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thesis entitled

AN EVALUATION OF UHF RADIO FREQUENCY IDENTIFICATION
TECHNOLOGY FOR APPLICATIONS IN ARCHAEOLOGICAL
REPOSITORY MANAGEMENT

presented by

REED CARLSON EPPELHEIMER

has been accepted towards fulfillment
of the requirements for the

MS degree in Packaging

Robb Clarke
Major Professor's Signature

05/05/2010
Date

AN EVALUATION OF UHF RADIO FREQUENCY IDENTIFICATION TECHNOLOGY FOR APPLICATIONS IN ARCHAEOLOGICAL REPOSITORY MANAGEMENT

By

Reed Carlson Eppelheimer

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Packaging

2010

ABSTRACT

AN EVALUATION OF UHF RADIO FREQUENCY IDENTIFICATION TECHNOLOGY FOR APPLICATIONS IN ARCHAEOLOGICAL REPOSITORY MANAGEMENT

By

Reed Carlson Eppelheimer

Radio frequency identification (RFID) has received a great deal of attention as an emerging automatic identification technology in supply chain management, personal identification, asset management, and academic arenas such as libraries and museums. Further, RFID implementation is improving informational access to researchers and the general public alike. While RFID has proven to be a useful tool for public libraries and museum collections, the potential benefit of RFID in the management of cultural resources extends beyond public facilities to the front lines of archaeological research: the artifact repository. This research evaluates the performance of an ultra-high frequency (UHF) RFID-enabled repository management system (R-RMS) for archaeological artifacts.

The R-RMS evaluation utilized a custom software program to perform the inventory and information management functions of documenting newly discovered artifacts, recalling object-specific database entries and auditing artifact inventories. Test scenarios were developed according to four subcategories; individual artifacts, bags of artifact groups, storage bins filled with artifact bags, and related reference materials. The results of on-site UHF testing at two active repositories conclusively demonstrated the efficacy of all R-RMS functions.

To my parents, thank you for everything.

ACKNOWLEDGEMENTS

First and foremost I would like to thank Dr. Robb Clarke for the academic, professional and personal guidance he has provided over the past four years. I cannot possibly overstate the appreciation I have for the opportunities I have been afforded through my work at the Michigan State University Auto-ID Research & Testing Center.

I would like to express my gratitude to my thesis committee members: Dr. Diana Twede for her teachings throughout my time at MSU, and Dr. Jon Frey for coordinating and providing insight on this project, which I have enjoyed so much.

Dr. Tim Gregory, Director of The Ohio State University Excavations at Isthmia, and Dr. Bill Lovis, Curator of Anthropology at the MSU Museum, also deserve recognition for allowing access to their respective repositories for RFID system evaluation.

A special thanks is owed to Mr. Cisco Garcia for his exceptional work in developing the RFID evaluation software used in this research.

I want to thank my mom and dad for always pushing me to pursue higher education and for providing the necessary resources to act on their advice. Thanks, also, to my brothers, whose individual achievements have always served to set the bar high around the dinner table.

And finally, to the professors, colleagues and friends who have made my last seven years the amazing experience that is was, thank you all. Go Green!

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KEY TO ABREVIATIONS

Auto-ID. . . . . Automatic Identification

CPG. . . . . .Consumer packaged goods

EPC. . . . . .Electronic Product Code

GUI. . . . . Graphical user interface

HDPE. . . . . High-density polyethylene

HF. . . . . High frequency

IC. . . . . .Integrated circuit

IFF. . . . . Identify friend or foe

LF. . . . . .Low frequency

PE. . . . . Polyethylene

RFID. . . . . .Radio frequency identification

RMS. . . . . .Repository management system

R-RMS. . . . . RFID-enabled repository management system

UHF. . . . . .Ultra high frequency

UID. . . . . .Unique identifier

UPC. . . . . .Universal Product Code

Chapter 1- Introduction

The term 'repository' refers to a range of institutions which provide ongoing care for collections (Sullivan & Childs, 2003). Repositories may be run by museums, private collectors, government organizations, tribal groups or academic research groups. Collections may contain a wide variety of materials and objects, or may be comprised entirely of a single type of item. The objects themselves may have historical or cultural importance, though this is, in no way, a requirement. In short, a repository can be as large, diverse and historically significant as the Smithsonian Repository, or as narrowly-focused and irrelevant as an old man's collection of antique hubcaps.

Despite the differences, all repositories are unified by the common goals of providing a proper storage environment for a group of objects and maintaining an accurate record of the collection, a practice generally referred to as curation. This section provides an overview of artifact curation basics and discusses common sources of error in traditional repository management systems (RMS).

The Modern Repository

This section presents an overview of typical artifact curation practices in an archaeological repository. Although the curatorial methods described in this thesis are applicable to a wide range of repositories, for the purposes of this research, the term repository will be used in reference to academic repositories which generate artifact collections through archaeological field-work.

In this type of repository, the collection is generated by the same organization that is responsible for ongoing care. As a result, a system is needed for managing artifacts and information at every step of the archaeological process. This process starts when an artifact is first acquired and registered in the repository records, and continues in perpetuity with the ongoing curation of an archaeological collection.

Creating Collections

The basic function of an RMS is to establish and maintain a link between physical artifacts and the associated historical record (Reibel, 1997, p. 44). Table 1 summarizes the steps for establishing this link as an artifact is registered in an RMS.

Table 1: Adding an artifact to a repository collection

Step in Processing	Function
Discovery	Record provenience Assign temporary identifier
Accessioning	Ledger entry created Accession card created
Cataloging	All related documentation assembled Accession card updated
Collections	Objects packaged using archival materials Storage location documented on accession card

When artifacts are found in the course of an archaeological survey, there is a great deal of data that must be collected along with the artifact to allow for meaningful study later. Depending upon the nature of the given excavation, the location of the discovery is recorded based on horizontal and vertical control points or with an established grid system (Fladmark, 1978, p. 83). Measurements are taken according to a predetermined precision level, which can range anywhere from a general geographic region, to GPS coordinates that specify the exact position of discovery in three dimensional space (Sullivan & Childs, 2003, p. 87). Data is recorded by archaeologists in the form of field notes, photographs and drawings. This information is collectively referred to as *provenience*, and provides a permanent record of the context in which an artifact is discovered. To provide a link between recovered objects and provenience, artifacts are given a temporary ID upon discovery, which is associated to the field records and associated data. In some cases, when sharing a single set of provenience, individual artifacts may be grouped based on predetermined divisions in space or common characteristics, to simplify in field operations. With the exception of large objects, such as architectural components which may be left in the field, artifacts are then transported from to laboratories for accessioning.

Accessioning is the process of formally taking a new object into the repository collection (Sullivan & Childs, 2003, p. 61). The first step is assigning a unique accession number for each object. An accession number may be determined arbitrarily, chronologically, or like an EPC number, with defined fields based on information about an object such as the year or location of discovery. A record is then created for the new accession number and documented, by hand or digitally, in the repository inventory ledger. The task of accessioning is completed by marking the object with the accession number (Reibel, 1997, p.71). Methods for labeling artifacts include hanging paper labels, affixed metal tags, or permanent ink applied directly to the objects surfaces. In the case of large objects, accessioning may take place in the field. Marking of such objects requires the use of weather resistant attachment methods, which have historically included painting or carving the surface, attaching metal and plastic tags, or simply relying on written records to identify and locate objects. The final step of accessioning is the creation of an accession card which is used, like a library card catalogue, to direct users to the location of desired objects and information.

Cataloging is the process of gathering all of the relevant documentation relating to an object, and documenting these sources in a common location (Sullivan & Childs, 2003, p. 63). Information may include object storage location, provenience data, and access information for any related reference materials such as drawings, photographs, field notes, or map, all of which may be managed using independent catalogues. Records may be electronic, although legacy methods resembling library card catalogues are still widely used.

Though many methods for cataloguing exist, the complex relationships between objects and information are commonly managed using a relational data structure. For example, individual objects maybe grouped in bags based on common features such as provenience or discovery date, and then the bags are subsequently grouped in storage bins. In this situation, it is necessary to maintain catalogues and ID systems for objects, bags, and bins, respectively. Information, too, is managed using a tiered structure, with accession numbers linked to field book entries, which may in turn be linked to maps, photos or any other related media.

Collections refers to the process of readying artifacts for long term storage. The preparation needed for long-term storage will vary based on the material, durability, chemical reactivity, value and size of an object, as well as environmental factors within the storage environment. Artifact packaging is not always required, but may include cushioning materials, bags, bins, crates and pallets. When packaging is needed, specialized archival materials are used to prevent harmful interactions with antiquities. Archival packaging materials, such as bags, bins and paper are manufactured to be acid-free, a property which limits the harmful transfer of chemicals from the packaging to artifacts, while extending the shelf life of the package itself. When packaging material is used, a bag or bin tag is created to allow identification of the contents without removing the primary package. This limits the amount of human interaction with often-fragile artifacts (Sullivan & Childs, 2003, p. 67).

Ongoing Curation

Once a link is established between collections and the associated historical records, the next function of an RMS is to provide a system for managing the collection in perpetuity. Table 2, at the top of the next page, summarizes these curatorial functions of an RMS.

Table 2: Ongoing curation at a repository

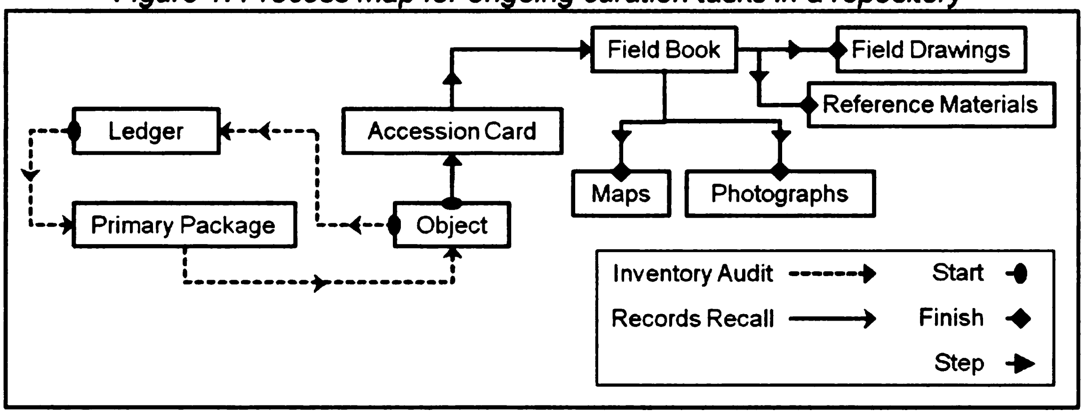
Curatorial Function	Purpose
Collections Management	Provenience maintained Inventory auditing
Ongoing Research	Finding objects for research Accessing historical records and objects

Collections management is an ongoing process which enables artifacts and records to be readily accessed within a storage facility. This is accomplished using some form of repository registration system, which acts like the memory of a repository, providing a permanent record of the entire collection contents (Reibel, 1997, p.12). The records are also used to perform inventory audits to identify lost, stolen or misplaced objects. In modern repositories, an inventory audit is completed through the labor intensive process of comparing a collections ledger to the physical collection, one object at a time, a task which can take months (Texas Instruments, 2010, Reibel, 1997, p. 100).

Enabling the use of collections for ongoing research, is another important function of a repository, and refers to the method by which artifacts and records are located and recalled, in order to facilitate further study. Depending on the system, finding a certain object or record may entail the use of a paper-based card catalogue or, in newer systems, an electronic database search. The effectiveness of this system is directly related to the quality of the inventory and data management system. While no specific set of regulations exist for how this system is constructed, many organizations do require minimum performance standards for these systems. An established method for testing the effectiveness of a collections management system is to simply select a random accession number from the repository catalogue and manually locate all associated records and objects.

Figure 1 shows the processes of taking inventory and recalling records, by tracing the pathways between objects and identifying documents as the aforementioned curation tasks are conducted.

Figure 1: Process map for ongoing curation tasks in a repository



The final role of a repository is to manage the release of artifacts, enabling the loan, transfer or disposal of an object. The process of deaccessioning describes the permanent removal of an object and all associated provenience, from a collection, and is necessary to keep an accurate inventory record when the ownership of an artifact is transferred, or when an object must be disposed of due to excessive deterioration, material hazards, or if it is confirmed that the object was acquired illegally (Sullivan & Childs, 2003, p. 72). Similarly, when on loan, inventory systems must indicate that the object is absent from the collection. However, additional information is also needed to record where the object has gone, who is responsible for it, and when it is expected back. A subsequent, complimentary system is also needed to establish within the inventory records when an object is returned.

Relational Object Management and Cascading Errors

Though effective if well maintained, an artifact management system can quickly grow in size, and become unwieldy. This problem is often caused by inadequate repository storage environments, limited funding for the indefinite care of artifacts, and the fragile nature of paper-based inventory and data management systems. Further compounding the problem, a paper-based system used for relating information to an object is inevitably subject to human error. Due to the level of interconnectedness between objects and records, if an error is made in any part of the inventory and information management system, the impact on provenience can be, as one archaeologist grimly described, "cascading errors" (Frey, 2009).

To illustrate the potential for error in this system consider the following example of an object within a paper-based system: The object is properly accessioned, catalogued, packaged in a bag with similar objects, grouped in a bin with similar bags, and placed on a shelf the repository warehouse. The object is described by a two page entry in a hand-written field book and the entry contains one additional reference to a technical drawing of the trench in which the object was found.

Type-1 failures occur when an accession card is misplaced, lost or destroyed, or an object itself is misplaced. While the object remains intact and identifiable, and the records remain intact, the ability to connect the two is temporarily lost.

Type-1 failures can be recognized in a complete inventory audit, and provenience may be restored if both the artifact and the accession card can be located.

Type-2 failures occur when an objects accession number is rendered illegible. In this case, the item can no longer be tied to permanent records and the provenience may be lost forever. Damage to labels can be caused by physical impacts, erosion from outdoor storage, degradation of the labeling substrates and even interference from animals. While artifacts such as sculptures, weaponry or other rare finds may maintain aesthetic or research value in the absence of provenience, the bulk of collections are comprised of objects of less significance, such as pottery shards, small animal bones or rusted metal refuse, which require detailed documentation to be of academic benefit. Often these items are simply discarded in the absence of provenience. Type-2 failures also result in inconsistencies in the inventory record, which still contains a record for the lost object, causing further inefficiencies in the process of accounting for collections.

Type-3 failures occur when an object label or catalogue record is lost or destroyed for an object which relate to a more than one artifact. For objects like bags and bins, if the label is rendered illegible, all objects within the bag or bin can also be considered lost. For objects like maps, site drawings and other general records, a labeling failure results in the inability to access certain portions of information relating to the entire group of related objects. Type-3 errors can be identified by an inventory audit and the provenience may be restored based on accession numbers.

Type-4 failures are the most severe with respect to impact on provenience, and occur when field books are lost or destroyed. When this happens, every record for every object described within is also lost. The affect to ongoing research is especially devastating when considering that field books may contain thousands of individual records, and may account for a full season of excavation and discovery. To hedge against potential threats, a secure method for managing the library of field books is critical, though they are often managed in the same manner as other records.

Regardless of where the inventory and data management failure occurs, the problem can be attributed to one of two root causes; ID impermanence, resulting in loss of provenience, or human error, resulting in inaccurate inventory records. Either way, the result is the same, an inability to efficiently access the materials needed to conduct ongoing research using archaeological repository collections.

Research Objective

This research evaluates the performance of an RFID system in conducting useful inventory management functions at archaeological repositories. Based on the curation methods described in this chapter, opportunities for beneficially applying RFID were identified and an RFID-enabled repository management system (R-RMS) was developed. The system included an accession function for registering new artifacts, a data management function for retrieving digital records, and an inventory function for performing inventory audits.

Test scenarios were designed to evaluate the basic operation of the R-RMS, and conducted in two different artifact repositories. Testing was performed in the environment of intended use in order to verify the operation of the RFID system, while also accounting for all potential sources of destructive interferences in the given repository environments. The results of the RFID system evaluation are used to develop a process diagram for effectively managing an artifact repository using RFID technology.

Chapter 2: Literature Review

The first decade of the twenty first century has seen radio frequency identification (RFID) technology evolve from relative obscurity into an entire family of tools for automated capture of object-identifying information. This chapter discusses RFID as a subset of the larger family of automatic identification (Auto-ID) technologies, and describes the technology in terms of operational and physical characteristics. A brief history of RFID technology development highlights major technological milestones and industry trends which have resulted in the recent growth of niche markets and closed-loop RFID applications, such as library and museum management systems.

Automatic Identification

Generally stated, the term *automatic identification* refers to any technology used to facilitate the transfer of information from one source to another, without the need for human input (Clarke, 2008). Common examples of automatic identification technologies include magnetic stripes on credit cards used to direct financial transactions, barcodes used to facilitate retails transactions and support supply chain operations, and biometric fingerprint and retinal scans used for secure access control. Each system utilizes a unique core technology to facilitate the transfer of information, while sharing the common goals of "identifying, tracking, recording, storing and communicating essential business, personal, or product data… providing fast and accurate collection and entry of data" (Association for Automatic Identificaton and Mobilty). The benefits of Auto-ID can be illustrated by considering the role of the UPC barcode in modern retail store check-out systems.

