0) in Tables 4-1 and 4-2 were close. However, the vertical alteration of test positions (either up or down) from reading antennas caused asymmetrical changes to the tags' read ranges. According to Tables 4-1 and 4-2, all read ranges at the upper position (x,0,23) were less than those at the lower position (x,0,-23).

### *Read Range Measurement of Moving Tags*

Table 4-3: A Summary of Moving Tag's Read Ranges at 500 feet/min (feet)

| Tag Serial Number | Controlled Tag | | Tested Tag | |
|---|---|---|---|---|
| | $\bar{x}$ | $s$ | $\bar{x}$ | $s$ |
| 9A52B | 7.38 | 0.75 | 7.19 | 0.83 |
| 9A547 | 7.61 | 0.49 | 7.31 | 0.72 |
| 9A577 | 6.53 | 0.84 | 6.76 | 1.11 |
| 9BE66 | 7.01 | 0.91 | 7.24 | 0.77 |
| 9BE6E | 7.26 | 0.74 | 7.10 | 1.13 |
| Total Average | 7.16 | 0.82 | 7.12 | 0.91 |

Table 4-3 summarizes the read range data of moving tags at 500 feet/min from the control experiment and the read range test. All read ranges were measured at (x,0,0) test position. Temperatures and relative humidity recorded during the tests were 68.70° F and 35.11%

[9] In a case of positive direction

humidity for controlled transponders and 68.63° F and 34.98% humidity for tested transponders. The $\bar{x}$ and $s$ values in Table 4-3 represent the average and standard deviation of data samples.

### *Relationship between Tag's Read Range and Moving Speed*

**Table 4-4: Comparison of Tag's Read Ranges at 0 and 500 feet/min (in)**

| Tag Serial Number | Controlled Tag | | Tested Tag | |
|---|---|---|---|---|
| | Non-moving Tag | Moving Tag | Non-moving Tag | Moving Tag |
| 9A52B | 135.13 | 88.56 | 134.22 | 86.28 |
| 9A547 | 130.82 | 91.32 | 131.84 | 87.72 |
| 9A577 | 137.71 | 78.36 | 136.91 | 81.12 |
| 9BE66 | 132.38 | 84.12 | 132.33 | 86.88 |
| 9BE6E | 134.49 | 87.12 | 133.11 | 85.20 |
| Total Average | 134.11 | 85.92 | 133.68 | 85.44 |

Table 4-4 shows the read range comparison of non-moving and moving transponders at (x,0,0) position. From this table, all read ranges of the non-moving tags (0 feet/min) were higher than those of the moving tags (500 feet/min). This indicates a reduction of a tag's read range when increasing a tag's moving speed.

### *Comparison of Non-moving RFID Tag Read Ranges*

Figures 4-1 and 4-2 present the average read range comparison of 9A547 tag from the control experiment and the read range test.