In a modern retail store, customer orders are processed by individually scanning barcodes printed on, or attached to, items being purchased. When scanned, Item-identifying information is optically captured, processed, and used to generate a running total of a customer order in a single step, without a worker manually keying in pricing information. The automation of order entry enables efficient customer processing and limits problems associated with human errors in data entry. These benefits of increased efficiency and error reduction are universal across all forms of Auto-ID (Glover & Bhatt, 2006, p. 4).

Another commonality among Auto-ID technologies is the underlying method by which data is stored, transferred and captured. Information is stored as a machine readable binary code, which is detected by a data capture device, converted to a digital signal and transferred to a host processor. In Universal Product Code (UPC) barcodes, an alphanumeric identifier is stored optically, as a series of vertical, black and white lines of varying thicknesses. The dimensional variations correspond to a binary code, representing the identifier. When the barcode is scanned by a laser, light is absorbed by the black lines and reflected by the white lines. The reflected light is detected by optical sensors within the scanner and then analyzed to extract the binary code. The resulting binary code is then translated back into the original alphanumeric identifier and transmitted to the host computer (Sweeny, 2005, p. 34).

Despite fundamental similarities in concept, the technologies used for storing and transferring machine-readable information vary widely. Magnetic stripe card technologies represent a binary code utilizing a strip of magnetically polarized metal particles, held within a binding medium. The particles are oriented positively or negatively, representing a binary 0 or 1, and are read by devices which detect the magnetic orientation of the particles. Common examples of magnetic stripe cards are access control cards, government issued ID cards, and the vast majority of modern credit cards.

Biometric technologies, like fingerprint or retinal scanning, work by analyzing the spatial relationships of key features in the images of scanned fingerprints or retina. The result is a binary code which is decoded and used to identify an individual.

Smart cards, despite taking the same form as magnetic stripe credit cards, hold identifying information on a small computer chip or microprocessor with, embedded within a plastic card. When placed into a reader, exposed electrical contacts on the card create a direct connection between the memory of the card and the reader unit, enabling the data transfer. Smart cards are most commonly seen in the forms of prepaid phone cards (Weier, 2009).

Another Auto-ID technology of note is the two dimensional (2D) barcode. Like UPC barcodes, 2D barcodes use optical scanning to transfer information. UPC scanners project a single line across the code and detect the line thickness, in one dimension. Therefore, the amount of data that can be stored by a 1D code is determined by the length of the barcode. 2D barcode scanners, on the other hand, project a beam of light like a flashlight, allowing information to be stored in two dimensions. The increased complexity of the spatial relationship between reflective and non-reflective areas allows for increased data storage density. As a result, the amount of data stored by a 2D code can be greatly increased, while the size of the code increases relatively little, compared to a 1D code. 2D barcodes codes can be printed for less than a cent and the information capacity of is comparable to RFID, making them an attractive alternative to RFID in some cases. Data capacity issues and operational characteristics are further discussed in a later section.

In the case of RFID, identifying information is stored, in binary, on a tiny computer chip, attached to the object being identified. The data is transferred using electromagnetic energy in the form of radio waves. The following section provides an overview of the components which make up an RFID system, and how these components interact to perform the task of automatic identification.

RFID System Components

All RFID systems operate using some variation of four basic components: a transponder, a reader, a reader-antenna and a host computer. The functionality of an RFID system can be enhanced with addition of supplemental devices such as machine vision sensors, RFID tag printers and label applicators. In addition to hardware, RFID middleware programs are run by the host computer in order to efficiently direct the operation of an RFID system and simplify information management.

Hardware Basics

Though a great amount of diversity exists in the physical form and operation of RFID hardware, all RFID systems include four primary components: a transponder, a reader, a reader-antenna, and a host computer (Sweeny, 2005).

RFID transponders, or tags, are used to store information used for object identification. A common form for RFID tags resembles a 2" x 4" mailing label. Integrated into the label is a tiny computer chip, called an integrated circuit (IC), attached to a metallic antenna. The IC memory holds a unique identifying number, as well as a small amount of internal logic to facilitate higher level functionality. The antenna is used to harness electromagnetic energy, receive commands from the RFID system, and emit a response signal carrying the data stored on the IC.

The reader-antenna, used to emit and receive RF signals, is comprised of a flat piece of metal within a protective housing, connected to a reader via coaxial cable. When an electrical signal, generated within the reader, reaches the metal plate within the antenna, the signal is transformed and emitted into the surrounding environment in the form of radio waves. This signal powers the operation of the transponder and carries operational commands from the reader. The tag response is subsequently received by the antenna, transformed back into an electrical signal and sent the reader.

The RFID reader is responsible for facilitating the operation of, and communication between, RFID transponders and a computer server. The reader contains computing hardware to store operational logic as well as radio equipment to generate and receive RF signals. Commands are initially sent from the computer interface to the logic portion of the reader, carrying instructions for performing functions such as writing information to tags, reading information from tags, and providing variable setting information, such as power levels, or specialized encoding specifications, which indicate how the basic tasks of writing and reading are to be performed (Glover & Bhatt, 2006, p.108).

Once the reader receives a command from the computer interface, it uses the internal radio signal generator to emit an RF signal via attached reader-antenna. The transponder response is then returned to the reader, where the signal is translated by the reader logic components and relayed to the computer interface for further processing.

Variations on these basic components include portable RFID units, which combine a reader, antenna and computer interface in a dingle handheld device, and reader/antenna combination units, which eliminate the need for an external antenna, allowing the units to be installed in areas where limited space is a concern. Other currently available RFID-enabled devices include RFID-barcode combination readers and a variety of RFID label printer/encoders designed to meet the scalability and performance requirements of disparate RFID applications.

Making Use of It All: Middleware

In order efficiently direct the operation of RF devices and extract actionable information from the extensive raw data, an automated solution is needed. Middleware is a software program on a host computer that serves as the necessary link between an RFID hardware network and a central information management system.

Based on either human or event-triggered events, middleware programs direct reader operation and perform tasks such as "RFID data dissemination, data filtering and aggregation, reading from and writing to a tag, reader integration in IT-service management, Privacy" (Lampe, 2009). To understand how the RFID system is used to accomplish these inventory tasks, it necessary to understand some of the reader commands used by the middleware program. Frequently used commands are displayed in Table 3, at the top of the next page.

Table 3: Common RFID Reader Commands

Command	Purpose	Reader Response
Read	Sends a command to acquire information from all transponders within the read field at a given point in time.	List of detected tags
Write	Sends a command to program specified information to the memory of a desired transponder.	Notification of success or failure All data programmed to the tag
Attenuate	Changes the power level of the RF signal emitted by the reader-antenna.	Notification of setting change
Mask	A mask is a filter used to direct reader commands to specific tags, and eliminate the generation of excessive and undesired read data.	Notification of setting change
AutoMode	Sets the reader to continually detect tags and store read data to reader memory.	Notification of setting change when activated Complete accumulated tag list (up to 5000 tags) when deactivated

In order for the operation of an RFID system to be of benefit, the data collected must be utilized to perform a useful function. In order to combine the tasks of device management and information management, middleware programs have two basic layers, "a general- purpose core architecture, extensible for pervasive computing applications, and an RFID-related application architecture that specializes in the generic agent architecture" (Thompson, 2006). This double layered approach is necessary because, while the memory capacity of RFID tags is always expandng, the information stored on the chip doesnot generally include complete object information. Instead, the tag data typically acts as a liscence plate which the middleware uses to retrieve object information from an independent electronic database.

The complexity of a middleware solution is determined by the complexity of the application, which may range from performing a single function to managing a complete RF-enabled enterprise. In the environment of a consumer packaged goods (CPG) supply chain, RFID event triggers may be anything from the arrival of a specific truck at a distribution center to a customer placing an online order. These triggers may be tied to perform any number of tasks such as, creating a bill of lading, verifying the contents of a customer order prior to shipment, or updating material planning systems to reflect changes in inventory demands. In any case, the middleware is responsible for gathering data from RFID tags, and then utilizing that data to direct the completion of a useful task.

The need for middleware is further demonstrated when considering that the number of UIDs reported in a normal day in a CPG supply chain could be in the millions per hour. In a network such as this, a single middleware program must be seamlessly networked to any number of geographically dispersed read-points, hosted on any number of computers, mobile devices or central servers.

Auto-ID with Radio Waves

RFID, like all forms Auto-ID technologies, offers the benefits of accelerated data capture and reduced error. There are, however, several unique advantages to using radio communication for identification, as opposed to magnets, optics or other identification mediums. These benefits include the ability of RFID systems to read tags through many common materials, acquire data quickly from multiple transponders and hold enough data to allow for a UID.

Electromagnetic energy is able to propagate through many common materials such as plastic, paper, rubber and wood. As such, RFID tags can be detected through many materials without the requirement of a direct line-of-site. Whether or not a tag can operate without a line-of-site is determined by how well radio waves propagate through the given material, a property called radiolucency (Clarke, 2008). This ability means that, for specialized application, tags can be completely embedded within an object to enhance transponder durability. This also means that individual transponders within a unitized population, such as a stretch wrapped pallet of tagged shipping cases, can be scanned in entirety, without removing the stretch-film. Replacing barcodes with RFID tags in the aforementioned grocery store check-out could potentially allow cashiers to scan an entire shopping cart of goods without touching a single item.

Another unique capability of RFID is the high speed at which systems can acquire data from transponders. Advertised read rates of tag read rates may range from 20-1000 tags/sec, though observed read rates are typically on the lower end of that range (Ramakrishnan & Deavours, 2007). Communication time can become an issue, however, when there is a large population of tags in the read field simultaneously. If the RF-antenna is not given adequate exposure time to complete a communication cycle with each transponder, objects may be missed.

In addition to transferring data quickly, RFID transponders have the capability to store up to 864 bits of data in the IC memory (Alien Technologies (II), 2008). The extensive on-board memory capacity allows RFID tags to hold enough data to provide a UID for 3.12^{144} different tagged objects, based on the 480-bit memory bank of the Alien Higgs 3 chip (Alien Technologies (II), 2008).

The concept of a UID is another important difference between UPC barcodes RFID. The data stored on UPC barcodes includes a manufacturer's ID number and a stock keeping unit (SKU). The code is designed to generically identify the product by type, for example, *1lb bag of Generic Brand Frozen Cod.* RFID tags, too, provide product and manufacturing information, but hold an additional UID which is designed to identify each object individually among a larger population of similar items, for example, *Generic Brand Frozen Cod- 1 lb bag #5968492.* The UID can also be used to gain a more granular view of a population of objects by allowing advanced filtering of tags and the abiltiy to selectively issue commands.

An RFID for (almost) any Situation

When implementing an RFID solution, it is important to understand how environmental and material interferences can impact the performance of RFID systems. Furthermore, in selecting RFID hardware for an application it is useful to understand how the operational characteristics of various RFID technologies can be used to overcome environmental hazards.

RFID, it turns out, is not a specific technology, but rather a collection of technologies which all operate in a similar way. A leader in RFID industry news and information, RFID Journal defines the term Radio Frequency Identification as, "any method of identifying unique items using radio waves" (RFID Journal (II), 2010). As this definition suggests, radio waves can be utilized in a number of ways to accomplish the goal of identification. Methods may differ in frequency, tag power source and in the integration of additional technologies. Each variant has distinct operational characteristics which are determined by the physics of the respective method. Examples of functional differences, commonly cited to guide application development decisions, include: read distance, communication speed, sensitivity to water or metal, and extended functional capabilities.

Physical Limitations

In the early years of RFID commercialization, a commonly used selling point was that RFID does not need line-of-site to operate. This claim, however, is only *sometimes* true. Certain materials can inhibit the operation of RFID systems by absorbing, blocking or otherwise interfering with RF energy. In these instances, a direct line-of-site may be required in order for a tag to be detected. The most commonly cited causes of material interferences with RFID systems are due to water and metal in the reading environment.

Water has a negative impact on RFID communication because it absorbs electromagnetic energy at certain frequencies (Clarke, 2008). The energy intended for powering the tag is thereby dissipated and as a result, little or no energy remains to power the transponder. This is a concern for RFID system developers because many environments contain water. Consider consumer products such as bottled beverages, fresh produce, meats, shampoos, windshield washing fluid. All of these products contain enough water to negatively impact the performance of RFID systems. Furthermore, uncontrolled water in the environment such as rain or humidity can also reduce the overall performance of an RFID system.

Metal objects can negatively affect RF communication in two ways. First, RF energy cannot propagate through metal. If a tag is surrounded on all sides, it will be unreadable, unless it is specifically designed for the given application. Metal can have a secondary impact on the performance of an RFID system by causing electromagnetic interference capable of detuning the delicate radio components of an RFID transponder. This detuning affect can causes a change in the resonant frequency of a transponder (Clarke, 2008). If a tag is detuned to the extent that it no longer responds to the specified frequency, the tag will no longer be able to communicate with the RFID system.

Metallic objects of concern in the CPG supply chain include packaging materials such as the common "tin" can or foil layered flexible packages, equipment handling machinery like clamp trucks and forklifts, metal storage racks, conveyor systems, and dock doors. RFID transponders can even be detuned and rendered inoperable by other transponders. This is a particular concern when considering the use of RFID for tagging small items which are stored in a high-density population of other transponders.

Frequency

Depending on how and where an RFID system is to be applied, a number of operational frequencies for communication exist, each offering a different set of benefits and short falls, based on the unique properties of various RF frequencies used for item identification.

When it comes to radio communication, interference can occur when to different signals are broadcast at the same frequency. As a result, governments allocate certain frequency bandwidths for certain communication needs. With respect to RFID, standards for frequency usage vary according to the regulatory body in charge of frequency allocation in a given geographic region. In the United States, for example, radio communication at a frequency band from 902 MHz to 928 MHz (commonly stated as 915 MHz) is designated ultra high frequency (UHF). In Europe, however, the UHF band refers to frequencies from 865- 868 MHz. For the purposes of this discussion, frequency bands from the United States are presented to illustrate the effect of frequency variation on the performance of an RFID system. Worldwide standards for UHF spectrum use are provided online by GS1, a global standards organization which focuses on standardizing new technologies for improving the efficiency and visibility of products as the move through the supply chain (GS1, 2009).

Low frequency (LF) and high frequency (HF) RFID systems operate using magnetic coupling at frequencies of 125 KHz and 13.56 MHz, respectively. In both cases, the effective read range is typically limited to under a meter. LF and HF radio waves, though limited in read distance are affected very little by metal or water, making them well suited to applications in animal tagging, asset management and payment systems, where read distance may not be critical, or desirable, and where metal and water may be a interfering factor.

Ultra high frequency RFID systems in the United States operate at an average frequency of 915 MHz. Communication is accomplished using propagated far-field RF signals, in a process called passive backscatter. Read ranges for UHF systems can commonly reach 30 ft, depending upon the system, making them ideal for large warehouse environments in the CPG supply chain. The performance of these systems, however, is heavily influence by water and metal. As previously suggested, this fact has proven a major stumbling block for wide spread supply chain adoption, due to the wide spread presence of environmental water and metal in the retail distribution environment.

Passive or Active

Another way in which RFID systems differ is based on where the transponder gets the energy for operation. The RFID systems discussed to this point are considered passive systems. This designation means that the energy required to power the operation of a transponder is emitted by the reader-antenna and harnessed by the transponder-antenna. When the tag is not within a suitable read range, the tag will not receive enough energy to operate, and will instead remain dormant until it moves to a position within the effective RF read field (ASTM International, 2009).

Fully active transponders are those which include a separate power source such as an internal battery. Rather than waiting for energy from a reader-antenna to respond, active tags are always operating. The additional energy allows the system to overcome much of the RF interference resulting from water and metal, and enables read ranges of over 1 kilometer (Sweeny (II), 2007). The additional power source also allows for the incorporation of additional functionality, such as environmental sensors or extended memory for continual data logging.

Depending on how active transponders are configured, battery life may be anywhere from several months to several years.

Despite the superior performance characteristics, the size and cost of active RFID transponders are both significantly greater than passive system, and is, as a result, primarily used for the management of high cost or high priority items. Active RFID has been used by the Department of Defense to track and locate shipping containers in theatres of war, and in the development of industrial real-time locating systems (RTLS) for asset tracking.

History of RFID Development

Once referred to as a solution looking for a problem, Radio Frequency Identification (RFID) has developed dramatically since being introduced in 1939as a World War II-era friendly-fire prevention tool (Kleefeld, 2005), into a diverse family of technologies with an equally diverse set of applications. This section focuses on the evolution of passive UHF RFID systems, from the first use of radio waves for identification, to modern closed loop systems designed for the purpose of academic enhancement.

A Slow Start for a New IDea

Like many modern technologies, RFID was first developed for applications within the military. Of British design, the identify friend or foe (IFF) system was designed to allow air base radar operators the ability to efficiently differentiate the generic radar "blips" of incoming planes as hostile or friendly (RFID Journal, 2005). This system used a radio signal generator at the base to broadcast a signal at a certain frequency. Archaic transponders mounted on friendly aircrafts, received this signal and then responded with an amplified signal of the same frequency. The presence or absence of the response signal was then used to determine the allegiance of the incoming craft.

Further developments in RF communication, throughout the 1950's and 1960's, resulted in the introduction of onboard internal memory for RFID transponders. "These types of systems often use '1-bit' tags – only the presence or absence of a tag could be detected, but the tags could be made inexpensively" (Landt, 2001). The tags were used primarily for anti-shoplifting applications. When an item was purchased, the single bit of data on the item tag would be changed from a 1 to a 0. If scanners at the store exit detected a tag displaying a 1, an alarm would be triggered, alerting workers that an un-purchased item was leaving the store.

In the 1970's and 1980's, various iterations of RFID were developed for specialty applications like nuclear waste management, animal identification, keyless entry, and automated highway toll systems. Transponder functionality was improved with increased memory capacity and the ability to reprogram tag data. These early systems primarily utilized LF and HF frequencies, employed a wide range of proprietary hardware, and were largely limited in scope due to the still-infantile nature of the technology.

It was not until the early 1990's that "IBM engineers developed and patented an ultra-high frequency (UHF) RFID system. UHF offered longer read range (up to 20 feet under good conditions) and faster data transfer" (RFIDJournal). The extended read range and improved data capabilities made UHF systems a primary candidate for applications in supply chain management. The idea of an RFID-enabled supply chain for the consumer packaged goods (CPG) industry, led to the establishment of the Auto-ID Center in 1999. Centered at the Massachusetts Institute of Technology (MIT), The Auto-ID Center was started as a joint effort between the Uniform Code Council, EAN International, Procter & Gamble and Gillett, to develop RFID for the CPG supply chain. By 2003, the Center had gained the support of over 100 major corporations, including the Department of Defense, and had led the development of critical RFID standards, providing the foundation upon which all future UHF systems would be built.

Standardization Nurtures RFID Growth

The development of certain operational standards was a critical step in the expansion of RFID in the CPG sector because, in order for the vision of an RFID-enabled supply chain to work, every organization that utilizes the tag must be able read and understand the information contained on the chip, regardless of who manufactured or last programmed the tag. Two standards were developed to establish these essential guidelines: The Electronic Product Code (EPC) standard, which established a few basic hardware definitions and a system for representing manufacturer and product information as a UID, and the Gen2 standard which provided a functionally-optimized, universal communication language for operation between compliant RFID transponders and readers, regardless of manufacturer.

EPCglobal was originally founded between The European Article Numbering/Uniform Code Council (EAN.UCC) and The Auto-ID Center at MIT. In

2004, EPCglobal approved the EPC standard which is "a numbering scheme that uniquely identifies all objects" (EPCglobal, 2006). The system is intended for identifying RFID tagged products within the global supply chain. Similar to the Universal Product Code for barcodes, an EPC number identifies the manufacturer, product class and other general identifying information. In addition to the standard indicators found in the UPC code, the EPC code includes information which identifies each object uniquely. So, whereas a UPC may identify an object as being a box of cereal, an EPC identifies the box of cereal individually among the larger population of cereal boxes from the same product line. Without this standard numbering format, retail stores, for example, would have to accommodate all of the specialized numbering schemes developed, for internal use, by individual manufacturers.

Having established the format of the information contained on EPC tags, the next standardization need was to ensure the interoperability of RFID hardware components from disparate manufacturers. While all transponders carried the same standardized EPC data set, the programming language used to transfer information from the transponder to the reader remained hardware-manufacturer-specific. This problem was a major obstacle for early RFID adoption in the CPG supply chain because companies found it difficult to justify the high cost of implementation without a guarantee that an RFID hardware infrastructure would remain relevant and compatible with future generations. The case for a standardized communication protocol for RFID hardware was further solidified by the need for universal operation of RFID transponders between partnered business entities, regardless of RFID manufacturer. The solution was the development of the Gen 2 air-to-air protocol standard.

Developed by EPCglobal and then adopted by ISO (International Organization for Standardization) in 2006, the Gen 2 standard established a standardized protocol for facilitating communication between EPC-compliant tags and readers, regardless of the hardware manufacturer. The standard established minimum requirements for tag memory capacity and internal logic capabilities, as well as the architectural design for RFID tag memory banks and a method for interacting with the stored data. Although Gen 2 compliant hardware components from disparate manufacturers can interact, it should be noted that the performance of the resulting system may not be optimized.

With the assurance of a stable operational platform, the UHF RFID industry focus moved from proprietary hardware development to application development and implementation. RFID mandates from the CPG giant Wal-Mart and the Department of Defense (DoD) served as a further catalyst that brought RFID from its state as an emerging technology, to center stage in the early 2000's.

Mandated Jumpstart for RFID

Wal-Mart, realizing the supply chain potential of RFID and holding the power to fuel the development of an entire industry for UHF RFID, in June 2003, issued a mandate to its top 100 suppliers that, beginning in 2005, all shipping containers received at select distribution centers were required to carry an EPC tag. The stated target of the Wal-Mart Initiative was to reduce stock-outs, by utilizing up-to-the-minute inventory records to manage their supply chain in real time.

Despite several successful small scale pilot tests with major suppliers throughout the early 2000's, by October 2007, the mandate for RFID had been altered and reduced to "three focus areas: (1) shipments going to Sam's Club; (2) promotional displays and products going to Wal-Mart stores; (3) tests to see RFID's impact in improving category management in select areas" (Supply Chain Digest, 2009).

Retrospective analysis of the Wal-Mart RFID program shows that the primary reasons for failing to meet expectations was the infantile nature of the hardware systems due to a lack of commercialization in UHF RFID industry and the absence of a sturdy foundation in technological standardization.

Shortly after the introduction of the Wal-Mart initiative, the DoD issued a similar mandate to every one of its 40,000 suppliers. By 2007, all shipping cases received at DoD facilities were required to carry an EPC tag. While the program faced similar setbacks as the Wal-Mart initiative, a DoD policy states a commitment to pursuing all relevant forms of Auto-ID technologies as the preferred tools for supply chain management (Department of Defense, 2003). This policy has allowed the DoD to continually adapt and grow with the RFID industry, without the financial restrictions of industry. The underlying focus of the DoD initiative was to gain greater visibility of material and supplies within distribution and storage networks. Along with the EPC mandate, an active tagging program was also pursued by the DoD for enhanced container tracking and security.

Other less notable RFID projects followed including an initiative to use HF RFID as part of a system for tracking of prescriptions drugs as part of the fight against the grey-market and counterfeit pharmaceutical trade. While the first five years of the 2000's brought sweeping standardization and an explosion in attention for the UHF RFID industry, the five years that followed were marked by a significant decline in interest from the consumer goods industry as pressure from the Wal-Mart mandate diminished and businesses slowly realized the complexity of executing a complete RFID supply chain solution and the simple fact that RFID was still too expensive and technologically underdeveloped.

Understanding Hype

When UHF RFID was first brought into the spotlight, there was a flurry of interest and disorganized activity within the industry. Slowly however, the technological limitations were realized and the industry lost momentum towards ubiquitous adoption. This is a common trend which is common to most emerging technologies, and is described by the Gartner Hype Cycle (Fenn, 2009).

With respect the cycle predicts that on the road to full adoption the technology will first experience an *innovation trigger*: the establishment of the Auto-ID Center and the Wal-Mart Mandate, leading to the *peak of expectations*: when media hype and additional mandates from the DoD and the healthcare industry gave credence to the potential of UHF RFID. Following the peak however, a dramatic decline in hype leads to *the trough of disillusionment*: when companies realized the costs and limitations of early UHF systems, and the mandates slowly lost momentum. Following the trough, Gartner predicts a stage called the *slope of* *enlightenment*. This stage is defined by the slow realization of technological development efforts and a rise in small scale development projects. This is roughly were the UHF RFID industry at the time of writing this thesis.

In summary of this concept, the author likens the development of the RFID CPG industry to the Big Bang: a lot of shock and awe all at once, followed by a few billion years of waiting for things to cool down before anything useful takes shape.

Growth of Closed-Loop RFID Markets

The 2009 Gartner Hype Cycle report puts RFID at the very base of the *slope of enlightenment* (Fenn, 2009). While the Gartner Cycle rating is based largely on the CPG industry, recent proliferation of RFID niche markets and closed-loop applications suggest that 'little brother' maybe a little bit ahead, on RFID.

A report from Information Week describes the current growth the UHF industry as "innovation-driven" (Weier, 2009), meaning that mandates are no longer the primary driving force in the development of RFID systems. In 2009, the largest user of RFID tags was the smart cards sector, which includes passports, state IDs and prepaid charge systems. The second largest user of tags, however, was not the military, retail sales or animal tracking. Instead the second biggest user of RFID tags was the undefined "Other" category, indicating a fragmented industry, engaged in developing an array of unique ways to use RFID (Weier, 2009).

A report published by ABI Research summarizes the effect of industry mandates on the current RFID industry, saying, "Many vendors, financial analysts, and industry observers were hopeful that (compliance programs) would provide dramatic year-over-year growth. While this did not happen, hope was never lost. Due to those (programs), passive UHF had a chance to mature in terms of standards, performance, form factors, and pricing" (Liard & Carlaw, 2009). These improvements paved the way for new RFID systems designed for small closed loop applications.

Closed-loop applications for RFID are those in which tags are only utilized by the organization that controls the system. This differs from open-loop systems such as CPG and military supply chains, which may attempt to utilize a single RFID tag to track objects as they pass between multiple of trading partners. For a system like this to function, however, information systems between partners must be compatible and a standardized data exchange format must be determined. Reconciling the plethora of data management systems utilized by various organizations proved a major stumbling block to early RFID adoption. Managing a closed-loop RFID system is comparatively easier, since a single organization can customize a complete RFID solution, without regard to compatibility or compliance issues with other businesses.

Table 4 provides several existing closed-loop RFID applications and a brief description of the basic project goals.

Table 4: Common closed-loop applications for RFID

Baggage Tracking	Efficient verification of luggage owner Reduce lost bags
Animal Tagging	Efficient identification of livestock Provide animal-specific tracking for disease monitoring

Table 4: Common closed-loop applications for RFID (cont'd)

Asset Management	Locating items within a storage environment Provide a record of usage and maintenance
Brickyard Management	Inventory Control
Pallet Rentals	Automate Shipping, Receiving, Repair Scheduling Automate Billing
Production Monitoring	Track work-in-process inventories Allow for efficient customization in manufacture-on-demand

RFID Applied for Academic Enhancement

The spread of RFID has not been limited to projects with the specific goal of direct financial returns. RFID has also been applied for the purpose of improving the management of, and access to information for both academic researchers and the general public.

Libraries around the country have used RFID to improve operations since 2000. The American Libraries Association (ALA) offers perspectives on RFID by highlighting the benefits of rapid charging/discharging, simplified patron self-charging/discharging, high reliability, high-speed inventorying, and automated materials handling (Boss, 2004). In the end, librarians spend less time organizing and more time helping patrons, while patrons spend less time searching and more time accessing relevant information. Library RFID systems emerged around 2000 and have traditionally utilized the HF band.

In 2010, The Vatican Museum Library began deploying an HF RFID system for managing a collection of over two million books, manuscripts and other priceless items. "RFID improves the way librarians manage their collections, streamlining and automating item retrieval, storage and inventory processes," said Bill Allen, marketing communications manager, Texas Instruments RFid

Systems©. When completed, the RFID system will allow a complete verification of the museum inventory to be completed in a single day, a process which once required shutting the museum down for an entire month out of every year.

HF RFID is also being utilized at The Malaysia National Museum, though not for the purpose of entertaining visitors. Here, the artifact management system has been designed for the specific purpose of caring for the artifacts, and maintaining a permanent connection between artifacts and the associated historical records (Berhad).

Museums, too, are finding RFID a useful in the management of artifact collections, while also experimenting with RFID enabled exhibits to enhance user experience and gain patronage. As early as 2004, The Museum of Natural History, in Aarhus, Denmark, deployed an HF RFID system designed to allow patrons to interact with exhibits using handheld PDA-style RFID readers. The exhibit included 50 uniquely tagged, stuffed birds that visitors could scan to gain instant access to a variety of multimedia feature relating to the bird species, including videos, articles and quizzes (Khan, 2004).

In 2008, Library Hi tech Journal published a research paper discussing an application of a similar RFID library system with added features of "... regional seeking and positioning for collections in mis-shelves or collections loss in library, statistics calculation in usage frequency and length of book reading, and instant library guiding service" (Yu, 2008). These functional additions to the ALA-envisioned RFID system were made possible by utilizing the long read range capabilities of UHF RFID.

Monetary returns, though not of primary concern, have also been realized through the implementation of RFID library and museum systems. Through increased efficiency in inventory management, the need for manual organization of books and historical artifacts is significantly reduced. Libraries and museums also benefit from the introduction of RFID as a result of the process control requirements for operating an RFID system. Manually driven inventory systems are subject to unintended variation over time and inconsistent performance due to the number of people who use the system, even without necessarily understanding how it works.

Given the numerous examples of recent RFID implementation successes in niche applications and closed-loop inventory management systems, as well as the recognized capability of RFID to enhance the way people access information, it is clear that the potential of RFID for managing archaeological collections, reaches far beyond the museum.

Chapter 3: Methodology

To evaluate the performance of modern UHF technology in performing basic repository management functions, a fully functional RFID-enabled repository management system (R-RMS) was developed for testing at two different archaeological repositories.

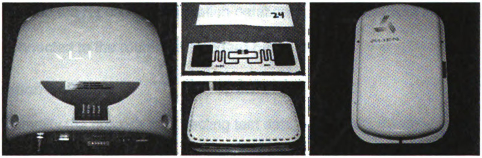
This chapter will describe the methods used to evaluate the R-RMS at an archaeological dig-site repository and at a university-run museum repository. It will detail he preparation and testing of RFID-enabled bags, storage bins, library books and individual artifacts. Test methods will be provided for using the R-RMS for accessioning objects, recalling electronic database entries and performing inventory audits.

Materials

RFID System Components

Evaluation of the R-RMS was conducted using an Alien Technologies ALR-9650, a Gen 2 compliant UHF RFID reader (Figure 2, left). The desktop reader unit measures 9” x 9” x 2” and includes a built in circular antenna. The combination reader/antenna is primarily designed for stationary use and was selected for this study based on its compact form factor and ease of operation. These features are of particular importance in a repository, where storage and research space is often at a premium, and system operators may not be experienced in the use of RFID equipment.

Figure 2: RFID system hardware components used for R-RMS testing



For extended range inventory tasks, an additional antenna was attached to the external antenna port on the reader. This study utilized an Alien ALR-9610-CR circularly polarized antenna (Figure 2, right), connected via twenty foot coaxial cable. A circularly polarized antenna was selected for orientation insensitivity in detecting transponders, a necessary property given the uncertainty of artifact tag orientations in storage.

The RFID transponders used in this research were also manufactured by Alien Technologies. The ALR-9662 Squiggle-SH RFID transponder (Figure 2, middle bottom) is a Gen 2 compliant, global use UHF tag. Global use tags are optimized for operation across a wide range of UHF bandwidths. This capability allows each tag to be read on any Gen 2 compliant reader anywhere in the world, regardless of regional UHF frequency regulations. This Squiggle-SH transponder is manufactured with a Higgs-3 integrated circuit that was selected for its optimized performance with Alien brand readers and the unique ability to selectively program portions of the EPC number, independently of the whole.

Network Components

The Alien ALR-9650 was connected to a host computer over a local network, which consisted of a Netgear 4-port wireless router (Figure 2, middle bottom). A Toshiba Satellite laptop running Windows Vista OS was used to host the R-RMS software and the repository information databases. The reader and the computer were connected to the router via standard Ethernet cords.

Evaluation Software

To simplify the process of collecting test data, an R-RMS middleware program was created specifically for this application. The Java-based evaluation software provided a graphical user interface (GUI) for directing operation of the RFID hardware and automatically managing an electronic database The R-RMS middleware included software features for tagging new items, recalling item-specific information and inventory auditing of an entire population.

The R-RMS middleware feature for tagging a new item was used to program the EPC data of object tags and create object entries in an electronic database. The task is accomplished by placing a new tag directly on the ALR-9650 desktop unit, typing object specific information into specified data fields, and then submitting the command using the GUI. This action triggers two distinct events in the evaluation middleware. First, a command is sent to the reader to program the tag EPC number. If the tag is programmed successfully, the software the updates the appropriate spreadsheets to include the new object entry. If the tag fails to program properly, the software will halt the operation, and an entry for the tag will not be created. This mechanism is necessary to avoid incomplete or duplicate object records resulting from failed or repeated attempts to program a tag for a given object.

The feature for retrieving object information was used to access electronic database records based on the EPC number of the RFID object tag. In operation, a tagged object is placed directly on the Alien ALR-9650 desktop unit and the evaluation middleware GUI is used to issue a command for the reader to perform a single read cycle. The objects detected in this scan are displayed as an on-screen list from which the desired item is selected. A complete digital record for the object is then displayed.

The inventory auditing feature was used to determine the presence or absence of every RFID tagged object in a repository collection. To perform an audit of a population, the first step was to submit a command for the reader to begin detecting tags in AutoMode, via the auxiliary antenna. With the reader continuously reading, the auxiliary antenna was used to scan the entire population of tags. Upon completion, a second command issued for the reader to stop detecting tags and to return a complete list of the tags detected during the scan. Based on an automated comparison of this list to the electronic database, the software generated two lists. The first list showed the object tags that were successfully detected during the inventory scan, indicating that these items were accounted for within the storage environment. The second list displayed any object tags that were present in the digital record, but were not detected during the inventory scan, indicating that these objects may not be present in the storage environment.