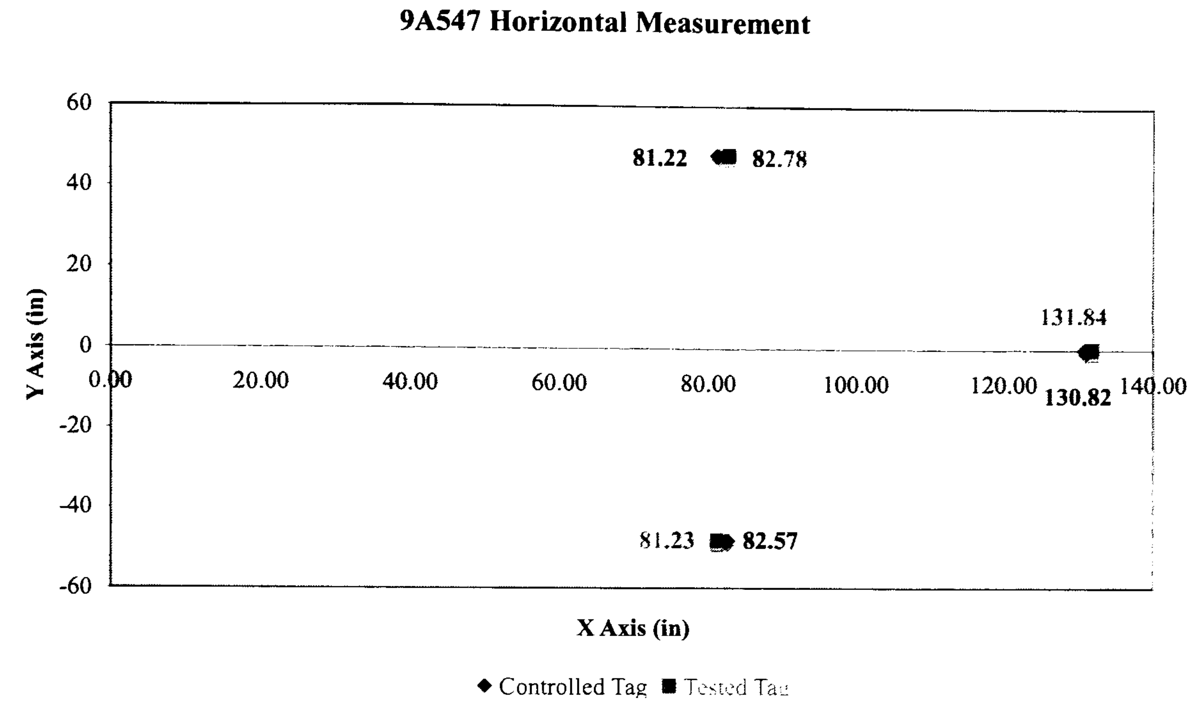



**Figure 4-1: Comparison of 9A547 Tag's Read Range Data in Horizontal Positions**

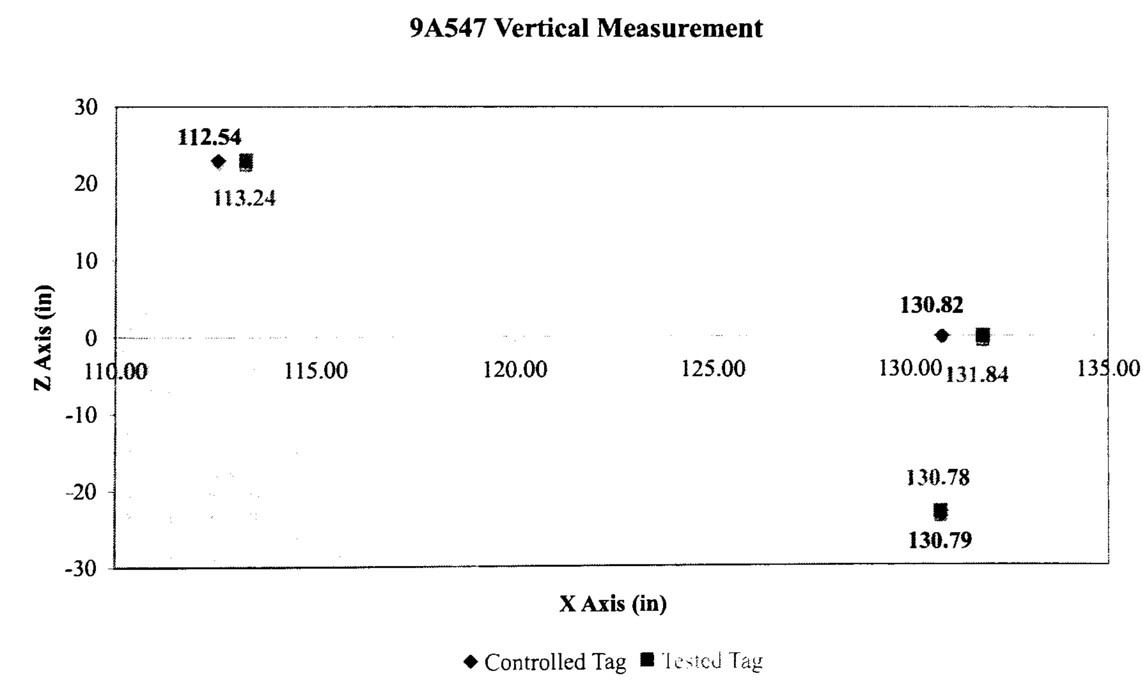



**Figure 4-2: Comparison of 9A547 Tag's Read Range Data in Vertical Positions**

From Figures 4-1 and 4-2, there were slight differences between the average read ranges of controlled and tested tags. The researcher's t test was used to determine the significant difference between these two data groups. Employing data from Tables 4-1 and 4-2, the t values were calculated from equation 3-1 and 3-2. Table 4-5 summarizes the t values for the non-moving tag's read range comparison.

**Table 4-5: The t Values for Non-moving Tag's Read Range Comparison**

| Tag Serial Number | Tag Positions | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| | t | t | t | t | t |
| 9A52B | 1.22629 | -2.01533 | -0.85290 | -0.14950 | -1.80655 |
| 9A547 | -1.32483 | -1.80678 | 1.83466 | -1.70653 | 0.00982 |
| 9A577 | 1.15829 | -1.09433 | -1.13491 | -0.41214 | 1.02187 |
| 9BE66 | 0.08856 | -1.73185 | -2.05341 | -2.04235 | 1.02950 |
| 9BE6E | 1.97279 | -1.75864 | -2.02990 | -1.37594 | 0.10097 |
| Total | 0.81292 | -2.04248 | -1.22473 | -1.53824 | 0.06873 |

According to the researcher's t test method described in Chapter 3, the read ranges of controlled and tested tags are different (or reject the null hypothesis) if the positive t value is more than $t_{\alpha/2}$ or the negative t value is less than -$t_{\alpha/2}$. For the $\alpha$ of 0.05 and the degree of freedom of 18[10], the $t_{\alpha/2}$ is equal to 2.101 (Mendenhall, Beaver, & Beaver, 2003).

In Table 4-5, all of the t values were either less than $t_{\alpha/2}$ or 2.101 or more than -$t_{\alpha/2}$ or -2.101. Therefore, there was no significant difference between the read ranges of controlled and tested transponders at 95% confidence.

[10] Degree of freedom is equal to $(n_1 + n_2 - 2) = (10 + 10 - 2) = 18$.

*Comparison of Moving RFID Tag Read Ranges*

**Table 4-6: The t Values for Moving Tag's Read Range Comparison**

| Tag Serial Number | t Values |
|---|---|
| 9A52B | 0.54237 |
| 9A547 | 1.08974 |
| 9A577 | -0.53158 |
| 9BE66 | -0.61963 |
| 9BE6E | 0.37053 |
| Total | 0.09478 |

Table 4-6 provides a summary of t values for identifying the difference between the moving tag's data from the control and read range tests. The t values for the read range comparison were calculated from data in Table 4-3.

All of the t values in Table 4-6 were either less than $t_{\alpha/2}$ or 2.101 or more than - $t_{\alpha/2}$ or -2.101. As a result, it can be concluded that, with 95% confidence, the read ranges of moving tags from the control experiment and the read range test were not significantly different.

*Research Discussion*

The test results discussed in the previous sections indicate the influence of a tag's position and speed to the read ranges of the RFID transponder. As a result, to determine the difference between the read ranges of tested and controlled tags, the characteristics of the transponder's read range at different positions and speeds need to be understood. A comparison of the tag's read ranges should be performed at several test positions and moving speeds.

Read ranges of a transponder vary when changing a tag's position. Theoretically, an RFID tag has its maximum read range at a position parallel to a read point or (x,0,0). From the experiment, read ranges decreased symmetrically when the transponder's position was moved on the horizontal axis. This is due to the radio transmission pattern of a read point and an RFID tag. However, asymmetrical changes of the transponder's read ranges occurred when there were vertical alterations of the tag's position. Read range was decreased at the position above the reading antennas, i.e. (x,0,23), while it was slightly increased when the tag was moved from (x,0,0) to (x,0,-23). This may result from the radiation pattern of the combined reading antennas or the reflection of radio waves on the lab floor that extends a tag's read range.

Another factor that affects a tag's read range is the speed of the transponder. The read range of the test transponder was decreased when the tag speed increased (from 0 to 500 feet/min). This is possibly explained by the tag's read time or the time used to interrogate data from a transponder. Typically, the read time of an RFID tag is in milliseconds. Having the same read time, the tag moving toward a read point at high speed will be closer to the reading antennas than the one moving at low speed. Therefore, the read range of a high-speed tag (i.e., a distance between reading antennas and a transponder when a tag is successfully read) is less than that of a low-speed tag.

According to the researcher's t statistical comparison, read ranges of controlled and tested tags at each test position and speed were not significantly different at 95% confidence. As a result, it can be concluded that the shock and vibration from the distribution cycle (i.e., motor freight, TL, non-unitized pallet) has no effect on the read range performance of the test transponder. This demonstrates the robustness of an RFID tag's ability to withstand physical hazard during the distribution of the test products. However, it should be noted that a lightweight product (8.5 lbs) was used in this thesis research; there should be an investigation of the effect on the RFID tag's performance from the distribution of heavyweight product. This will be discussed later in Chapter 5.

# CHAPTER 5: CONCLUSION

### *Thesis Conclusion*

This thesis research was performed to investigate the effect of shock and vibration during distribution on the performance of an RFID transponder. The RFID system selected for this study was the passive, Ultra-high frequency (865 to 956 MHz) system that complied with the requirements of Wal-Mart and the DoD. The performance of an RFID tag was determined based on a transponder's read range. Two types of experiments were conducted in this research. These were the test protocols used to identify the read range characteristics of an RFID transponder and the simulation of the product distribution cycle based on the ASTM D 4169-04 standard. The effect of shock and vibration on RFID tags was examined through the comparison of a transponder's read range from the control experiment and the read range test. Test results demonstrated no statistical difference between the two groups of data. These results indicate that the shock and vibration generated from simulated product distribution do not have any effect on the performance of an RFID transponder.

### *Recommendations for Future Research*

The examination of the effect of shock and vibration to the RFID tag performance in this thesis study was restricted to a single type of transponder, product, package, and distribution cycle. While changes to one of these factors could alter the results of the research, it also creates opportunities for further studies. Recommendations for future research are as follows.

1) As discussed at the end of Chapter 4, the effect on an RFID transponder of shock and vibration from the distribution of heavyweight product should be investigated. The increase of product weight will increase the magnitude of shock and vibration during the

distribution process. It would be interesting to examine whether there is any effect of heavyweight product distribution on an RFID tag's performance.

2) Besides increasing product weight, changing the assurance level to I increases the intensity of the distribution cycle test to an RFID transponder and, therefore, is recommended for future study.