In summary, the evaluation middleware was developed to simplify the tasks of tagging objects, accessing information and verifying inventory. These functions can be applied in a repository to individual artifacts, artifact group bags, storage bins and library books. Regardless of object type, operation of the middleware program is unchanged.

Dig-Site Repository Testing

Description of Dig-Site Testing Environment

The Temple of Poseidon in Isthmia, Greece has been an active archaeological site since 1952. Throughout the last half-century, researchers from the University of Chicago, the University of California Los Angeles, and The Ohio State University have managed the extensive collection of artifacts and information, generated through continued excavation. As the basis for artifact management at the dig-site repository, an accession card system was used to establish relationships between artifact bags, bins, books and other reference materials, based on paper ID labels for each class of object.

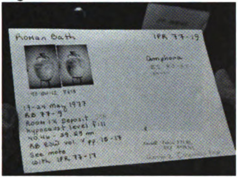
Testing of the R-RMS was conducted in the long term storage annex of the dig house which included a countertop along one wall, a bookshelf along an adjacent wall, and two rows of floor-to-ceiling metal shelving for organizing a collection of plastic storage bins for artifacts. A diagram of the dig-site repository test site is provided in Appendix I. Repository management testing focused on three classes of objects: bags, bins and books.

Bags are a class of objects that are stored in the dig-house. The most commonly observed primary package for the long-term storage of artifacts was archival-grade polyethylene (PE) bags. Due to the wide range of artifacts found on-site, the sizes and contents of bags vary greatly. Less common artifacts, such as fine pottery, toys and weapons are documented and packaged individually. Items such as building tile fragments, which occur more frequently, are grouped based on common provenience, documented as a single lot of items, and then consolidated in a single bag. In many cases, impact absorbing sheets of archival-grade PE bubble-wrap were folded in half and placed inside storage bags to form a protective lining.

Figure 3: Labeled Artifact Bags

Bags were identified using laminated ID cards placed inside each bag, but outside the layer of bubble-wrap for convenient readability (Figure 3). Each bag tag displayed the following data fields: *Accession Number*, *Area*, *Trench*, *Grid*, *TopElev*, *BotElev*, *ExDate*, *Notebook* and *Page*. Additionally,

Figure 4: Artifact Accession Card



for every artifact documented, an accession card was created to aid researchers in locating the desired objects and accessing historical records (Figure 4,).

Bags were grouped based on common artifact characteristics and consolidated in high density polyethylene (HDPE) storage bins measuring either 15 x 23 x 8 inches or 15 x 23 x 6 inches (Figure 5). A standardized method for packing bags into bins was not given due to the wide variety materials, sizes and shapes of artifacts requiring bin storage.

Figure 5: Bagged artifacts in opened top HDPE storage bin

On the outside of each bin, centered along the exposed 15 inch dimension, was attached a hand-written tag that displayed the accession number of each bag contained within. Metal racking was used for bin storage, with shelves configured to hold four bins each, two stacks of two bins (Figure 6).

Figure 6: Closed top storage bins on metal shelf

The last piece of the inventory and information management system was the library of hand written field books (Figure 7, top of next page). The books comprise every formally documented piece of information relating to every artifact

Figure 7: Shelf of Handwritten Field Books

recovered in the history of the excavation. Entries are organized chronologically according to the date of discovery. Books are searched using a hand-written card catalogue system.

RFID Bag Management Evaluation

Twelve RFID test bags were created for the evaluation of bag-level RFID inventory management operations. Assorted terracotta pottery shards from a mass storage bin comprised of artifacts lacking provenience were placed into archival grade PE bags, measuring seven inches by ten inches. As per repository practice, a sheet of bubble wrap was folded in half and placed in the bag as a padded liner. Lastly, an RFID tag was placed inside each bag, outside the layer of bubble wrap.

Test 1: Bag-Level Accessioning

To test the reliability of the RFID system in performing the task of accessioning artifact bags, the evaluation middleware was used to program an RFID tag and create a digital ledger entry for each of the twelve test bags.

Test bags were placed on the Alien ALR-9650 such that the transponder was face down and centered over the reader's antenna component. Each bag tag was individually tested a single time using the accessioning feature of the test software. Data fields were populated with information used to uniquely identify test bags. The success or failure of each trial was determined in Test 2.

Test 2: Recalling Bag-Specific Information

To evaluate the performance of the RFID system in providing quick access to bag-specific reference materials, the evaluation middleware was used to scan bag tags and access digital ledger entries.

Test bags were placed on the Alien ALR-9650 desktop unit in the same position as Test 1. Each bag tag was trialed one time in accordance with operation of the information recall feature of the test software. Success or failure of each trial was determined by verifying accuracy of the bag-identifying information displayed on-screen.

The results of Test 2 trials were also used to determine the success or failure of the Test 1 trials for accessioning bags. Due to the mechanism for preventing the generation of erroneous ledger entries, only successfully programmed bag tags will have a ledger entry. Therefore, if a bag entry was successfully recalled, the success of the accessioning process was also demonstrated.

Test 3: Simple Bag Inventory Scan

Upon completion of Tests 1 and 2, the twelve tagged artifact bags were placed in an HDPE storage bin, measuring 15 x 23 x 8 inches, as per standard dig-house practice (Figure 8). The artifact bin was then scanned twice, using the inventory audit function of the evaluation middleware, once with the bin in each of the two possible shelf positions. First, the storage bin was tested when placed directly on the metal shelf of a storage rack,

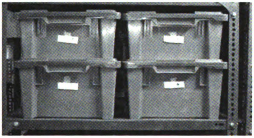
Figure 8: RFID tagged artifact bags in a storage bin

in the standard orientation, with another bin stacked on top. Then the test bin was tested when placed on top of another bin on the storage rack, again, in the standard orientation. The number of reads per tag was recorded for each one of the inventory trials.

RFID Bin Management Evaluation

Test specimens for bin inventory testing consisted of an existing inventory of plastic artifact storage bins. Using the test-software, seventy-nine RFID bin tags were created and then randomly attached, one per bin. Masking tape was used to hold tags flat against the outside of the bin, in a horizontal orientation, centered along the exposed 15 inch dimension of the bin (Figure 9). The seventy-nine test bins comprised one complete face of the metal storage racking.

Figure 9: Tagged storage bins on metal shelf



Test 4: Tagging new bins

To test the reliability of the R-RMS in performing the task of accessioning artifact bins, the evaluation middleware was used to program an RFID tag and create a digital ledger entry for each of the seventy-nine test bins.

Prior to accession testing, the seventy-nine transponder specimens were assigned a number from one to seventy-nine, and labeled using a permanent marker. The Alien Squiggle-SH transponders were then programmed using the same method as Test 1, accessioning bags. Data fields were left blank, with the exception of the field for *Description*, which was populated with the same number written on the tag being programmed. The success or failure of each trial was determined in Test 5.

Test 5: Retrieving Bin-Specific Information

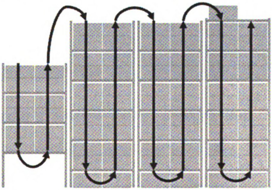
To evaluate the performance of the RFID system in providing quick access to bin-specific reference materials, the middleware was used to scan bin tags and access digital ledger entries.

Using the same method as Test 2, each bin tag was trialed one time in accordance with operation of the middleware feature for recalling object information. Success or failure of each trial was determined by verifying the accuracy of the identifying information displayed on-screen. These results were then used to determine the success or failure of bin accessioning trial, as previously discussed.

Test 6: Taking bin inventory

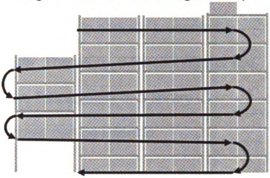
After randomly attaching the seventy-nine newly programmed bin tags to test bins, the evaluation middleware was used to perform bin inventory testing in accordance with the "Take Inventory" software function. Three techniques were evaluated for scanning the population of tagged bins using the auxiliary antenna: column scanning, row scanning and random scanning.

Figure 10: Column scanning technique



The first scanning technique moved the auxiliary antenna in an alternating up-and-down motion to scan adjacent columns of bins (Figure 10). The second scanning technique moved the antenna in an alternating left-to-right motion to scan adjacent rows of bins (Figure 11). The third scanning technique did not establish a pattern for scanning RFID bins. After each inventory trial, the number of reads for each tag was recorded. The test was repeated thirty times for each scanning technique to allow for statistical analysis of the test data.

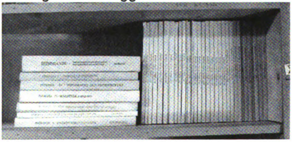
Figure 11: Row scanning technique



RFID Book Management Evaluation

Test samples for evaluating the RFID book management system were created using thirty-nine books from the dig-house library collection: seven hardcover volumes and thirty-two paperback journals. An RFID tag was placed inside the front cover of each book with the long edge of the tag wedged into the binding, centered to the height of the book. After completing accessioning and scanning trials, the tagged books were moved to a wooden bookshelf for inventory testing (Figure 12).

Figure 12: Tagged Books on Shelf



Authentic handwritten notebooks were not used for testing due to strict regulations aimed at preventing Type-4 errors of lost field notes. However, the thirty-two journals used for testing were taller and thinner than the authentic books, resulting in a denser tag population than would be seen in the repository library. Due to this comparatively higher-density tag population, and the effects of tag-to-tag interference, the library auditing test scenario actually presented a greater challenge for collecting RFID read data. Therefore, if functionality of the R-RMS is successfully demonstrated, then the functionality of a library management system for the authentic field notes can be inferred.

Test 7: Tagging new books

To test the reliability of the RFID system in performing the task of accessioning new books, the evaluation middleware was used to program an RFID tag and create a digital ledger entry for each of the thirty nine test books.

Test books were placed on the Alien ALR-9650 such that the bound edge of the book was centered over the reader's antenna component, and then programmed using the established method for object accessioning. Data fields were populated with accurate information relating to the book being accessioned, in order to create a complete ledger entry for each sample book. The success or failure of each trial was determined in Test 5.

Test 8: Retrieving book-specific information

To evaluate the performance of the RFID system in providing quick access to book-specific reference materials, the evaluation middleware was used to scan book tags and access digital ledger entries.

Using the established method for recalling object information, each book tag was trialed one time in accordance with operation of the R-RMS middleware. Success or failure of each trial was determined by verifying the accuracy of the identifying information displayed on-screen. These results were then used to determine the success or failure of book accessioning trials, as previously discussed.

Test 9: Taking Book Inventory

After accessioning, tagged books were placed back on the wooden bookshelf for book inventory testing. The evaluation middleware was used to perform book inventory testing in accordance with the inventory auditing software function.

Book inventory scans were conducted with the auxiliary antenna pointed towards the books, held about two feet away from the shelf while scanning. The antennae was moved from right to left across the shelf and then back, left to right, for each inventory trial. Four trials were conduced and the number of reads per trial was recorded for each tag.

Museum Repository Testing

Following the evaluation of R-RMS capabilities at the dig site repository, the RFID system was tested further at an artifact repository for a university-run museum. While much of the dig site testing was intended to verify several functional capabilities of the RFID system for repository management applications, testing at the museum repository was aimed at validating the performance of the item-level inventory auditing feature.

Description of Museum Testing Environment

Unlike the rustic environment of the dig-house, the museum repository was housed in a university class room. Along one wall of the room was a row of eight metal cabinets, with inside dimensions of 27 x 30 x 72 inches each. Inside the cabinets, artifacts were simply organized, often times without primary packaging, on roll-out metal shelves, measuring 24 x 29 inches. Artifacts accession numbers were written directly on the surface of the items with India ink, due to the lack of packaging to facilitate attachment of paper ID cards.

The computer, network and RFID equipment were assembled on a metal desk which was located along a wall, adjacent to the row of metal cabinets, approximately twelve feet from the storage cabinets to be tested. A diagram of the museum repository testing environment is provided in Appendix II

Item-Level RFID Management

Evaluation of the R-RMS item-level inventory auditing function was performed at the museum repository using 157 artifacts from the MSU Artifact Teaching Collection. Prior to on-site testing, the evaluation software was used to create an RFID tag and an electronic ledger entry for each of the artifacts to be tested. The information needed to create an accurate artifact ledger was provided by an existing inventory list for the collection. The 157 artifacts were housed in and on top of two adjacent storage cabinets, on twelve different metal shelves.

Due to the lack of primary packaging for unitizing objects and RFID transponders, the pre-programmed tags were placed alongside the associated artifacts, in a manner which attempted to recreate realistic variations in tag position. Given the wide range of items, general rules were developed for placing tags with certain types of objects. For tagging bowls and pottery, RFID tags were placed inside individual vessels. Arrowheads, stone hand-tools and other ancient blades were stored flat on the metal shelves, and were relatively dispersed from surrounding artifacts. As a result, tagging was accomplished by neatly laying tags flat, on top of the artifacts. By contrast, tagging of densely populated loose items such as Clovis artifacts or lithic fragments was accomplished more haphazardly, by placing tags as close to the correct artifacts as possible.

Test 10: Taking Item Level Inventory

With all of the artifact tags in place, the R-RMS inventory feature was tested in accordance with operation of the "Take Inventory" feature of the test software. Before each trial, every pull-out shelf which held a tagged artifact was fully extended for scanning by the auxiliary antenna. Upon starting the inventory scan, the antenna was swept over the top of each shelf, starting at with the highest shelf and working downward. Each shelf was scanned for three to five seconds before being pushed back into the cabinet, revealing the next shelf below. Inventory scans were completed when all twelve shelves had been scanned.

The result of each trial was documented, identifying which items were detected and which items were not. Item-level inventory trials were repeated thirty times to ensure statistical validity.

Chapter 4: Results

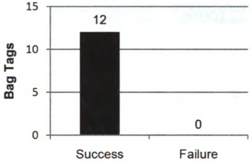
This chapter presents the results of RFID repository management system evaluations conducted at the dig-site repository for excavations at The Temple of Poseidon in Isthmia, Greece, and the Michigan State University Museum repository.

Bag Testing

Test 1: Tagging new bags

The results of Test 1, accessioning new bags, are displayed in Figure 13, below. The graph shows the total number of bag tags, out of twelve, which were successfully programmed on the first attempt, and total number which failed to program on the first attempt.

Figure 13: Success and failure totals for first attempt bag accession trials

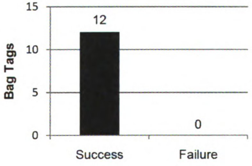


In bag tag accession trials, 100% of the twelve bag tags were successfully programmed on the first attempt. The complete bag database generated by the evaluation software in this test is presented in Appendix III.

Test 2: Retrieving bag-specific information

Figure 14 depicts the results of Test 2, recalling database records from bag tags. The graph shows the number of tags, out of twelve, which returned the correct information from the electronic database after the first attempt, and the number of tags which failed on the first attempt.

Figure 14: Success and failure totals for first attempt bag records recall



Results show that bag specific information was successfully recalled on the first attempt for 100% of the twelve bag tags.

Test 3: Simple Bag Inventory

A single inventory scan was conducted with the bin of RFID tagged bags placed on top of another shelved bin (off shelf), and then again with the bin placed directly on the metal shelf beneath another bin (on shelf). Table 5 shows the results of Test 3, inventory auditing of bag tags. The table shows the total number of reads for each of the twelve bag tags during a single inventory trial of each bin placement scenario.

Table 5: Read count data from simple inventory scans of unitized bags

Bag ID #	Off Shelf	On Shelf
1	24	19
2	19	22
3	43	35
4	20	28
5	12	15
6	26	2
7	22	25
8	20	29
9	33	19
10	21	34
11	14	16
12	20	24
Average	**22.83**	**22.33**
Std Dev	**8.31**	**9.1**
Min	**12**	**2**
Max	**43**	**35**

The bag inventory scan results show that 100% of tags were detected an average of 22.83 times each, in the inventory scan of the off shelf artifact storage bin. 100% of bag tags were also detected in the inventory scan of the storage bin placed directly on the metal shelf, though a lower average read rate was observed of 22.33 per tag.

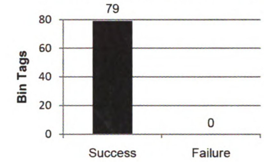
In the off shelf inventory scan of the bin of RFID tagged artifact bags Tag 3 was read the most, 43 times, while Tag 5 was read the least, 12 times. When the bin was placed directly on the metal shelf, Tag 3 was again read the most, 35 times. Tag 6, however, was only read twice despite being read 26 times in the preceding off-shelf inventory trial. Later review of the bag tag placement revealed that Tag 6 had shifted in the bag and been pressed flat against the bottom of the bin by the associated artifact, the top of a broken terracotta amphora.

Bin Testing

Test 4: Tagging new bins

The results of Test 4, tagging new bins, are displayed in Figure 15, below. The graph shows the total number of bin tags, of seventy-nine, which were successfully programmed on the first attempt, and total number of tags which failed to program on the first attempt.

Figure 15: Success and failure totals for first attempt bin accession trials

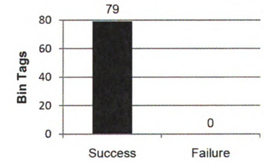


In bin tagging trials, 100% of the seventy-nine bin tags were successfully programmed on the first attempt. The complete bin database generated by the evaluation software in this test is presented in Appendix IV.

Test 5: Retrieving Bin-Specific Information

Figure 16 depicts the results of Test 5, recalling database records from bin tags. The graph shows the number of tags, of seventy-nine, which returned the correct information from the electronic database after the first attempt, and the number of tags which failed on the first attempt.

Figure 16: Success and failure totals for first attempt bin records recall trials



Results show that bin-specific information was successfully recalled on the first attempt for 100% of the bin tags.

Test 6: Bin Inventory

The bin inventory auditing results summarized below are based on a statistical analysis of the average number of reads per trial for each bin tag. For each of the three scanning techniques, the average bin tag read rate was determined and used to compare the performance of the techniques in performing inventory audits on the seventy-nine RFID-tagged storage bins. The interquartile range (IQR) was also determined by the statistical analysis, and used to determine the degree of performance variation between individual tags, according to the scanning technique.

- Using a row scanning technique, 100% of bin tags were detected in every trial.
- Using a column scanning technique, 100% of bin tags were detected in every trial.
- Using a random scanning technique, 100% of bin tags were detected in every trial.
- The row scanning technique showed the highest average read rate per bin tag, 14.8 per trial.
- Column scanning and random scanning techniques showed similar average read rates for bin tags, 10.7 and 10.8 reads per trial, respectively.
- The highest read rate for a bin tag, 31.6 reads per trial, was observed using a row scanning technique. The lowest read rate for a bin tag, 3.4 reads per trial, occurred when using a random scanning technique.
- The row scanning technique showed the most variation in bin tag read rates, with an IQR of 8.6 reads per tag.
- The column scanning technique showed the less variation in bin tag read rates than the row scanning technique, with an IQR of 4.6 reads per tag.
- The random scanning technique showed the least variation in bin tag read rates, with an IQR of 3.4 reads per tag.

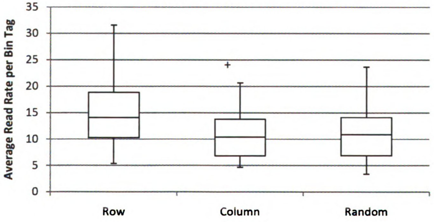
Table 6 displays the data for the bin inventory results listed above. A complete test summary of individual bin tag read rates is provided for each of the three scanning techniques in Appendices V (a), (b) and (c).

Table 6: Summarized bin tag read rate data

	Row Scan	Column Scan	Random Scan
Average	14.84	10.70	10.75
Median	14.07	10.37	10.87
Q1	10.23	6.83	6.85
Q3	18.85	13.77	14.10
IQR	8.62	6.93	7.25
Max	31.57	20.67	23.67
Min	5.33	4.63	3.37

Based on the data in Table 6, Figure 17 displays a box-and-whisker diagram for each of the three inventory scanning techniques. Box-and-whisker diagrams display distribution information for a data set. The upper and lower quartiles are used to define a box, representing the IQR. The median value is displayed as a line within the IQR box. It is clear from this diagram that the row scanning technique showed the highest read rates for bin tags.

Figure 17: Statistical analysis of reads for each tag by scanning method



While it is important to maximize the readability of tags to ensure accurate inventory auditing, it is equally important to ensure repeatability of the results as well. The bin inventory auditing results summarized below are based on a statistical analysis of the average number of reads per bin tag for each trial. The IQR is used to determine the degree of variation across thirty trials, for each of the scanning techniques. The observed variation between trials indicates the repeatability, and subsequently the reliability, of the three inventory auditing methods.

- The row scanning technique showed the least variation in average per-trial read rates, with an IQR of 1.8 reads per tag.
- The column scanning technique showed more variation across thirty trials than the row scanning technique, with an IQR of 4.4 reads per tag.
- The random scanning technique showed the most variation across thirty trials, with an IQR of 3.4 reads per tag.

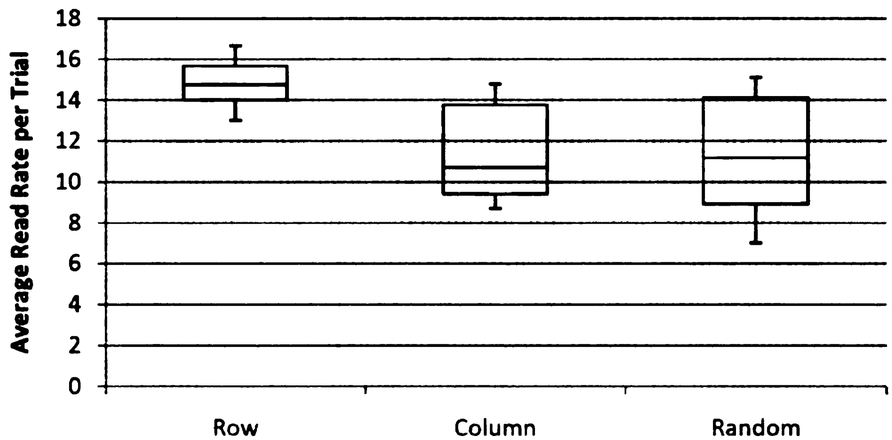
Table 7 displays the data for the bin inventory results listed above. A complete test summary of individual trial read rates is provided for each of the three scanning techniques in Appendix VI.

Table 7: Summarized per-trial read rate data

	Row Scan	Column Scan	Random Scan
Average	14.84	10.70	10.75
Median	14.75	10.71	11.16
Q1	13.83	9.42	8.63
Q3	15.67	13.77	14.10
IQR	1.84	4.35	5.47
Max	16.56	13.91	16.10
Min	12.99	8.68	7.00

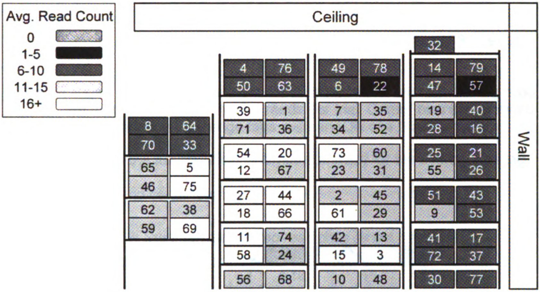
Based on the average per-trial read rates displayed in Table 7, Figure 18 displays a box-and-whisker diagram for each of the three scanning techniques. From this diagram it is clear that the row scanning technique resulted in the least variation, as well as the highest read rates for bin tags, across thirty trials.

Figure 18: Statistical analysis of reads for each trial by scanning method



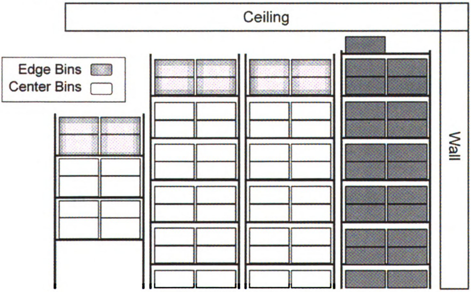
Regardless of bin inventory scanning technique, a trend of relatively lower read rates was observed for bin tags located on the top row and far-right column of the shelving unit (Edge Bins), as compared to tags more centrally located on the shelves (Center Bins). An example of this trend can be seen in Figure 19, at the top of the next page, which shows the average read rate of bin tags, for all bin inventory trials combined. The diagram depicts the shelf position of each tagged storage bin, identified by the randomly assigned bin ID number. Each bin is patterned to indicate the average read rate of the respective tag according to the arbitrarily determined ranges of: less than 1, 1-5, 6-10, 11-15, or 16 and above. Similar figures for row, column and random scanning techniques are provided in Appendices VII (a), (b) and (c).

Figure 19: Overall average bin tag read counts



To formally evaluate this trend, a statistical analysis was conducted to determine performance differences between edge and center bin tags, as defined by Figure 20.

Figure 20: Edge bins and center bins for statistical analysis



The summarized results, below, are based on the statistical analysis which looked at the average number of reads per trial for each bin tag.

- Tagged edge bins showed an average bin tag read rate of 8.2 reads per trial, with an IQR of 2.2 reads per trial.
- Tagged center bins showed a significantly higher average bin tag read rate than edge bins, with 15.2 reads per trial. Center bins also showed greater variation than edge tags, with an IQR of 4.0 reads per trial.

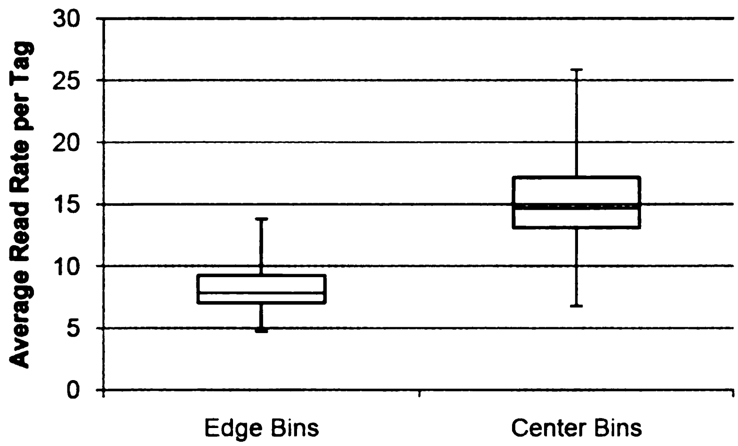
Table 8 displays the full statistical analysis summary for the average bin tag read rates of edge and center bin tags.

Table 8: Summarized bin tag read data by bin position

	Edge Bins	Center Bins
Average	8.18	15.21
Standard Deviation	1.99	3.38
Median	7.82	14.71
Q1	7.02	13.09
Q3	9.25	17.13
IQR	2.23	4.04
Max	13.79	25.86
Min	4.72	6.78

Based on the statistical analysis data in Table 8, Figure 21 displays a box-and-whisker diagram for edge and center bin tags, respectively.

Figure 21: Statistical analysis of reads for each tag by bin position



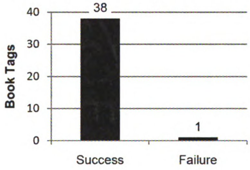
Based on Figure 21, it is clear that the centrally located tagged bins perform better, according to tag read rates, than bins located along the top and right-side of the shelving unit.

Book Testing

Test 7: Tagging new books

The results of Test 7, tagging new books, are displayed in Figure 22. The graph shows the total number of book tags, out of thirty-nine, which were successfully programmed on the first attempt, and total number which failed to program on the first attempt.

Figure 22: Success and failure totals for first attempt book accession trials



In book accession trials, 97% of book tags (38 of 39) were successfully programmed on the first attempt. Though the exact cause of the single failure is uncertain, the process of programming an RFID tag does require a complex exchange of information between tags and readers, which can be easily disrupted by environmental interferences or the presence of unexpected tags in the read field.

The complete book database generated by the evaluation software in this test is presented in Appendix VIII.

Test 8: Retrieving Book-Specific Information

Figure 23 depicts the results of Test 8, recalling database records from book tags. The graph shows the number of book tags, of thirty-nine, which returned the correct information from the electronic database after the first attempt, and the number of tags which failed on the first attempt.

Figure 23: Success and failure totals for first attempt book records recall trials

Results show that book-specific information was successfully recalled on the first attempt for 97% of book tags (38 of 39). The failure in recalling object-specific information was caused by the initial programming failure in Test 7, as the result of a specific software feature which prevents data from being entered into the database if a tag is not programmed properly.

Upon discovering the tag programming failure, a second programming attempt was made using the same RFID tag, resulting in a successfully programmed tag and a properly updated database entry.

Test 9: Book Inventory

Table 9 shows the average number of reads per book tag, across a total of four book auditing trials. Data is organized according to a random tag number, determined when the tag is programmed.

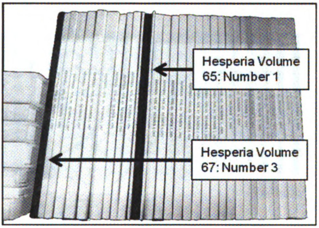
Table 9: Average number of reads per book tag

Tag #	Book	Average	Std Dev	Min	Max
1	Volume 67: Number 2	8.00	2.83	6	10
2	Volume 63: Number 2	3.50	0.71	3	4
3	Volume 66: Number 3	5.50	2.12	4	7
4	Volume 63: Number 1	4.00	1.41	3	5
5	Volume 61: Number 4	5.50	3.54	3	8
6	Volume 61: Number 3	5.00	2.83	3	7
7	Volume 61: Number 1	3.00	2.83	1	5
8	The Metal Objects	9.50	4.95	6	13
9	Sculptures I	8.00	4.24	5	11
10	Volume 61: Number 1	5.50	3.54	3	8
11	Volume 65: Number 1	1.50	0.71	1	2
12	Volume 64: Number 2	3.50	2.12	2	5
13	Temple of Posseidon	9.00	4.24	6	12
14	Volume 65: Number 2	3.00	1.41	2	4
15	Volume 65: Number 1	2.50	2.12	1	4
16	Volume 62: Number 4	5.00	2.83	3	7
17	Volume 61: Number 1	5.50	3.54	3	8
18	Volume 61: Number 1	5.50	3.54	3	8
19	Volume 61: Number 2	5.50	3.54	3	8
20	Volume 63: Number 3	2.50	0.71	2	3
21	Volume 66: Number 4	7.50	2.12	6	9
22	Volume 63: Number 1	2.50	0.71	2	3
23	Volume 67: Number 1	8.50	2.12	7	10
24	The Hexamillion and The Fortress	9.00	4.24	6	12
25	Volume 63: Number 4	3.00	1.41	2	4
26	Sculpture II: Marble Sculptures	9.50	3.54	7	12
27	Volume 64: Number 1	2.50	0.71	2	3
28	Topography and Architecture	7.50	3.54	5	10
29	Volume 64: Number 3	2.00	0.00	2	2
30	Volume 64: Number 4	2.50	0.71	2	3
31	Volume 64: Number 3	2.50	0.71	2	3
32	Volume 62: Number 3	3.50	0.71	3	4
33	Volume 63: Number 2	2.00	1.41	1	3
34	Volume 66: Number 1	5.00	1.41	4	6
35	Volume 66: Number 2	5.00	2.83	3	7
36	Volume 65: Number 4	4.50	2.12	3	6
37	Volume 67: Number 3	14.00	5.66	10	18
38	Volume 65: Number 3	3.50	2.12	2	5
39	The Late Bronze Age Settlement	9.50	3.54	7	12
	Overall	**5.26**	**2.84**	**1**	**18**
				Range	
				1-10	2-18

Based on the data in Table 9, 100% detection of book tags was observed in each inventory trial, with an overall average of five reads per tag per trial. The book tag for Hesperia Volume 67: Number 3 showed the overall highest detection rate, with an average of 14 reads per trial, while Hesperia Volume 65: Number 1 read the least, with an average of 1.5 reads per trial.

One reason for this discrepancy in RFID tag detection rate may be based on the thickness and relative position of the tagged books on a shelf (Figure 24). As previously mentioned, RFID tags can experience interference from other RFID tags. In this tagging scenario, all of the RFID tags were placed at the same location within the cover of the books. As a result, when shelved, the RFID book tags directly align with other RFID tags in adjacent books. The poorest performing book tag, Hesperia Volume 65: Number 1 was sandwiched between two other tags. In addition, the books which contained the interfering tags were the two thinnest books in the library collection. This means that the tag for Hesperia Volume 65: Number 1 was closer to two adjacent tags than any of the other book tags in the middle of the row. In contrast, the superior read rate of the book tag for Hesperia Volume 67: Number 3 may be the result of the book being placed on the end of the row of books. While the majority of tags have the potential for

Figure 24: RFID-tagged books showing highest and lowest reading book tag



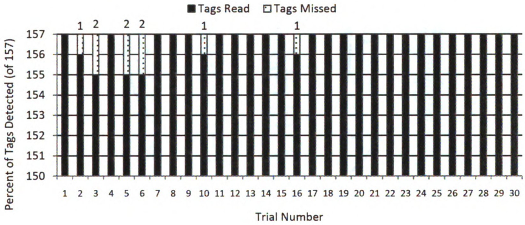
interference from two adjacent tags, books on the end of rows have only one potential source for tag-to-tag interference.

Museum Repository Testing

Test 10: Item-level Inventory

Test results displayed in this section are from item-level inventory testing conducted at the museum repository. Figure 25 shows the number of tags, out of 157, that were detected in each of the thirty inventory trials, a total 4710 potential tag reads overall. Results show missed tags in six of the thirty trials, with no trial missing more than two of the 157 item tags.

Figure 25: Number of item-level tags detected in each inventory trial

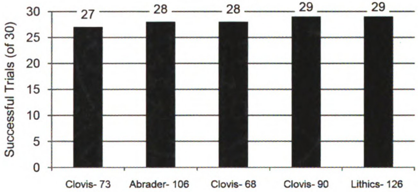


Results of item-level inventory auditing trials show a total of nine missed tags across all thirty trials. This is equivalent to an RFID item-tag detection rate of 99.8% (4701 of 4710). Figure 26, at the top of the next page, presents this data as a pie chart.

Figure 26: RFID tag detection rates for item-level inventory scans

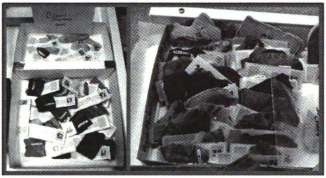
Of the 157 items, only five tags were missed in one or more times across thirty trials. The total number of successful inventory trials for each of these fives item tags is shown in Figure 27.