3) Applying the test protocols from this thesis study to different RFID transponders is recommended. This will help to evaluate and compare the robustness of RFID tags in the distribution environment.

4) While this research was limited to only one distribution cycle, the effect of other distribution cycles on RFID tags should also be studied. The recommended distribution cycles are the cycle for train transportation, the cycle for export/import shipment (by sea), and the cycle that has high temperature and relative humidity conditions.

5) The adjustment of the read range measurement protocol, e.g., adding more test positions or tag speeds, will increase the understanding of the radiation pattern between reading antennas and the RFID transponder or the relationship between read range and the speed of the tag.

# REFERENCES


American Society for Testing and Materials. (2004). *ASTM D 4169-04: Standard Practice for Performance Testing of Shipping Containers and Systems*. West Conshoshocken: ASTM International.

Ames, R. (Ed.). (1990). *Perspectives in Radio Frequency Identification*. New York: Van Nostrand Reinhold.

Association of Automatic Identification and Mobility. (2000). *Draft Paper on the Characteristics of RFID-Systems*. Retrieved November 12, 2004, from http://www.aimglobal.org/technologies/rfid/resources/RFIDCharacteristics.pdf

Association of Automatic Identification and Mobility. (2004). *Guidance from AIM Global's RFID Expert Group: Proposed Guidelines for the Use of RFID-Enabled Labels in Military Logistics: Recommendations for Revision of MIL-STD-129*. Retrieved November 30, 2004, from http://www.aimglobal.org/standards/changes/REG0401_v1.05.pdf

Association of Automatic Identification and Mobility. (2001). *Radio Frequency Identification – RFID: A Basic Primer*. Retrieved October 10, 2004, from http://www.aimglobal.org/technologies/rfid/resources/papers/rfid_basics_primer.asp

Association of Automatic Identification and Mobility. (2001). *Radio Frequency Identification: A Glossary*. Retrieved October 7, 2004, from http://www.aimglobal.org/technologies/rfid/ resources/RFIDGlossary.pdf

Blue, L. & Powel, K. (n.d.). *Matrics White Paper: EPC And Radio Frequency Identification (RFID) Standards*. Retrieved August 30, 2004, from http://www.matrics.com/resource/

Department of Defense. (2004). *Frequently Ask Questions: Standards and Tag Data Requirements*. Retrieved December 5, 2004, from http://www.acq.osd.mil/log/ logistics_materiel_readiness/organizations/sci/rfid/rfid_faq.htm#Standards_and_Tag

EPCglobal. (2004). *EPC Tag Data Standards Version 1.1 Rev.1.24: Standard Specification.* Retrieved November 11, 2004, from http://www.epcglobalinc.org/standards_technology/ EPCTagDataSpecification11rev124.pdf

EPCglobal. (2003). *What Is the Electronic Product Code (EPC)?* Retrieved November 11, 20004, from http://www.epcglobalinc.org/about/faqs.html#7

Finkenzeller, K. (2003). *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification* (2nd ed.). (Rachel Waddington, Trans.). West Sussex: Wiley.

Goodwin, D. (2004). [Interview with Dr. Daniel Goodwin, Professor at Department of Packaging Science, Rochester Institute of Technology]

Harrop, P. (2001). Radio City: Radio Frequency Identification (RFID). Brand, no.1, Nov.-Dec. 2001, 20-31.

High Tech Aid. (2004). *ISO/IEC RFID Related Standards.* Retrieved November 15, 2004, from http://www.hightechaid.com/standards/RFID_Standards_SC31.htm

Hodges, S. & Harrison, M. (2003). *Demystifying RFID: Principles & Practicalities.* Retrieved October 6, 2004, from http://www.autoidlabs.org/researcharchive

Hyperdictionary. (n.d.). Meaning of Universal Asynchronous Receiver/Transmitter. Retrieved December 2, 2004, from http://www.hyperdictionary.com/dictionary/ Universal+Asynchronous+Receiver%2fTransmitter

Institute of Electrical and Electronics Engineers. (1997). *IEEE Standard Definitions of Terms for Radio Wave Propagation.* New York: IEEE.

International Safe Transit Association. (2003). *ISTA Tests.* Retrieved November 10, 2004, from http://www.ista.org/Testing/Tests.htm

Landt, J. (2001). *Shrouds of Time: The History of RFID.* Retrieved October 5, 2004, from http://www.aimglobal.org/technologies/rfid/resources/shrouds_of_time.pdf

Lansmont. (n.d.). *Vibration Test System: Model 7000 Vibration Tester.* Retrieved November 20, 2004, from http://www.lansmont.com/TestEquipment/Vibration/VibSystems/ Vib7000.htm

Matrics. (2004). *AR 400 Reader User's Manual.* Rockville: Matrics.

Matrics. (2004). *Dual Directional Panel Antenna Data Sheet.* Retrieved December 1, 2004, from http://www.matrics.com/products/antennas.shtml

Matrics. (2004). *Matrics Tag Family Data Sheet.* Retrieved December 1, 2004, from http://www.matrics.com/products/tags.shtml

Mendenhall, W., Beaver, R. J. & Beaver, B. M. (2003). *Introduction to Probability and Statistics* (11th edition). Pacific Grove: Brooks/Cole-Thomson Learning.

Medina, J. D. P. (2000). "A Test Protocol to Characterize the Effect of Active Interference on the Performance of Radio Frequency Identification Systems." Diss. University of Pittsburgh.

NCIT Okinawa. (2004). *Virtual Museum: Zone 2.* Retrieved November 8, 2004, from http://www2.nict.go.jp/dk/c218/EN/VM/02/index01.html

O'Conner, M. C. (2004). *RFID Journal: Intermec Suspends Royalties for 60 Days.* Retrieved November 12, 2004, from http://www.rfidjournal.com/article/articleview/1220/1/1/

Procter, K. (2004). [Interview with Karen Proctor, Professor at Department of Packaging Science, Rochester Institute of Technology]

Qualitative Reasoning Group. (n.d.). *How Is Data Put on Radio Waves?* Retrieved November 8, 2004, from http://www.qrg.northwestern.edu/projects/vss/docs/Communications/1-how-is-data-put-on-radio-waves.html

RFID Journal. (n.d.). *RFID Journal: Electronic Product Code FAQs*. Retrieved November 11, 2004, from http://www.rfidjournal.com/article/articleview/219

RFID Journal. (n.d.). *RFID Journal: Glossary of RFID Terms*. Retrieved October 16, 2004, from http://www.rfidjournal.com/article/articleview/208

RFID Journal. (2003). *RFID Journal: Wal-Mart Expands RFID Mandate*. Retrieved January 10, 2004, from http://www.rfidjournal.com/article/articleview/539/1/1/

Rommel, J. (2004). *Matrics White Paper: Understanding the Wal-Mart Initiative: Making Sense of EPC Standards and Wal-Mart RFID Requirements.* Retrieved December 1, 2004, from http://www.matrics.com/cgi/registration.php?id=WP_WALMART&type=PDF

Sabetti, A. (1998). *Applications of Radio Frequency Identification.* Retrieved October 10, 2004, from http://www.aimglobal.org/technologies/rfid/resources/papers/applicationsofrfid.htm

Salt, D. (2002). Synchrotrons – Making the Light Fantastic: Glossary. Retrieved October 20, 2004, from http://www.science.org.au/nova/068/068glo.htm

Sarma, S. E. & Engels, D. W. (2002). *RFID Systems, Security & Privacy Implications*. Retrieved October 10, 2004, from http://www.autoidlabs.org/researcharchive

Scharfeld, T. A. (2001). "An Analysis of the Fundamental Constraints on Low Cost Passive Radio-Frequency Identification System Design" Diss. Massachusetts Institute of Technology.

Symbol Technologies. (2004). *AR 400 Data Sheet.* Retrieved December 3, 2004, from ftp://symstore.longisland.com/Symstore/pdf/RFID/AR_400_0904.pdf

Zeller, C. (2001). Draft of RFID Test Plan. Retrieved August 5, 2004, from http://www.autoid.org/2002_Documents/wg3_sg1/WG3SG1_054_RFID_drTestPlan.doc

# APPENDIX A

## The Calculation of Compression Strength for the ASTM D 4169 Test Schedule D

The calculation of compression strength for the test schedule D is presented as follows.

$$L = M_f \times J \times \left(\frac{l \times w \times h}{K}\right) \times \left(\frac{H-h}{h}\right) \times F$$

where:

L = computed load (lbf)

$M_f$ = product density, 10 lb/ft$^3$

J = 1 lbf/lb

H = height of stack in transit vehicle, in this case was 108 in

h = height of shipping container, 11 5/8 in

l = length of shipping container, 9 4/7 in

w = width of shipping container, 13 4/7 in

K = 1,728 in.$^3$/ ft$^3$,

F = factor equal to 1

$$\therefore \quad L = 10 \times 1 \times \left(\frac{9\tfrac{4}{7}" \times 13\tfrac{4}{7}" \times 11\tfrac{5}{8}"}{1{,}728}\right) \times \left(\frac{108" - 11\tfrac{5}{8}"}{11\tfrac{5}{8}"}\right) \times 1$$

$$= 72 \text{ lbs}$$

# APPENDIX B

## Test Results of RFID Tags' Read Range Measurement

### Table B-1: Read Ranges of 9A52B Tag from the Control Experiment (in)

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 133.25 | 84.69 | 84.38 | 109.69 | 135.25 |
| 2 | 133.63 | 85.13 | 84.44 | 109.75 | 136.63 |
| 3 | 134.00 | 85.50 | 85.13 | 110.13 | 137.63 |
| 4 | 134.25 | 86.13 | 86.75 | 110.25 | 138.19 |
| 5 | 134.44 | 86.63 | 87.25 | 111.00 | 138.75 |
| 6 | 135.38 | 86.88 | 87.94 | 111.94 | 138.88 |
| 7 | 136.00 | 87.13 | 88.31 | 112.13 | 139.00 |
| 8 | 136.63 | 87.31 | 88.31 | 112.75 | 139.25 |
| 9 | 136.63 | 87.50 | 89.25 | 113.81 | 139.50 |
| 10 | 137.13 | 88.00 | 89.25 | 114.50 | 141.25 |

### Table B-2: Read Ranges of 9A547 Tag from the Control Experiment (in)

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 127.25 | 77.88 | 80.00 | 111.50 | 128.75 |
| 2 | 128.75 | 78.88 | 80.38 | 111.56 | 129.25 |
| 3 | 129.50 | 79.13 | 81.38 | 111.69 | 129.88 |
| 4 | 129.88 | 80.50 | 81.44 | 111.88 | 130.13 |
| 5 | 130.00 | 81.44 | 82.75 | 112.19 | 130.38 |
| 6 | 131.50 | 81.75 | 83.56 | 112.31 | 130.50 |
| 7 | 132.25 | 82.38 | 83.94 | 112.75 | 131.69 |
| 8 | 132.44 | 83.25 | 83.94 | 113.25 | 132.19 |
| 9 | 132.63 | 83.50 | 84.06 | 113.75 | 132.38 |
| 10 | 134.00 | 83.50 | 84.25 | 114.56 | 132.75 |

**Table B-3: Read Ranges of 9A577 Tag from the Control Experiment (in)**

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 135.31 | 78.50 | 82.63 | 112.38 | 137.50 |
| 2 | 135.31 | 78.50 | 83.75 | 112.63 | 137.75 |
| 3 | 136.88 | 80.38 | 84.50 | 113.38 | 138.00 |
| 4 | 137.63 | 80.63 | 84.88 | 113.13 | 138.00 |
| 5 | 137.63 | 80.63 | 84.88 | 115.25 | 138.50 |
| 6 | 137.88 | 80.81 | 85.00 | 115.63 | 139.25 |
| 7 | 137.88 | 82.06 | 85.38 | 116.13 | 140.75 |
| 8 | 138.38 | 82.75 | 85.94 | 116.56 | 142.25 |
| 9 | 139.50 | 83.38 | 86.00 | 117.63 | 142.38 |
| 10 | 140.75 | 84.13 | 86.50 | 117.88 | 142.63 |

**Table B-4: Read Ranges of 9BE66 Tag from the Control Experiment (in)**

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 130.38 | 79.50 | 78.00 | 113.19 | 129.38 |
| 2 | 131.25 | 79.75 | 80.25 | 113.25 | 129.88 |
| 3 | 131.56 | 80.00 | 81.31 | 113.50 | 130.13 |
| 4 | 132.25 | 81.63 | 81.88 | 114.00 | 130.50 |
| 5 | 132.63 | 81.75 | 83.25 | 115.25 | 131.00 |
| 6 | 132.00 | 82.25 | 83.44 | 115.63 | 131.88 |
| 7 | 132.75 | 82.75 | 84.56 | 115.63 | 132.88 |
| 8 | 132.88 | 84.00 | 85.75 | 115.88 | 133.25 |
| 9 | 133.00 | 84.00 | 86.13 | 116.75 | 134.00 |
| 10 | 135.13 | 85.00 | 86.50 | 117.50 | 134.50 |

**Table B-5: Read Ranges of 9BE6E Tag from the Control Experiment (in)**

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 131.88 | 81.56 | 83.63 | 114.25 | 136.50 |
| 2 | 133.13 | 82.75 | 83.13 | 114.44 | 137.69 |
| 3 | 133.13 | 83.50 | 83.13 | 114.69 | 138.00 |
| 4 | 133.19 | 83.88 | 83.75 | 114.69 | 138.25 |
| 5 | 134.13 | 84.13 | 84.75 | 114.88 | 138.69 |
| 6 | 135.13 | 84.13 | 85.00 | 115.06 | 139.00 |
| 7 | 135.25 | 85.25 | 86.38 | 116.50 | 139.38 |
| 8 | 135.25 | 86.50 | 86.88 | 116.63 | 140.31 |
| 9 | 136.50 | 87.25 | 87.00 | 117.00 | 141.75 |
| 10 | 137.38 | 87.88 | 87.94 | 119.75 | 142.00 |

**Table B-6: Read Ranges of 9A52B Tag from the Read Range Test (in)**

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 130.25 | 85.00 | 85.75 | 110.25 | 137.63 |
| 2 | 132.25 | 85.25 | 85.88 | 110.50 | 138.38 |
| 3 | 133.25 | 85.81 | 86.00 | 111.00 | 138.56 |
| 4 | 133.88 | 86.56 | 86.88 | 111.19 | 138.81 |
| 5 | 134.44 | 87.19 | 87.56 | 111.50 | 139.44 |
| 6 | 134.94 | 88.13 | 88.00 | 111.88 | 140.00 |
| 7 | 134.94 | 88.13 | 88.31 | 112.19 | 140.50 |
| 8 | 136.00 | 88.25 | 89.13 | 112.38 | 140.69 |
| 9 | 136.00 | 88.63 | 90.13 | 112.50 | 141.00 |
| 10 | 136.25 | 88.63 | 90.13 | 113.50 | 141.00 |