Figure 27: Number of successful trials for the five items that were missed in at least one trial



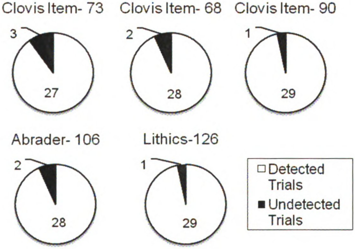
Analysis of the five items to go undetected at least once reveals that four of them belonged to groups of comparatively small artifacts such as Clovis items or lithic fragments, which both were stored without primary packaging in densely packed trays (Figure 28, at the top of the next page). Possible explanations for this observation include tag-to-tag interference and inadequate exposure time for detecting every tag in the tray. Despite this potential for tag-to-tag interference, even the worst performing tag, assigned to *Clovis- 73*, was still detected in 27 of the 30 trials, or 90% of the time.

Figure 28: Densely Populated Loose Items



The overall inventory detection success for each of the five missed tags is displayed in Figure 29.

Figure 29: Overall inventory detection rates for missed item-tags



Aside from occasional missed reads from the decidedly difficult-to-read item tags, the only other tag to be missed in at least one trial was for the Abrader. The Abrader was constructed entirely of stone and wood, materials which do not interfere with RFID readability, and the object was stored in an area of low tag density Despite these favorable tagging conditions, the tag did not read in two trials. In the course of testing it was observed that the tag had shifted from its original placement on top of the Abrader, and was laying flat on the metal shelf during the unsuccessful inventory scans. Once discovered, the tag was re-placed before continuing inventory trials.

Chapter 5: Conclusions and Discussion

Based on the R-RMS evaluation, it is concluded that UHF radio frequency identification technology can be successfully applied for the purpose of archaeological repository management.

This chapter will present the conclusions drawn from repository testing and discuss the suitability of UHF technology for archaeological repository management. The lessons learned from this research are presented as they relate to an RFID-enabled artifact accessioning system and a repository management tool for inventory auditing.

Unlike previous chapters that divided discussion of the repository management system (R-RMS) evaluation according to test numbers, this chapter will combine test scenarios and present conclusions under three subsections: dig-house artifact accession system, dig-house inventory management and museum inventory management. Table 10 shows the relation of test scenarios to R-RMS functions as described herein.

Table 10: R-RMS functions as related to RFID test scenarios

R-RMS Function	Related Test Scenarios
Dig-House Repository: Artifact Accessioning	Test 1: Bag-Level Accessioning Test 2: Recalling Bag-Specific Information Test 4: Tagging new bins Test 5: Retrieving Bin-Specific Information Test 7: Tagging new books Test 8: Retrieving book-specific information
Dig-House Repository: Inventory Auditing	Test 3: Simple Bag Inventory Scan Test 6: Taking bin inventory Test 9: Taking Book Inventory
Museum Repository: Inventory Auditing	Test 10: Taking Item Level Inventory

Dig-House Repository: Artifact Accessioning

R-RMS testing at the dig-house repository was 99.2% successful (129 of 130) in performing the functions of programming transponder EPC data, creating object entries in an electronic database, and using RFID tag data to recall object-specific database entries. Therefore, the R-RMS is capable of consistently performing the basic functions of an RFID-enabled repository accession system.

Based on the one instance of tag programming failure, functionality was demonstrated for the software mechanism for preventing erroneous database entries, and the tag was successfully programmed on the second attempt.

Dig-House Repository: Inventory Auditing

An RFID system used for the task of inventory auditing must be able to collect RFID read data from a large population of object tags and communicate the accumulated read data back to the host computer for processing. Dig-site inventory testing of the R-RMS resulted in a 100% detection rate of the possible 7,290 tags across bag, bin and book inventory audit trials. Therefore, the RFID system is determined to be capable of reliably and accurately performing inventory auditing at the archaeological dig-site repository.

In addition to validation of the RFID inventory system as a whole, the following conclusions were drawn from R-RMS inventory audit testing at the dig-house repository:

- Bag tags within a closed storage bin can be successfully detected without removing the bin's lid.
- Metal shelving can negatively impact the readability of RFID bag tags when tags are positioned flat against the bottom of the storage bin.
- Readability issues associated with shelving placement can be alleviated if attention is given to ensure that no bag tags are positioned against the bottom of storage bins. Alternatively, a thin layer of foam padding may provide sufficient separation from the metal surface to make the tag readable.
- The readability of RFID tagged bins is affected by the placement of the bins on storage shelves. Bins placed around the perimeter of a storage shelf, near a physical structure such as a wall or ceiling, did not read as often as bins that were located further from the barriers, towards the center of the shelf.

- A complete inventory audit of seventy-nine bins can be completed in less than twenty seconds.
- For bin inventory auditing, a row scanning technique will collect tag data with 100% accuracy, more consistently than column or random scanning techniques.
- Given the success of detecting tags on the test books, and that authentic field notebooks are thicker than the books tested, the R-RMS can function properly with authentic field notebooks.

Museum Repository: Inventory Auditing

Item-level inventory testing at the museum repository showed a 99.8% detection rate of 157 tagged artifacts inside metal cabinets across thirty trials (4701 of 4710). Therefore, the RFID system is capable of effectively and accurately performing item-level inventory audits in the museum repository.

- Item-level RFID tags functioned at 99.8% in the metal-heavy environment of artifact storage cabinets.
- RFID tags on artifacts that are stored without packaging in a dense population can be successfully detected. To ensure reliability, these objects should be scanned slower, and at a closer range than less densely populated items.
- Using the R-RMS, a complete inventory audit of 157 tagged artifacts can be conducted in less than one minute.
- Readability of item tags can be negatively affected by metal cabinet shelves. To avoid this problem, an effort should be made to place tags where they will not be in close proximity to metal shelving, metallic artifacts, or other tags.

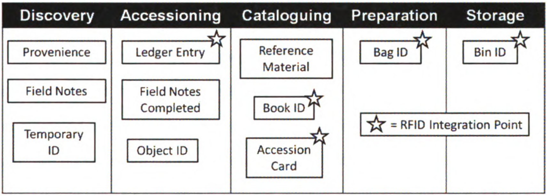
The RFID-Enabled Repository

This section synthesizes the findings of the RFID repository management system evaluation in order to develop a process map for utilizing an R-RMS to manage archaeological collections from discovery through ongoing curation in an RFID-enabled repository.

The Transition from Paper to Microchips

Transitioning to an RFID-enabled repository management system from a paper-based system requires updating or replacing some of the basic object identifying documents to incorporate RFID technology. Additional updates to supporting technologies, such as networking and data storage hardware, may also be necessary. Figure 30 illustrates the technology updates that would be required for implementation of an RFID accessioning and inventory system, like the one evaluated in this research.

Figure 30: Points of integration for RFID in artifact processing



The first change to the initial processing of artifacts is the elimination of the hand-written ledger notebook, used during the task of accessioning. Rather than writing a new object entry in a ledger notebook, information is entered into an R-RMS software program and used to automatically update an electronic ledger. The primary benefit of a digital ledger is the ability to efficiently organize entries. For example, if two related objects are documented in a handwritten ledger at different times, the ledger cannot be updated to display the entries next to one another. By contrast, modern database systems have advanced data editing tools for maintaining organized collections records.

The next change to an existing system would be the incorporation of an RFID tag with bag ID labels. Using an approach similar to the "Tag New Item" method from this research, RFID tags would be programmed and then affixed to the reverse side of the paper label. This practice, however, would require a change in the processing of bagged artifacts. Generally, bag ID tags are created during the 'preparation' stage. The R-RMS described in this thesis, however, would require the creation of bag tags during the 'accessioning' stage, when the RFID tag is programmed.

Bin ID labels would require changes similar to RFID bag labels. Using an approach similar to the "Tag New Item" method, RFID tags would be programmed and then affixed to storage bins or ID labels using the pressure sensitive adhesive tag backing. Unlike bag labels, the process of creating bin labels would still be performed during the storage preparation stage, due to the fact that bins are not utilized until the final stage of artifact 'storage'.

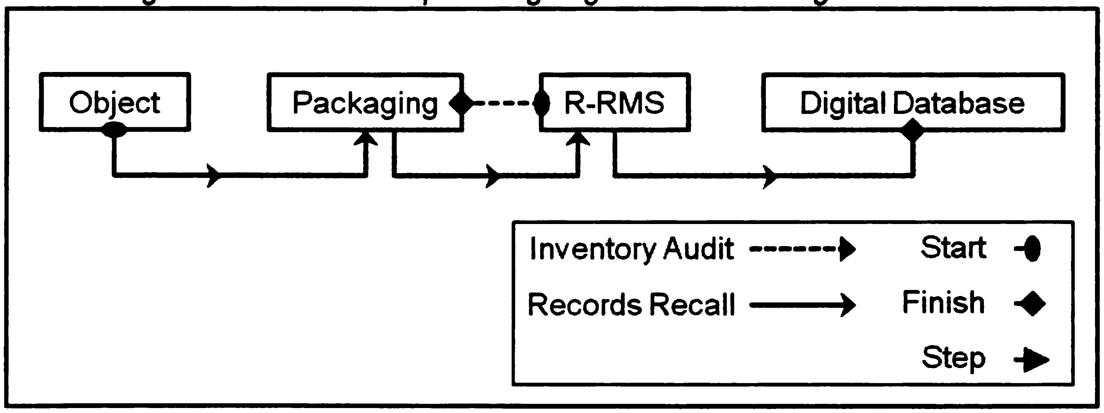
The accession card system would be changed dramatically by an R-RMS, and may even be eliminated. The purpose of an accession card is to document all of the reference materials assembled during the 'cataloguing' stage of initial processing. By using an electronic database, it is possible to add the accession card information to the original ledger entry at a later time, thus eliminating the need for the separate cards entirely. Alternatively, a paper based accession card system may still be maintained in conjunction with an R-RMS as an emergency back-up for electronic records.

RFID book tags would also be introduced for managing field notes and other library reference material. The traditional method for labeling books, displaying a title on the front cover and book spine, would remain unchanged. When a new book is added to the library collection, an RFID tag would be programmed and affixed to the book, according to a predefined tag placement method.

Ongoing Curation with RFID

The ultimate goal of an R-RMS is a perfect system for the ongoing curation of archaeological artifacts. Using RFID to instantly recall electronic database records and to perform periodic inventory audits is a significant step toward this goal. As such, once an RFID system is established in a repository, complete with RF-labels and electronic records for bags, bins and books, the next step is to utilize the technology infrastructure for the tasks of recalling records and auditing artifact collections, as shown in Figure 31.

Figure 31: Process map for ongoing curation in using an R-RMS



To streamline to process of locating artifact-specific reference materials, the R-RMS can be used to scan bag ID labels and instantly access complete artifact records from an electronic database. The intermediate step of consulting an accession card is eliminated, reducing the potential for Type 1 failures in the repository, and providing accelerated access to information for researchers.

Although bin and book tags would be primarily used for inventory auditing, they could also be applied beneficially to recall database entries. Bin tags can be used to reduce unnecessary handling of antiquities by using the R-RMS to recall identifying information for every item associated with a bin tag. In doing so, the complete contents of the storage container can be determined without ever touching an artifact or even removing the lid. In a similar process, using the database linkage between entries for artifacts and books, book tags could be scanned to determine every artifact documented in a given book. Scanning book tags using the same method evaluated in this thesis, could also power a library check in/out feature. Using RFID personnel cards, responsibility could be assigned for loaned book, providing accountability for all Type-4 failures in maintaining provenience.

With pressure from government agencies, tribal heritage organizations and self-imposed ethical standards to maintain accurate collections records, periodic inventory auditing is a critical function of repository management. The R-RMS eliminates the manual, line-by-line, ledger-to-object comparison method of inventory auditing, and instead was an RFID middleware tool for automatically determining missing items from a collection based on a single RFID scan of the storage environment.

Verifying the proper location of storage bins is an important task for maintaining an organized repository. Bins maybe moved from their storage location to enable further study of the contents, to gain access to bins lower in a stack, or simply to make room for other research activities. When this happens, there is no guarantee that a bin will be returned to the proper location. In a dig-site repository, the bin inventory feature could be used to scan the storage environment and identify any instances of bins missing from storage. Given the low density distribution of bin transponders and the RF-transparence of plastic storage bins, inventory scans of the dig-site repository could be completed in a matter of minutes. The efficiency of the system would allow for bin inventory verification as frequently as desired, even daily. According to statistical analysis of bin inventory scanning techniques, a column scanning technique reliably performs with 100% accuracy, with less variation in tag read rate. The column method should therefore be employed for all bin inventory auditing.

Verifying the proper location of artifacts is a critical task for maintaining an organized repository. Artifacts are constantly being accessed, studied, loaned out, and generally moved throughout an archaeological repository environment. Like storage bins, there is never a guarantee that an object moved will be properly returned to storage. Considering the museum repository environment, an item-level inventory auditing tool would be used to frequently verify the accuracy of artifact inventory records. Unlike bins, however, item level tags may require a more meticulous scanning technique than dispersed artifact tags.

Without a well organized library of reference materials for documenting the provenience of every artifact in a repository collection, ongoing research efforts can be hindered by the inability to efficiently locate relevant documentation, if at all. Managing books with an R-RMS would allow for frequent book inventory audits to identify missing books, a critical step towards avoiding Type-4 errors of lost field notebooks.

In summary, the R-RMS system evaluated by this research is capable of performing the repository management tasks of accessioning, recalling records from an electronic database and performing inventory audits on RFID-tagged artifacts, bags, bins and books.

Chapter 6: Future Considerations

The R-RMS system proposed and evaluated by this research has been functionally demonstrated for applications in managing archaeological collections. The opportunities for RFID in archaeology, however, are not confined to the four walls of the repository. This section presents potential opportunities for functionally expanding the R-RMS to include new hardware and artifact tracking capabilities. Additionally, scalability issues are presented and recommendations are made for further developing and implementing a full-scale RFID repository solution.

Expanding the R-RMS

Managing Bulk Artifacts

While smaller artifacts can be collected from a site and later stored in a repository, bulk items are those which are too big for this research approach to be practical. Instead, bulk items, such as architectural block fragments, are studied in the field and then left in place. Since no bag or bin is used, all identifying information must be attached directly to the object itself.

Throughout the history of excavations at the Corinth site, many unsuccessful attempts have been made to develop a method for joining bulk items and identifiers. There are two primary considerations for developing a bulk-item identification method: aesthetic impact and ID-permanence. Any permanent marking will negatively impact the aesthetics of an artifact, so the footprint of the attachment mechanism must be minimized. Additionally, the objects are stored outside, and are, therefore, subjected to weathering. If the identifier is not designed to withstand erosion, and the identifier becomes unreadable, the connection between the object and the documented historical record is severed. The difficulty in balancing these to requirements for marking objects can be seen by looking at discontinued marking techniques from the last 50 years.

Figure 32: Carved identifier on bulk artifact

Carving the accession number into objects was used to provide a very resilient identifier, but resulted in a major disruption to the objects appearance (Figure 32). Painting the accession number on the artifact minimized the aesthetic impact and allowed the option for later removal if desired, but was subject to rapid degradation from the elements. Yet another marking technique used a spike nail

Figure 33: Tin plate identifier on bulk artifact

to attach tin plates, stamped with accession numbers, to bulk-items (Figure 33). Aesthetic impact was initially limited to a single nail hole and the tin plate was thought to be a reasonably permanent identifier. As time progressed, however, the tin corroded, staining the artifacts with rust and rendering the plates unreadable.

If an R-RMS system is to be applied for the management of bulk items, an aesthetically acceptable method for attaching transponder to artifacts will need to be developed and tested for performance and durability. In order to satisfy the requirement of permanence, transponders should be attached to bulk items in such a manner that the tag is protected from exposure to the elements, physical impacts, and malicious destruction. Ideally, this would entail removing a small, non-critical portion of the object and embedding the tag into the artifact itself. To reduce the aesthetic impact of imbedding transponders, a drill might be used to create a small diameter hole, just deep and wide enough to accommodate a tag. The hole could then be filled with any number of epoxies or sealants, which could be color matched to the object to further reduce visual disruption.

Specialty RFID Hardware

The functionality of the R-RMS system could also be expanded using specialized RFID hardware such as RFID tag printers and handheld RFID reader units. Using a compact RFID tag printer, designed for niche applications, item labels could be created in a single step that would also eliminate the need to print a separate human-readable tag.

The R-RMS system could also be enhanced by the integration of hand-held reader units for applications in the field. In the aforementioned case of managing bulk items, handheld readers are a necessity because the artifacts cannot be brought to the RFID system. In addition to enabling the management of bulk artifacts, the handheld readers could also be used to document newly discovered artifacts in the field, at the moment of discovery, thus reducing the risk of Type-3 failures resulting from the loss of temporary field ID tags associated to a group of artifacts with shared provenience.

Scalability Considerations

As the number of artifacts being managed by an RMS system increases, so does the amount of computing power needed operate the system. The evaluation software developed for this research stored information using a set of Microsoft (MS) Excel spreadsheets. While the Excel platform was more than capable of managing the three small test spreadsheets, the program is primarily designed for the purpose of displaying and analyzing arrays of data, rather than organizing large collections of data. Efficiently managing collections larger than 100,000 objects would require a more powerful database format such as MS Access or SQL database programs specifically designed to organize large collections of data.