## Table B-7: Read Ranges of 9A547 Tag from the Read Range Test (in)

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 129.25 | 79.75 | 79.75 | 112.25 | 128.75 |
| 2 | 129.88 | 81.50 | 79.88 | 112.25 | 128.75 |
| 3 | 131.88 | 81.81 | 79.88 | 112.38 | 129.19 |
| 4 | 131.88 | 81.88 | 80.50 | 113.13 | 130.38 |
| 5 | 132.13 | 82.25 | 80.75 | 113.38 | 130.88 |
| 6 | 132.25 | 82.56 | 80.75 | 113.38 | 131.25 |
| 7 | 132.25 | 82.88 | 80.88 | 113.50 | 131.81 |
| 8 | 132.69 | 84.25 | 81.75 | 113.50 | 131.81 |
| 9 | 133.00 | 85.44 | 83.75 | 114.00 | 132.31 |
| 10 | 133.25 | 85.50 | 84.44 | 114.63 | 132.69 |

## Table B-8: Read Ranges of 9A577 Tag from the Read Range Test (in)

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 135.25 | 79.50 | 84.25 | 111.25 | 137.75 |
| 2 | 135.56 | 80.00 | 84.56 | 113.19 | 138.13 |
| 3 | 135.69 | 80.75 | 84.69 | 114.06 | 138.25 |
| 4 | 135.88 | 81.38 | 85.06 | 115.88 | 139.06 |
| 5 | 136.25 | 81.44 | 85.31 | 116.06 | 139.19 |
| 6 | 137.19 | 81.75 | 85.81 | 116.44 | 139.19 |
| 7 | 137.38 | 82.63 | 86.00 | 116.69 | 139.38 |
| 8 | 137.94 | 82.75 | 86.00 | 116.69 | 139.56 |
| 9 | 138.75 | 85.00 | 86.31 | 117.00 | 139.63 |
| 10 | 139.25 | 86.63 | 86.38 | 117.00 | 139.75 |

**Table B-9: Read Ranges of 9BE66 Tag from the Read Range Test (in)**

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 129.50 | 80.50 | 83.63 | 114.38 | 130.31 |
| 2 | 130.88 | 81.44 | 83.81 | 115.00 | 130.31 |
| 3 | 131.50 | 82.44 | 84.44 | 115.13 | 130.56 |
| 4 | 131.63 | 82.63 | 84.63 | 115.44 | 130.75 |
| 5 | 131.88 | 83.25 | 85.06 | 116.63 | 130.75 |
| 6 | 132.63 | 84.25 | 85.25 | 116.63 | 130.75 |
| 7 | 133.00 | 84.69 | 85.50 | 117.00 | 131.00 |
| 8 | 133.50 | 84.94 | 85.69 | 117.00 | 131.00 |
| 9 | 134.25 | 85.06 | 85.81 | 118.00 | 132.19 |
| 10 | 134.50 | 85.38 | 86.00 | 118.31 | 133.13 |

**Table B-10: Read Ranges of 9BE6E Tag from the Read Range Test (in)**

| Test Number | Test Position | | | | |
|---|---|---|---|---|---|
| | (x,0,0) | (x,48,0) | (x,-48,0) | (x,0,23) | (x,0,-23) |
| 1 | 131.00 | 83.00 | 84.63 | 112.25 | 135.63 |
| 2 | 131.44 | 84.00 | 85.25 | 114.25 | 137.63 |
| 3 | 131.75 | 84.25 | 85.75 | 116.31 | 137.81 |
| 4 | 132.63 | 84.56 | 86.00 | 117.00 | 138.31 |
| 5 | 132.88 | 85.38 | 86.44 | 117.13 | 138.50 |
| 6 | 133.88 | 85.50 | 86.75 | 118.00 | 139.75 |
| 7 | 133.88 | 85.94 | 87.06 | 118.25 | 139.88 |
| 8 | 134.00 | 86.44 | 87.38 | 118.31 | 140.38 |
| 9 | 134.38 | 87.13 | 87.50 | 119.00 | 141.44 |
| 10 | 135.31 | 88.13 | 88.25 | 119.75 | 141.44 |

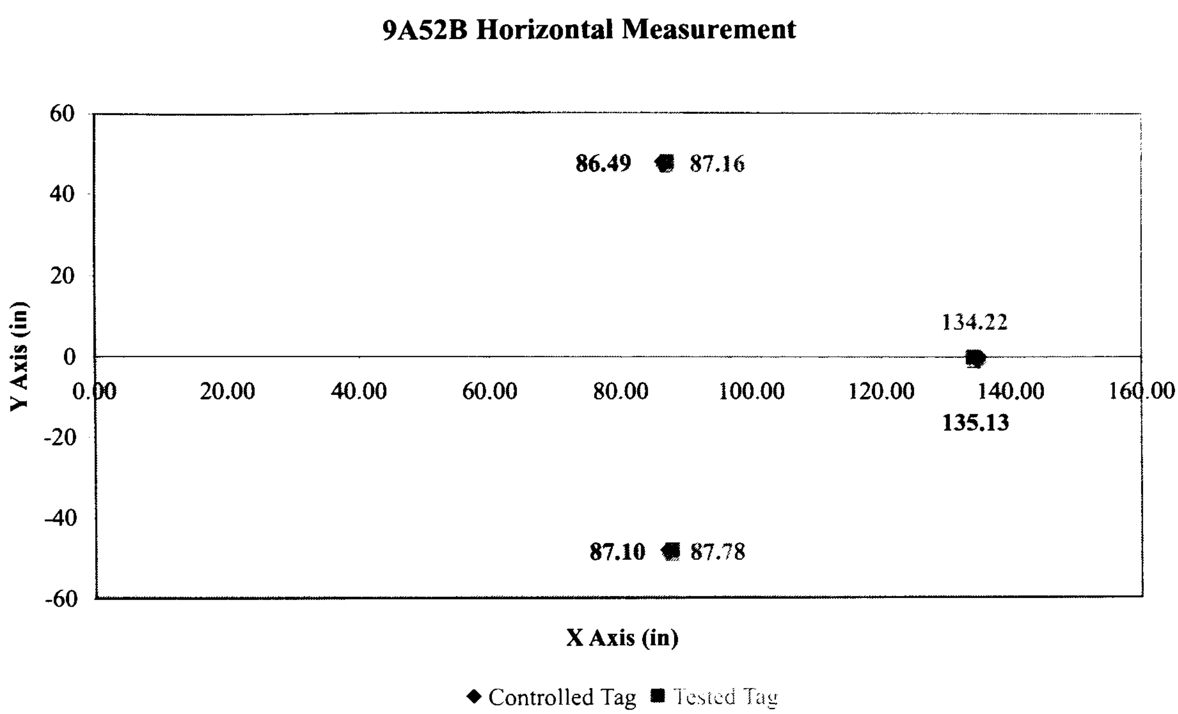



**Figure B-1: Comparison of 9A52B Tag's Read Range Data in Horizontal Positions**

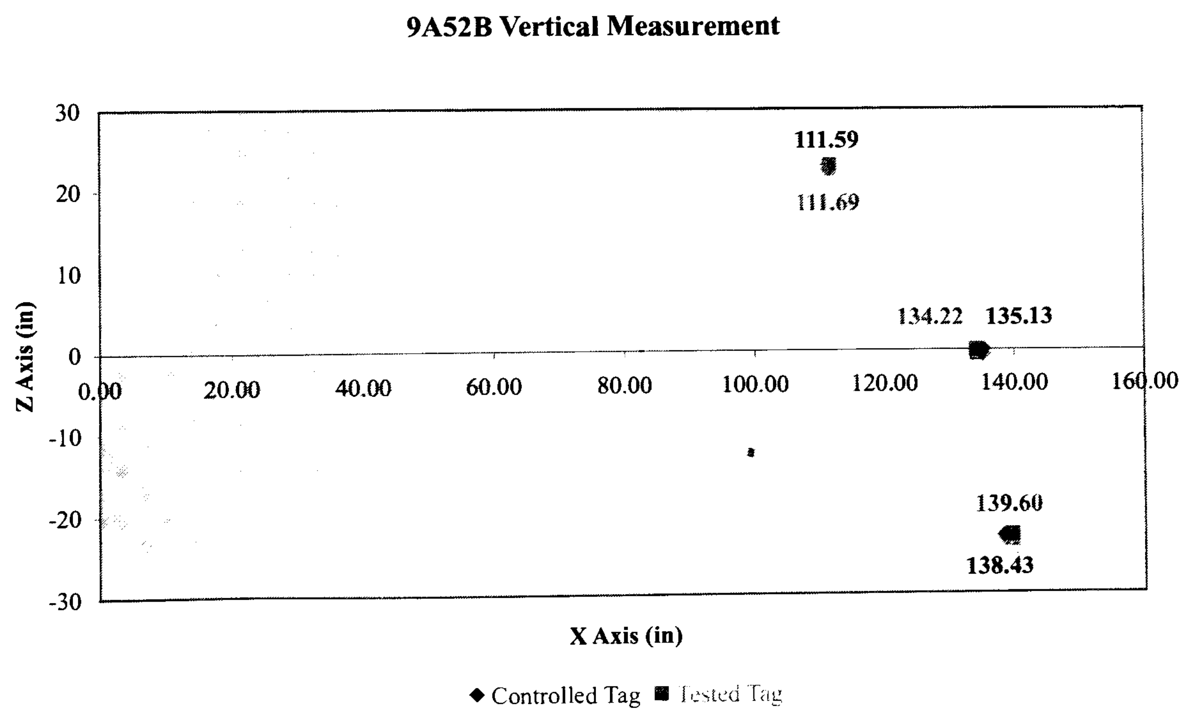



**Figure B-2: Comparison of 9A52B Tag's Read Range Data in Vertical Positions**

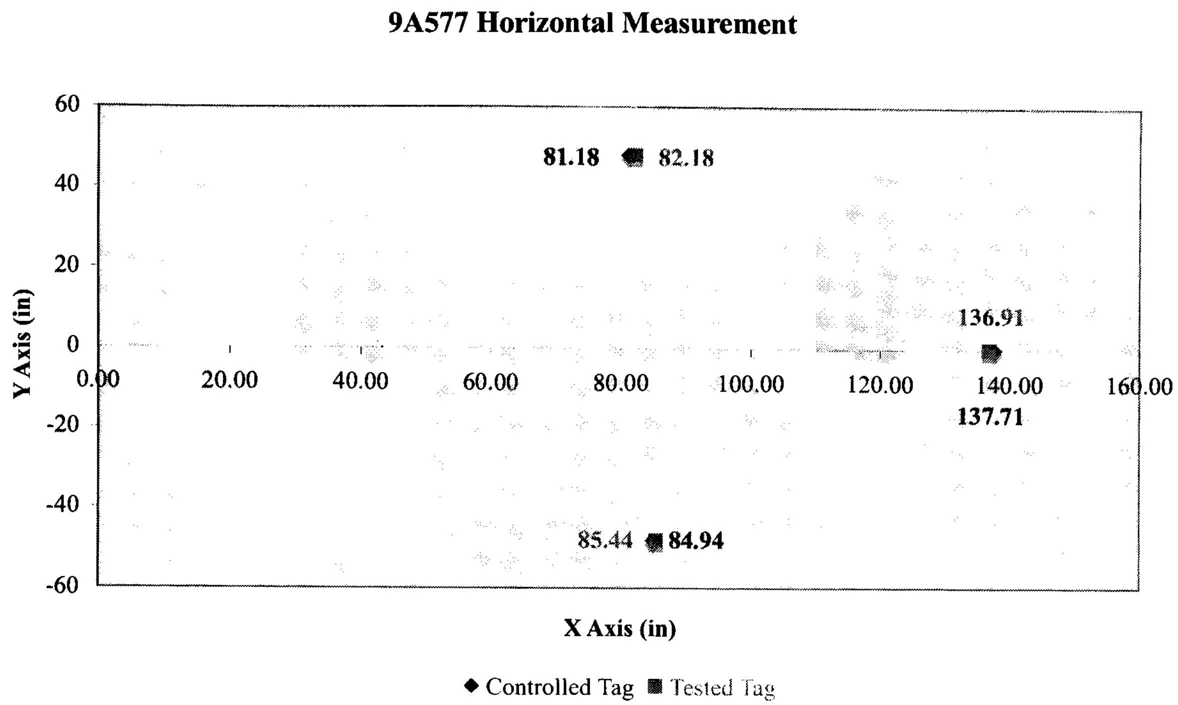



**Figure B-3: Comparison of 9A577 Tag's Read Range Data in Horizontal Positions**

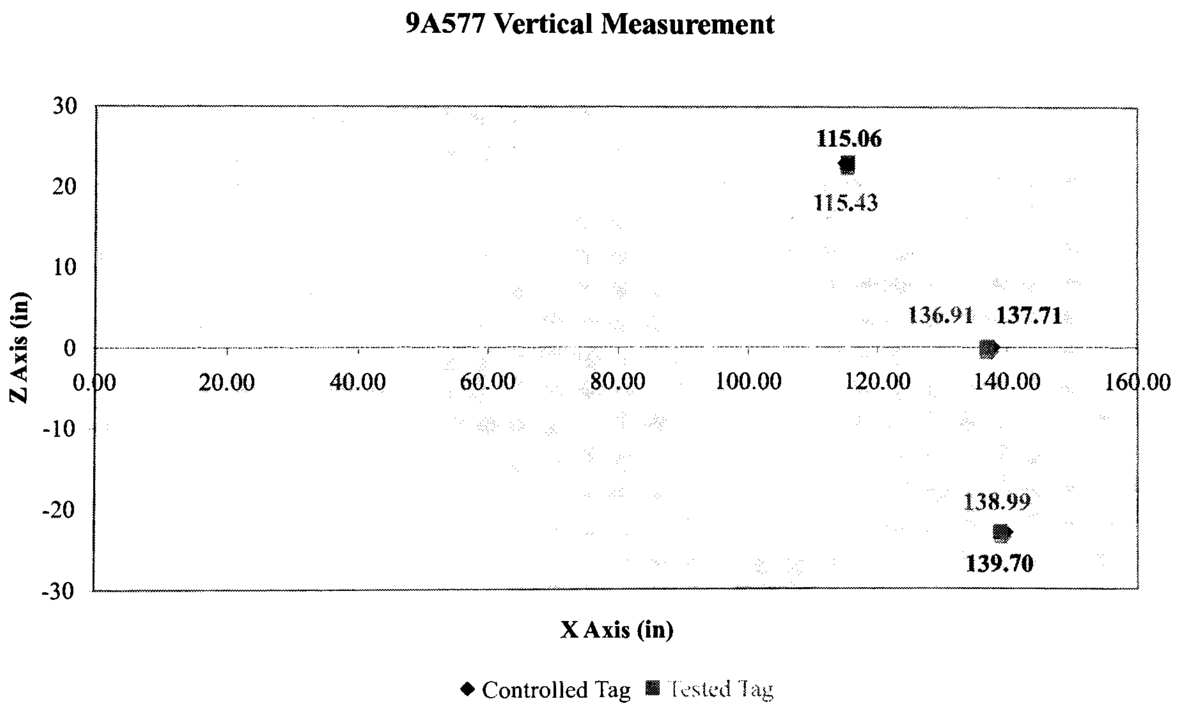



**Figure B-4: Comparison of 9A577 Tag's Read Range Data in Vertical Positions**

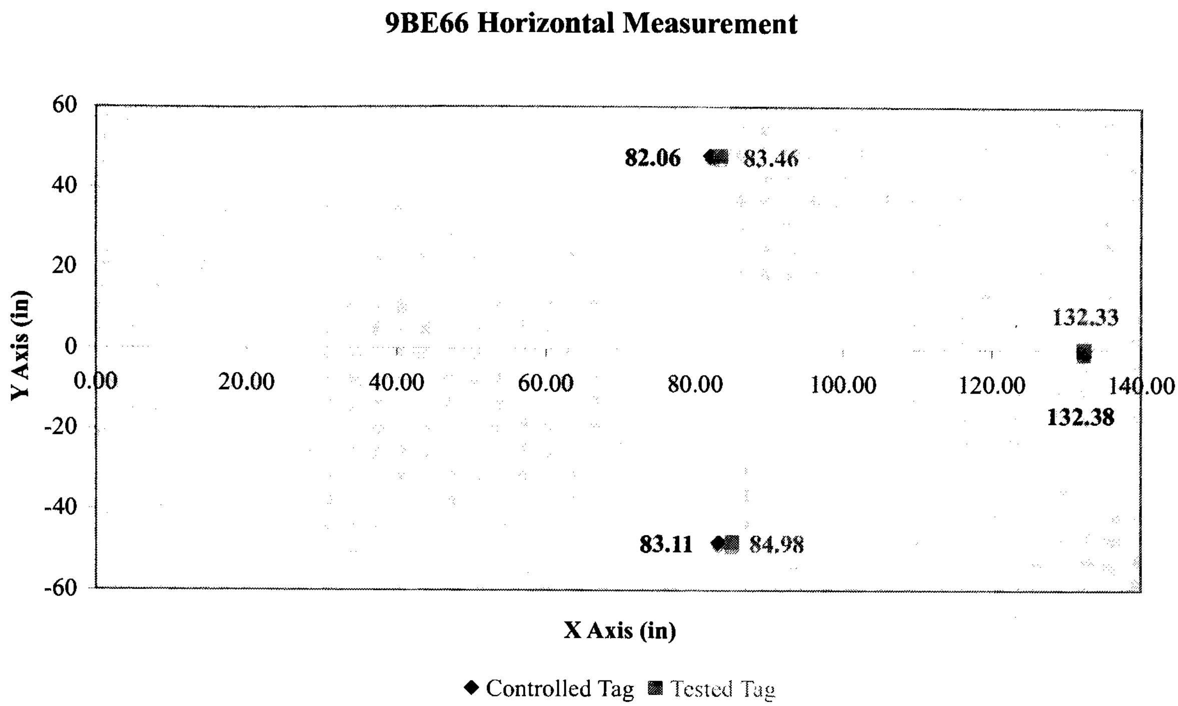



**Figure B-5: Comparison of 9BE66 Tag's Read Range Data in Horizontal Positions**

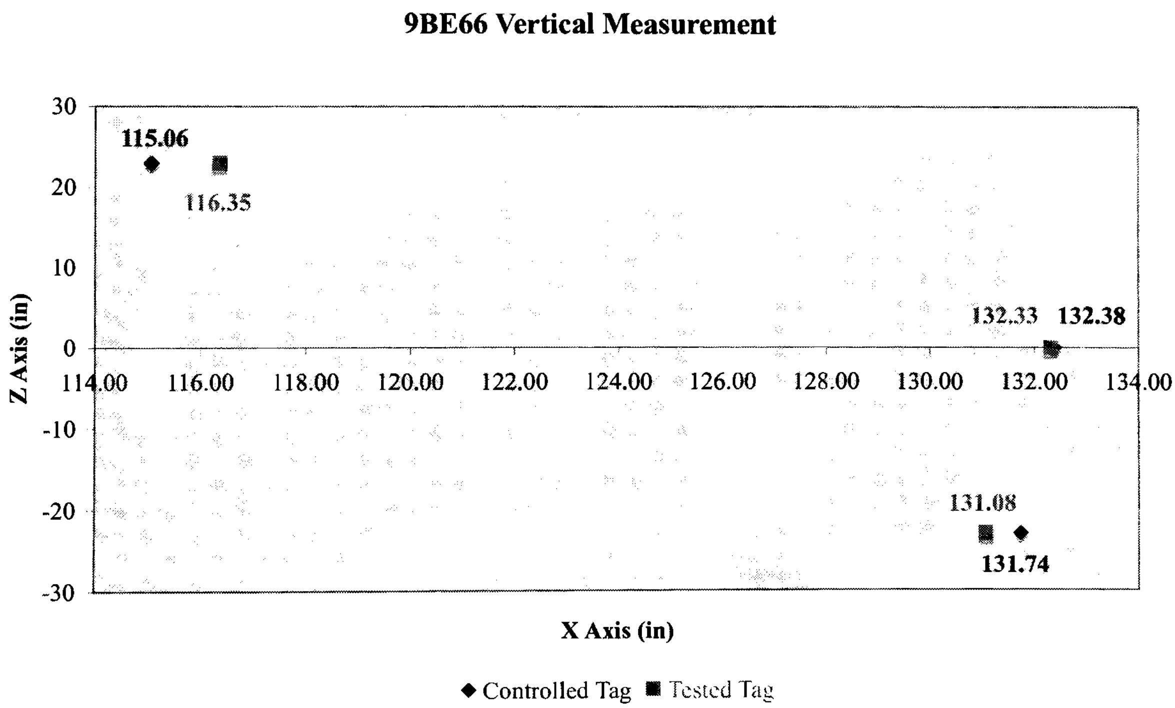



**Figure B-6: Comparison of 9BE66 Tag's Read Range Data in Vertical Positions**

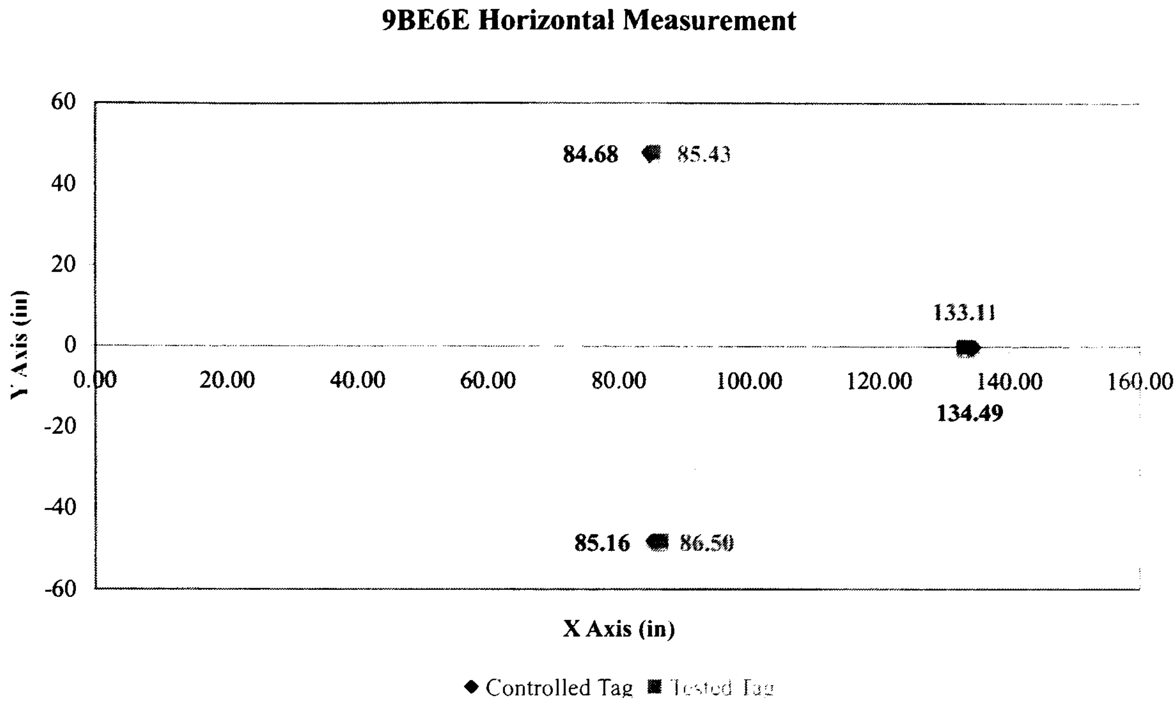