Another information management technique of note is that of cloud networking, also called software as a service (SaaS). In a cloud network, rather than hosting a database on a local data storage device, information is accessed online, stored at a remote location and managed by a SaaS provider. An R-RMS utilizing a cloud network could allow interoperability of RFID tagged artifacts from one repository to another, and could provide the basis for improved information sharing capabilities between researcher organizations.

Statistical Validity Testing

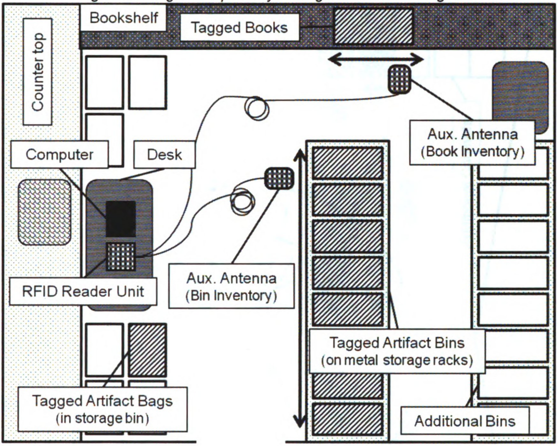
Statistically valid tests were performed to quantify the effect of different scanning techniques on the performance of RFID bin inventory auditing. The remaining evaluation scenarios for artifacts, bags and books, however, were largely qualitative in nature. This is a product of the research being primarily focused on the conceptual development of a specialized RFID system for repository applications. To further understand the performance of UHF RFID systems in a repository, the following topics should be pursued:

- The effect of book thickness on the readability of RFID library tags
- The effect of bin contents and position on the readability of bag tags
- Tag attachment methods for bulk artifacts

Recognizing the importance of validating a system in its entirety, the author recommends that statistically valid tests be done, in the environment of intended use, on all R-RMS features prior to implementing future versions of an RFID repository management system.

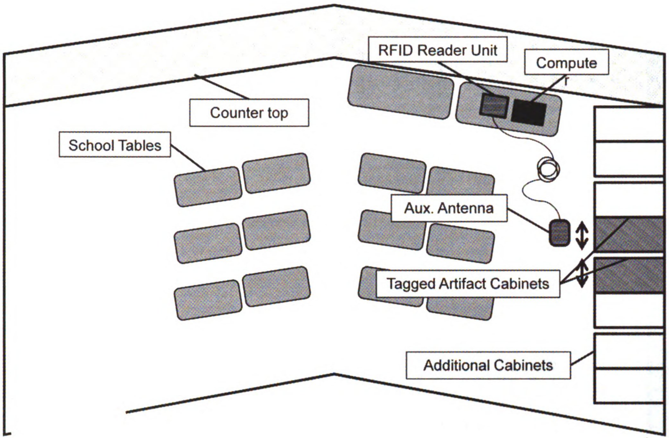
Appendix I: Dig-Site Repository

Figure 34: Dig-site repository testing environment diagram



Appendix II: Museum Repository

Figure 35: Museum repository testing environment diagram



Appendix III: Dig- Site Bag Database

Table 11: Dig-site bag database (faux data)

Item UID	Tag ID	Date	Trench	Description of Contents
2222 3412 DC03 0119 2409 7637	4	6.25.2009	Shards Bin	seven flat shards
2222 3412 DC03 0119 2409 7580	7	6.25.2009	Shards Bin	about 10 flat shards
2222 3412 DC03 0119 2409 7620	10	6.26.2009	Dhards Bin	eight flat shards and a pottery handle
2222 3412 DC03 0119 2409 7623	12	6.25.2009	Shards Bin	three large flat shards
2222 3412 DC03 0119 2409 7624	6	6.25.2009	Shards Bin	Amphora top w/ broken handles
2222 3412 DC03 0119 2409 7621	2	6.25.2009	Shards Bin	2 amphora bases
2222 3412 DC03 0119 2409 7618	8	6.25.2009	Shards Bin	Handfull of small shards. One large curved piece
2222 3412 DC03 0118 0826 5323	11	6.25.2009	Shards Bin	seven pottery shards
2222 3412 DC03 0119 2409 7627	3	6.25.2009	Shards Bin	fifteen or so small shards
2222 3412 DC03 0119 2409 7628	1	6.25.2009		four shards and an amphora base
2222 3412 DC03 0119 2409 7625	9	6.25.2009	Shards Bin	three amphora bases
2222 3412 DC03 0119 2409 7630	5	6.25.2009	Shards Bin	8 small and 3 medium sized shards

Appendix IV: Dig-Site Bin Database

Table 12: Dig-Site Bin Database

Item UID	Date Tagged	Area	Content
1111 3411 B802 0116 1436 5599			1
1111 3411 B802 0116 1436 5600			2
1111 3411 B802 0116 1436 5601			3
1111 3411 B802 0116 1436 5602			4
1111 3411 B802 0116 1436 5645			5
1111 3411 B802 0116 1436 5644			6
1111 3411 B802 0116 1436 5640			7
1111 3411 B802 0116 1436 5639			8
1111 3411 B802 0116 1436 5637			9
1111 3411 B802 0116 1436 5636			10
1111 3411 B802 0116 1436 5635			11
1111 3411 B802 0116 1436 5634			12
1111 3411 B802 0116 1436 5633			13
1111 3411 B802 0116 1436 5629			14
1111 3411 B802 0116 1436 5628			15
1111 3411 B802 0116 1436 5627			16
1111 3411 B802 0116 1436 5626			17
1111 3411 B802 0116 1436 5625			18
1111 3411 B802 0116 1436 5621			19
1111 3411 B802 0116 1436 5622			20
1111 3411 B802 0116 1436 5624			21
1111 3411 B802 0116 1436 5609			22
1111 3411 B802 0116 1436 5619			23
1111 3411 B802 0116 1436 5608			24
1111 3411 B802 0116 1436 5620			25
1111 3411 B802 0116 1436 5613			26
1111 3411 B802 0116 1436 5611			27
1111 3411 B802 0116 1436 5612			28
1111 3411 B802 0116 1436 5618			29
1111 3411 B802 0116 1436 5616			30
1111 3411 B802 0116 1436 5614			31
1111 3411 B802 0116 1436 5605			32
1111 3411 B802 0116 1436 5603			33
1111 3411 B802 0116 1436 5646			34
1111 3411 B802 0116 1436 5604			35
1111 3411 B802 0116 1436 5606			36
1111 3411 B802 0116 1436 5607			37
1111 3411 B802 0116 1436 5662			38
1111 3411 B802 0116 1436 5661			39

Table 12: Dig-Site Bin Database (cont'd)

1111 3411 B802 0116 1436 5659			40
1111 3411 B802 0116 1436 5658			41
1111 3411 B802 0116 1436 5657			42
1111 3411 B802 0116 1436 5653			43
1111 3411 B802 0116 1436 5650			44
1111 3411 B802 0116 1436 5649			45
1111 3411 B802 0116 1436 5654			46
1111 3411 B802 0116 1436 5663			47
1111 3411 B802 0116 1436 5655			48
1111 3411 B802 0116 1436 5660			49
1111 3411 B802 0116 1436 5652			50
1111 3411 B802 0116 1436 5651			51
1111 3411 B802 0116 1436 5647			52
1111 3411 B802 0116 1436 5679			53
1111 3411 B802 0116 1436 5669			54
1111 3411 B802 0116 1436 5664			55
1111 3411 B802 0116 1436 5673			56
1111 3411 B802 0116 1436 5665			57
1111 3411 B802 0116 1436 5684			58
1111 3411 B802 0116 1436 5683			59
1111 3411 B802 0116 1436 5680			60
1111 3411 B802 0116 1436 5666			61
1111 3411 B802 0116 1436 5677			62
1111 3411 B802 0116 1436 5678			63
1111 3411 B802 0116 1436 5667			64
1111 3411 B802 0116 1436 5675			65
1111 3411 B802 0116 1436 5670			66
1111 3411 B802 0116 1436 5671			67
1111 3411 B802 0116 1436 5672			68
1111 3411 B802 0116 1436 5674			69
1111 3411 B802 0116 1436 5668			70
1111 3411 B802 0116 1436 5676			71
1111 3411 B802 0116 1436 5682			72
1111 3411 B802 0116 1436 5681			73
1111 1002 1003 1004 1005 1011			74
1111 3411 B802 0116 1436 5731			75
1111 3411 B802 0116 1436 5688			76
1111 3411 B802 0116 1436 5687			77
1111 3411 B802 0116 1436 5686			78
1111 3411 B802 0116 1436 5685			79

Appendix V(a): Bin Inventory Tag Data, Row Scanning Technique

Table 13: Row scanning average read rate data for each tag

Bin ID	Average	Median	Q1	Q3	IQR	Max	Min
1	17.43	17.00	15.25	19.00	3.75	23.00	10.00
2	17.70	17.00	16.00	19.00	3.00	24.00	12.00
3	19.77	20.00	17.25	21.00	3.75	27.00	14.00
4	10.50	11.00	9.25	12.00	2.75	13.00	5.00
5	24.00	24.00	23.00	26.00	3.00	28.00	14.00
6	8.97	9.00	8.00	10.00	2.00	13.00	5.00
7	18.40	19.00	16.25	21.00	4.75	23.00	13.00
8	9.77	9.00	8.00	11.75	3.75	16.00	4.00
9	14.97	15.00	13.00	16.75	3.75	23.00	8.00
10	11.03	11.00	9.25	12.75	3.50	16.00	7.00
11	18.57	18.50	16.25	20.00	3.75	23.00	13.00
12	23.77	23.50	22.25	26.00	3.75	31.00	18.00
13	11.40	11.00	10.00	12.00	2.00	16.00	5.00
14	9.30	9.00	8.00	10.00	2.00	14.00	7.00
15	18.10	18.00	16.00	20.00	4.00	22.00	15.00
16	8.40	8.00	7.00	9.00	2.00	12.00	6.00
17	10.17	10.00	8.00	12.00	4.00	15.00	7.00
18	31.57	29.50	25.00	36.75	11.75	45.00	21.00
19	14.00	14.00	12.00	15.00	3.00	20.00	10.00
20	26.73	27.00	24.00	28.00	4.00	34.00	18.00
21	12.87	12.00	11.00	14.75	3.75	19.00	7.00
22	5.33	5.00	5.00	6.00	1.00	9.00	3.00
23	20.23	20.00	18.25	21.75	3.50	33.00	15.00
24	15.97	16.00	15.00	17.00	2.00	22.00	12.00
25	12.70	13.00	11.00	14.00	3.00	19.00	9.00
26	10.30	10.00	9.00	11.00	2.00	16.00	6.00
27	20.13	19.50	17.25	23.00	5.75	25.00	15.00
28	11.80	11.50	11.00	13.00	2.00	15.00	9.00
29	18.03	18.00	16.25	20.00	3.75	23.00	12.00
30	8.50	8.00	7.00	9.75	2.75	14.00	5.00
31	19.13	19.00	17.25	20.00	2.75	26.00	14.00
32	8.23	8.00	7.00	9.00	2.00	13.00	5.00
33	13.13	13.00	11.00	14.75	3.75	19.00	8.00
34	17.23	17.00	16.00	19.75	3.75	22.00	12.00
35	15.67	16.00	14.00	16.75	2.75	22.00	12.00
36	17.40	18.00	15.00	19.75	4.75	22.00	12.00
37	9.27	9.00	7.25	10.00	2.75	20.00	6.00
38	14.77	15.00	13.25	16.00	2.75	20.00	10.00
39	20.30	20.00	19.00	22.00	3.00	26.00	13.00
40	13.37	13.00	12.00	14.75	2.75	22.00	9.00
41	8.03	8.00	7.00	9.00	2.00	11.00	4.00
42	14.07	14.00	13.00	15.00	2.00	20.00	9.00
43	11.47	11.50	9.00	14.00	5.00	20.00	5.00
44	20.90	21.00	19.25	22.00	2.75	28.00	15.00
45	15.23	15.00	13.25	17.00	3.75	21.00	8.00

Table 13: Row scanning average read rate data for each tag (cont'd)

46	17.80	17.50	16.00	20.00	4.00	24.00	10.00
47	9.80	9.50	9.00	10.75	1.75	13.00	7.00
48	11.27	11.00	10.00	12.00	2.00	17.00	7.00
49	7.27	7.00	7.00	8.00	1.00	10.00	4.00
50	7.00	7.00	6.00	8.00	2.00	9.00	3.00
51	9.87	10.00	8.25	11.00	2.75	14.00	5.00
52	11.63	11.50	10.00	12.75	2.75	16.00	9.00
53	13.00	12.00	12.00	14.00	2.00	20.00	8.00
54	25.23	26.00	24.25	27.00	2.75	32.00	15.00
55	15.87	15.50	14.00	17.00	3.00	22.00	11.00
56	12.33	12.00	11.00	14.00	3.00	17.00	9.00
57	6.53	7.00	5.25	7.00	1.75	10.00	4.00
58	19.80	19.50	17.00	22.00	5.00	27.00	11.00
59	19.90	20.00	19.00	21.00	2.00	26.00	12.00
60	20.00	20.00	18.25	21.75	3.50	25.00	16.00
61	17.37	18.00	16.00	19.75	3.75	24.00	11.00
62	16.80	17.00	15.25	18.75	3.50	22.00	10.00
63	6.60	6.00	5.25	8.00	2.75	9.00	4.00
64	13.63	13.00	11.00	16.75	5.75	23.00	8.00
65	20.23	20.00	18.00	22.00	4.00	26.00	14.00
66	19.27	19.00	17.00	22.00	5.00	26.00	15.00
67	19.37	20.00	17.25	21.00	3.75	26.00	13.00
68	14.07	14.00	12.00	16.00	4.00	19.00	10.00
69	23.07	23.00	21.00	26.00	5.00	27.00	15.00
70	11.63	11.00	10.00	13.00	3.00	18.00	7.00
71	16.80	17.00	15.00	18.75	3.75	22.00	12.00
72	11.23	11.00	10.00	12.00	2.00	18.00	8.00
73	20.87	21.00	18.25	22.75	4.50	26.00	16.00
74	14.13	14.00	13.00	16.00	3.00	18.00	10.00
75	27.23	27.00	26.00	29.00	3.00	37.00	16.00
76	8.40	8.50	7.25	9.00	1.75	13.00	3.00
77	9.13	9.00	8.00	10.00	2.00	15.00	7.00
78	9.73	10.00	9.00	10.00	1.00	13.00	5.00
79	7.27	7.00	6.25	8.00	1.75	12.00	5.00

Appendix V(b): Bin Inventory Tag Data, Column Scanning Technique

Table 14: Column scanning average read rate data for each tag

Bin ID	Average	Median	Q1	Q3	IQR	Max	Min
1	13.87	14.00	11.00	16.00	5.00	25.00	9.00
2	10.90	11.00	9.25	12.00	2.75	17.00	5.00
3	15.83	15.50	14.25	18.00	3.75	21.00	10.00
4	9.07	9.00	8.00	10.00	2.00	15.00	7.00
5	13.73	13.00	11.25	15.00	3.75	23.00	10.00
6	6.30	6.00	5.00	7.00	2.00	15.00	3.00
7	10.37	10.00	9.00	12.00	3.00	16.00	6.00
8	6.77	6.50	5.00	8.00	3.00	12.00	4.00
9	8.07	8.00	6.00	10.00	4.00	14.00	4.00
10	11.27	11.00	10.00	12.75	2.75	17.00	7.00
11	20.67	21.00	19.00	23.00	4.00	28.00	11.00
12	14.47	14.00	11.00	17.75	6.75	27.00	8.00
13	11.43	11.00	10.00	13.00	3.00	18.00	8.00
14	7.40	7.00	6.00	9.00	3.00	10.00	4.00
15	16.13	16.00	13.25	19.00	5.75	25.00	9.00
16	6.57	6.50	5.25	7.75	2.50	10.00	4.00
17	5.57	5.00	4.00	6.00	2.00	18.00	3.00
18	25.73	26.00	22.00	30.75	8.75	39.00	14.00
19	10.00	9.00	8.25	11.00	2.75	16.00	7.00
20	19.93	19.00	17.00	22.75	5.75	30.00	14.00
21	5.73	5.00	5.00	7.00	2.00	9.00	4.00
22	5.47	5.00	4.00	6.00	2.00	14.00	3.00
23	9.70	9.50	8.00	12.00	4.00	16.00	4.00
24	15.87	16.50	14.00	18.00	4.00	22.00	9.00
25	6.90	6.00	5.00	8.00	3.00	14.00	4.00
26	5.63	5.00	4.00	7.00	3.00	11.00	2.00
27	16.77	16.50	14.00	20.00	6.00	30.00	9.00
28	9.47	9.00	8.00	10.75	2.75	15.00	7.00
29	11.83	12.00	9.25	14.00	4.75	20.00	6.00
30	6.23	6.00	5.00	7.00	2.00	10.00	3.00
31	12.47	12.00	10.00	15.75	5.75	20.00	5.00
32	7.53	7.00	6.00	8.00	2.00	21.00	4.00
33	9.00	9.00	7.00	11.00	4.00	14.00	5.00
34	11.83	11.00	10.00	13.75	3.75	19.00	8.00
35	11.33	11.00	9.25	13.00	3.75	18.00	7.00
36	11.20	10.00	8.00	14.00	6.00	19.00	6.00
37	4.67	4.00	3.00	6.00	3.00	10.00	2.00
38	11.83	12.00	10.00	14.00	4.00	20.00	7.00
39	13.80	14.00	11.00	16.00	5.00	19.00	6.00
40	8.83	8.00	7.00	10.00	3.00	15.00	5.00
41	5.40	5.00	4.00	6.75	2.75	9.00	2.00
42	12.57	12.00	11.00	13.75	2.75	18.00	7.00
43	5.20	5.00	3.25	6.00	2.75	10.00	3.00
44	18.33	17.00	15.25	22.00	6.75	30.00	8.00
45	10.50	10.50	9.00	12.00	3.00	17.00	4.00