**Figure B-7: Comparison of 9BE6E Tag's Read Range Data in Horizontal Positions**

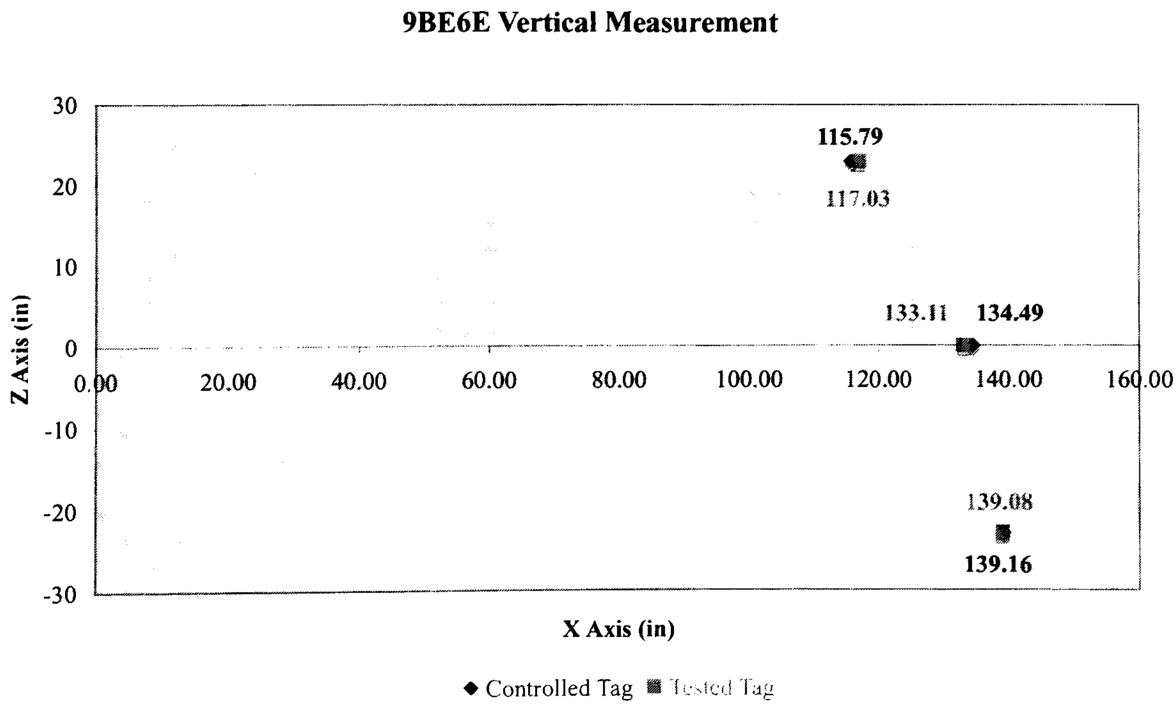



**Figure B-8: Comparison of 9BE6E Tag's Read Range Data in Vertical Positions**

**Table B-12: Read Ranges of Moving Tags from the Control Experiment (feet)**

| Test Number | Tag Serial Number (Test Position, x,0,0) | | | | |
|---|---|---|---|---|---|
| | 9A52B | 9A547 | 9A577 | 9BE66 | 9BE6E |
| 1 | 6.25 | 6.92 | 5.33 | 5.83 | 6.00 |
| 2 | 6.75 | 7.17 | 5.67 | 5.92 | 6.50 |
| 3 | 6.83 | 7.25 | 6.00 | 6.00 | 6.58 |
| 4 | 7.08 | 7.33 | 6.08 | 6.75 | 7.00 |
| 5 | 7.17 | 7.50 | 6.25 | 6.83 | 7.33 |
| 6 | 7.25 | 7.58 | 6.42 | 7.33 | 7.42 |
| 7 | 7.42 | 7.75 | 6.67 | 7.42 | 7.42 |
| 8 | 8.17 | 7.83 | 7.50 | 7.42 | 8.08 |
| 9 | 8.42 | 8.25 | 7.67 | 8.17 | 8.08 |
| 10 | 8.50 | 8.50 | 7.67 | 8.42 | 8.17 |

**Table B-13: Read Ranges of Moving Tags from the Read Range Test (feet)**

| Test Number | Tag Serial Number (Test Position, x,0,0) | | | | |
|---|---|---|---|---|---|
| | 9A52B | 9A547 | 9A577 | 9BE66 | 9BE6E |
| 1 | 5.92 | 6.17 | 5.33 | 6.00 | 5.50 |
| 2 | 6.08 | 6.33 | 5.67 | 6.58 | 5.83 |
| 3 | 6.58 | 6.67 | 5.67 | 6.58 | 6.00 |
| 4 | 7.00 | 7.25 | 6.42 | 6.75 | 6.33 |
| 5 | 7.17 | 7.50 | 6.58 | 7.00 | 6.75 |
| 6 | 7.33 | 7.50 | 6.83 | 7.42 | 7.92 |
| 7 | 7.42 | 7.58 | 6.92 | 7.83 | 7.92 |
| 8 | 7.83 | 7.67 | 7.17 | 7.83 | 8.00 |
| 9 | 8.25 | 8.00 | 8.17 | 8.17 | 8.25 |
| 10 | 8.33 | 8.42 | 8.83 | 8.25 | 8.50 |