Table 14: Column scanning average read rate data for each tag (cont'd)

46	8.70	8.00	7.00	10.75	3.75	18.00	5.00
47	7.37	7.00	6.00	8.75	2.75	15.00	4.00
48	10.17	10.00	9.00	11.00	2.00	15.00	7.00
49	6.23	6.00	5.25	7.00	1.75	9.00	4.00
50	6.33	6.00	5.00	7.75	2.75	14.00	4.00
51	6.60	6.00	5.00	8.00	3.00	14.00	3.00
52	10.80	10.50	10.00	12.00	2.00	14.00	7.00
53	4.77	4.00	3.25	5.75	2.50	9.00	3.00
54	18.57	19.50	15.25	22.75	7.50	25.00	9.00
55	8.70	8.00	7.00	10.75	3.75	16.00	5.00
56	15.97	16.00	15.00	18.00	3.00	23.00	7.00
57	4.87	5.00	4.00	6.00	2.00	8.00	3.00
58	18.57	18.50	16.00	21.75	5.75	31.00	4.00
59	11.27	11.00	9.25	12.75	3.50	19.00	4.00
60	9.70	10.00	7.25	11.00	3.75	16.00	2.00
61	15.00	15.50	12.00	17.00	5.00	25.00	10.00
62	12.07	11.50	9.00	14.00	5.00	21.00	5.00
63	5.53	6.00	5.00	6.00	1.00	9.00	2.00
64	9.13	10.00	7.00	11.00	4.00	13.00	4.00
65	11.93	12.00	9.00	15.00	6.00	21.00	6.00
66	14.03	13.50	11.25	16.50	5.25	26.00	6.00
67	11.37	11.00	8.00	13.75	5.75	19.00	6.00
68	16.87	17.00	16.00	18.00	2.00	24.00	4.00
69	14.83	14.00	12.00	17.75	5.75	22.00	5.00
70	6.23	6.50	5.00	8.00	3.00	9.00	3.00
71	11.47	12.00	9.00	13.00	4.00	18.00	4.00
72	7.03	6.50	6.00	8.00	2.00	11.00	3.00
73	12.00	11.00	11.00	14.75	3.75	22.00	4.00
74	16.20	16.00	15.00	18.00	3.00	24.00	9.00
75	15.63	15.50	13.00	19.00	6.00	22.00	6.00
76	7.47	7.00	6.00	9.00	3.00	13.00	4.00
77	4.63	5.00	3.25	5.00	1.75	9.00	2.00
78	7.67	8.00	6.00	8.75	2.75	11.00	3.00
79	5.20	5.00	4.00	6.00	2.00	8.00	3.00

Appendix V(c): Bin Inventory Tag Data, Random Scanning Technique

Table 15: Random scanning average read rate data for each tag

Bin ID	Average	Median	Q1	Q3	IQR	Max	Min
1	13.77	14.00	11.00	16.00	5.00	21.00	5.00
2	14.00	14.00	11.25	16.00	4.75	20.00	6.00
3	16.60	17.00	14.00	20.00	6.00	22.00	10.00
4	6.97	7.00	6.00	8.00	2.00	12.00	1.00
5	14.77	14.00	13.00	17.75	4.75	25.00	6.00
6	6.03	6.00	4.25	8.00	3.75	11.00	1.00
7	13.03	13.00	11.00	15.00	4.00	22.00	8.00
8	5.73	5.00	4.00	7.00	3.00	12.00	2.00
9	10.17	11.00	7.00	12.00	5.00	20.00	6.00
10	10.43	10.50	8.25	13.00	4.75	17.00	2.00
11	16.30	15.50	13.00	20.00	7.00	25.00	10.00
12	16.73	16.00	11.25	21.75	10.50	34.00	5.00
13	11.30	12.00	9.25	14.00	4.75	17.00	1.00
14	5.97	6.00	5.00	7.75	2.75	11.00	1.00
15	15.53	17.00	12.00	19.00	7.00	21.00	6.00
16	5.80	6.00	4.00	7.00	3.00	11.00	2.00
17	6.73	6.50	6.00	8.00	2.00	11.00	1.00
18	20.27	17.50	16.00	23.00	7.00	37.00	10.00
19	10.07	10.00	8.00	13.00	5.00	19.00	3.00
20	23.67	22.50	18.00	27.75	9.75	46.00	11.00
21	8.33	8.00	6.00	10.00	4.00	17.00	3.00
22	3.37	3.00	2.00	4.75	2.75	7.00	1.00
23	14.23	14.00	12.00	16.00	4.00	22.00	8.00
24	14.20	14.50	12.00	17.00	5.00	20.00	6.00
25	8.97	9.00	7.25	10.75	3.50	20.00	3.00
26	6.23	6.00	3.25	8.00	4.75	16.00	2.00
27	14.27	15.00	11.00	17.00	6.00	23.00	7.00
28	8.90	8.50	7.25	11.00	3.75	16.00	3.00
29	14.23	13.50	10.00	17.00	7.00	26.00	5.00
30	6.60	7.00	4.25	8.00	3.75	12.00	2.00
31	14.53	14.00	12.00	17.50	5.50	27.00	7.00
32	6.00	6.00	5.00	7.00	2.00	11.00	1.00
33	8.93	8.00	7.00	10.00	3.00	17.00	5.00
34	13.37	13.50	12.00	14.75	2.75	20.00	8.00
35	12.30	12.00	10.00	14.00	4.00	22.00	7.00
36	12.77	13.00	10.25	16.00	5.75	22.00	7.00
37	6.40	7.00	5.00	8.00	3.00	11.00	1.00
38	9.30	10.00	8.00	10.75	2.75	14.00	4.00
39	13.80	14.00	11.25	15.00	3.75	23.00	8.00
40	8.50	8.00	6.00	10.75	4.75	20.00	2.00
41	6.43	7.00	5.00	8.00	3.00	11.00	2.00
42	12.60	12.50	8.50	16.00	7.50	20.00	3.00
43	7.80	8.00	6.25	9.75	3.50	17.00	2.00
44	16.80	18.00	14.25	19.75	5.50	24.00	8.00
45	12.60	12.50	11.00	15.00	4.00	19.00	5.00

Table 15: Random scanning average read rate data for each tag (cont'd)

46	9.10	9.00	6.25	10.75	4.50	18.00	5.00
47	6.30	6.00	5.00	8.00	3.00	11.00	1.00
48	11.03	11.00	8.25	14.00	5.75	16.00	4.00
49	5.33	5.00	4.00	6.00	2.00	10.00	1.00
50	4.60	4.00	4.00	6.00	2.00	7.00	2.00
51	7.43	8.00	5.00	9.00	4.00	15.00	2.00
52	10.87	11.00	9.00	13.00	4.00	18.00	5.00
53	6.70	6.00	4.25	8.75	4.50	16.00	3.00
54	18.50	19.00	15.25	21.00	5.75	29.00	12.00
55	10.10	10.00	8.00	12.00	4.00	26.00	3.00
56	10.93	11.00	10.00	12.75	2.75	17.00	5.00
57	4.27	4.00	3.00	5.00	2.00	8.00	2.00
58	14.73	13.50	12.00	17.75	5.75	26.00	6.00
59	10.97	10.00	9.00	12.00	3.00	17.00	7.00
60	12.80	12.00	11.00	14.75	3.75	26.00	8.00
61	15.33	15.50	13.00	17.75	4.75	23.00	7.00
62	10.10	10.00	8.00	11.00	3.00	21.00	6.00
63	5.23	5.00	4.00	7.00	3.00	9.00	3.00
64	8.20	8.00	6.00	9.00	3.00	16.00	5.00
65	11.10	11.00	8.25	13.00	4.75	22.00	4.00
66	13.43	13.00	11.25	16.00	4.75	21.00	7.00
67	14.20	15.00	11.00	17.00	6.00	23.00	7.00
68	12.40	13.00	9.50	14.00	4.50	22.00	6.00
69	14.30	13.50	12.00	17.00	5.00	23.00	8.00
70	6.33	5.00	4.25	7.00	2.75	15.00	3.00
71	11.73	12.00	10.00	13.75	3.75	18.00	6.00
72	8.07	9.00	6.25	10.00	3.75	14.00	3.00
73	16.53	16.50	14.00	19.00	5.00	26.00	10.00
74	11.97	11.00	9.00	14.00	5.00	24.00	5.00
75	15.43	15.00	12.00	17.00	5.00	27.00	7.00
76	6.60	6.00	5.00	8.00	3.00	12.00	3.00
77	7.07	6.50	5.25	8.75	3.50	15.00	1.00
78	7.37	7.00	6.00	8.00	2.00	13.00	4.00
79	4.63	5.00	3.00	6.00	3.00	10.00	1.00

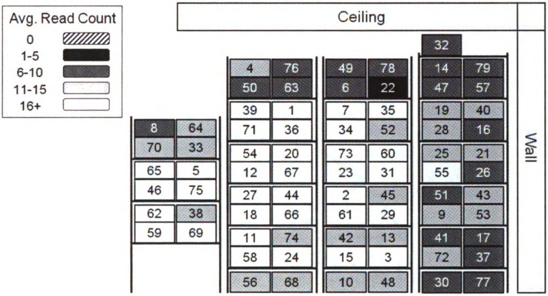
Appendix VI: Bin Inventory Trial Data

Table 16: Bin inventory average read rate data for each trial

	Average Read Rate per Trial			
Trial #	Column Scan	Row Scan	Random Scan	Overall
1	11.04	13.86	11.16	12.02
2	8.68	16.04	10.19	11.64
3	9.42	15.67	12.10	12.40
4	9.33	16.56	13.34	13.08
5	9.48	16.19	10.78	12.15
6	9.03	15.91	12.44	12.46
7	9.19	14.80	11.66	11.88
8	9.41	13.61	13.65	12.22
9	9.42	13.89	11.71	11.67
10	8.95	13.67	9.89	10.84
11	9.14	14.85	11.94	11.97
12	9.75	14.18	12.27	12.06
13	9.81	13.41	12.46	11.89
14	11.95	15.65	12.39	13.33
15	10.73	16.08	12.89	13.23
16	13.91	15.86	16.10	15.29
17	11.54	15.66	11.94	13.05
18	10.48	14.30	11.47	12.08
19	12.04	15.37	8.96	12.12
20	9.16	14.63	8.91	10.90
21	11.29	15.65	10.10	12.35
22	10.68	14.71	11.16	12.19
23	13.30	14.43	7.97	11.90
24	11.73	15.80	9.08	12.20
25	11.16	15.66	7.00	11.27
26	12.52	14.43	8.43	11.79
27	12.20	13.95	8.80	11.65
28	12.27	13.37	7.89	11.17
29	11.94	12.99	8.70	11.21
30	11.35	14.20	7.05	10.87
Average Read Count	**10.70**	**14.84**	**10.75**	**12.10**
Maximum Read Count	**13.91**	**16.56**	**16.10**	**15.29**
Minimum Read Count	**8.68**	**12.99**	**7.00**	**10.84**
Standard Deviation	**1.44**	**1.00**	**2.15**	**0.89**

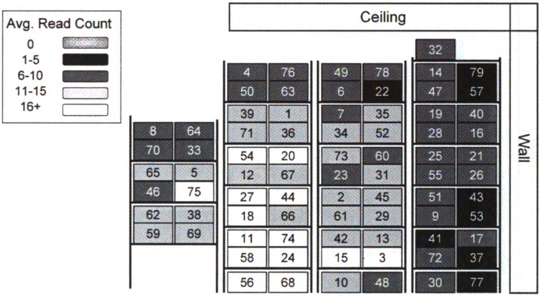
Appendix VII(a): Bin Tag Read Rates by Tag Position: Row Scan Technique

Figure 36: Average read rate per bin tag: row scanning technique



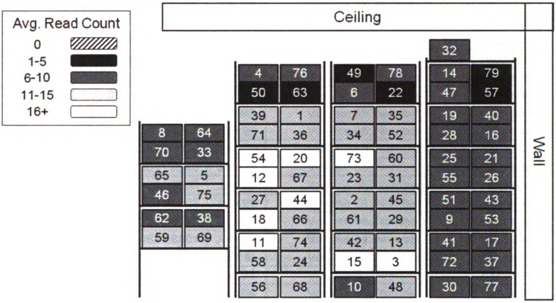
Appendix VII(b): Bin Tag Read Rates by Tag Position: Column Scan Technique

Figure 37: Average read rate per bin tag: column scanning technique



Appendix VII(c): Bin Tag Read Rates by Tag Position: Random Scan Technique

Figure 38: Average read rate per bin tag: random scanning technique



Appendix VIII: Dig-Site Book Database

Table 17: Dig-Site Book Database

Item UID	Date	Book Title	Dig Site
3333 3412 DC03 0119 2409 7626	July 98	Volume 67: Number 3	Hesperia
3333 1002 1003 1004 1005 1006	Apr 98	Volume 67: Number 2	Hesperia
3333 3412 DC03 0117 0611 8793	Jan 98	Volume 67: Number 1	Hesperia
3333 3412 DC03 0117 0611 8784	Oct 97	Volume 66: Number 4	Hesperia
3333 1002 1003 1004 1005 1008	July 97	Volume 66: Number 3	Hesperia
3333 3412 DC03 0119 2409 7616	Apr 97	Volume 66: Number 2	Hesperia
3333 3412 DC03 0119 2409 7579	Jan 97	Volume 66: Number 1	Hesperia
3333 3412 DC03 0119 2409 7617	Oct 96	Volume 65: Number 4	Hesperia
3333 3412 DC03 0119 2409 7634	July 96	Volume 65: Number 3	Hesperia
3333 3412 DC03 0117 0611 7039	April 96	Volume 65: Number 2	Hesperia
3333 3412 DC03 0117 0611 7040	Jan 96	Volume 65: Number 1	Hesperia
3333 3412 DC03 0117 0611 7036	Jan 96	Volume 65: Number 1	Hesperia
3333 3412 DC03 0117 0611 8805	July 95	Volume 64: Number 3	Hesperia
3333 3412 DC03 0117 0611 8803	Oct 95	Volume 64: Number 4	Hesperia
3333 3412 DC03 0117 0611 8801	July 95	Volume 64: Number 3	Hesperia
3333 3412 DC03 0117 0611 7037	April 95	Volume 64: Number 2	Hesperia
3333 3412 DC03 0117 0611 8798	Jan 95	Volume 64: Number 1	Hesperia
3333 3412 DC03 0117 0611 8795	Oct 94	Volume 63: Number 4	Hesperia
3333 3412 DC03 0117 0611 8781	July 94	Volume 63: Number 3	Hesperia
3333 1002 1003 1004 1005 1007	April 94	Volume 63: Number 2	Hesperia
3333 3412 DC03 0117 0611 8792	Jan 94	Volume 63: Number 1	Hesperia
3333 1002 1003 1004 1005 1009	Jan 93	Volume 63: Number 1	Hesperia
3333 3412 DC03 0117 0611 8807	April 93	Volume 63: Number 2	Hesperia
3333 3412 DC03 0117 0611 8806	July 93	Volume 62: Number 3	Hesperia
3333 3412 DC03 0117 0611 7043	Oct 93	Volume 62: Number 4	Hesperia
3333 3412 DC03 0117 0611 7026	Jan 92	Volume 61: Number 1	Hesperia
3333 3411 B802 0116 1436 5721	July 92	Volume 61: Number 3	Hesperia
3333 1002 1003 1004 1005 100A	Oct 92	Volume 61: Number 4	Hesperia
3333 3412 DC03 0117 0611 8778	Jan 92	Volume 61: Number 1	Hesperia
3333 3412 DC03 0117 0611 8779	Jan 92	Volume 61: Number 1	Hesperia
3333 3412 DC03 0117 0611 8780	April 92	Volume 61: Number 2	Hesperia
3333 3412 DC03 0117 0611 7035	Jan 92	Volume 61: Number 1	Hesperia
3333 3412 DC03 0117 0611 7033	1952	The Metal Objects	Isthmia
3333 3412 DC03 0117 0611 8796	1967	Sculpture II: Marble Sculptures	Isthmia
3333 3412 DC03 0117 0611 8794	?	The Hexamillion and The Fortress	Isthmia
3333 3412 DC03 0117 0611 7034	1952	Sculptures I	Isthmia
3333 3412 DC03 0117 0611 8799	?	Topography and Architecture	Isthmia
3333 3412 DC03 0117 0611 7038	?	Temple of Posseidon	Isthmia
3333 3412 DC03 0119 2409 7638	?	The Late Bronze Age Settlement	Isthmia

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