A Technical, Financial, and Policy Analysis of the RAMSES RFID Inventory Management System for NASA's International Space Station: Prospects for SBIR/STTR Technology Infusion

by

Abraham T. Grindle

Honors B.S. Aerospace Engineering
Saint Louis University, 2006

Submitted to the Engineering Systems Division and the
Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degrees of

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and Master of Science in Aeronautics and Astronautics

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ABSTRACT

Engineering, management, and social science methodologies have been employed to analyze a new asset tracking and management system for human spaceflight applications. The Massachusetts Institute of Technology and Aurora Flight Sciences developed Rule-based analytic Asset Management for Space Exploration System (RAMSES) via NASA Small-Business Technology Transfer (STTR) Phase I and Phase II contracts. RAMSES leverages Generation II passive Radio Frequency Identification (RFID) technology to automate the tracking the tens of thousands of small, portable cargo assets that are currently stored onboard the International Space Station (ISS).

A Monte Carlo Net Present Value analysis found that RAMSES is likely to have significant positive value for NASA when ISS inventory transactions are concentrated in a subset of the total cargo transfer bag (CTB) population, and/or if ISS Operations are continued into 2018/2020. The volume, mass, and accuracy of the RAMSES system have a significant impact upon the estimated NPV. Testing of the prototype hardware in reduced-gravity conditions reaffirmed the viability of the system. Metals cargo objects were detected with up to 100% accuracy, paper with 96%, and water with roughly 93%.

Finally, a comparative analysis of RAMSES and five other NASA Small-Business Innovation Research (SBIR) / Small-Business Technology Transfer (STTR) projects identified three non-technical characteristics and/or informal processes that might be unique to SBIR/STTR technologies that are successfully infused into the mainstream NASA innovation system. These included pre-proposal knowledge exchanges between companies and NASA, strong matching of a project with a relevant NASA COTR, and the availability of an infusion opportunity.

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NOMENCLATURE

α	=	percentage of inventory transactions that can be automated by RFID system
β	=	system effectiveness parameter
B	=	benefits, U.S. dollars ($)
C	=	costs (or capital), U.S. dollars ($)
g	=	acceleration due to gravity at Earth's surface, 9.81 meters/second ^{2}
N	=	number of years
r	=	discount rate, %
n	=	number of iterations
NPV_0	=	initial Net Present Value based on "best-information" values ($)
NPV_i	=	revised Net Present Value based on iteration of variable X undergoing sensitivity analysis ($)
s	=	seconds
μ	=	percentage of automate-able inventory transactions that are detected by RFID system
X_0	=	initial value of variable undergoing sensitivity analysis
X_i	=	revised value of variable undergoing sensitivity analysis

Chapter 1: Introduction

Preamble

We can no longer go it alone. It does not matter if the challenge is space exploration, climate change, health care, education, transportation, agriculture, poverty alleviation, or one of the multitude of other issues in our world today that one might choose to tackle. We are coming to understand that no single person – and more importantly, no single discipline - can independently solve such challenges. We live in an extremely complex, heterogeneous world in which the pace of change and the degree of interconnectivity are accelerating by the nanosecond. Our systems and challenges are no longer purely social or purely technical (if indeed they ever were); all contain significant elements of both. Therefore, teams and approaches which bring together the social, engineering, and management sciences have the potential to make unique and significant contributions to some of the greatest challenges which our world faces today.

This limited master's thesis does not claim to address any challenge of such global importance. However, it does attempt to apply this holistic, multi-disciplinary perspective and methodology to a meaningful problem in the complex realm of human spaceflight. Hardware testing, probabilistic financial modeling, and policy analysis are all brought to bear on this challenge. In the end, the results demonstrate that the problem can indeed be solved, but only with an approach that is both technical and non-technical in nature.

Background and Problem Statement

The challenges of human spaceflight are daunting. Among the greatest of these challenges are the logistical demands of a long-duration mission such as the International Space Station (ISS) or a crewed lunar outpost. Tens of thousands of small, portable items are currently stored onboard the International Space Station (ISS). These items include consumables and provisions of all sorts, from food and office supplies to clothing and spare parts. Maintaining an accurate record of the quantities and locations of these assets is a significant task, scheduled to consume some 4.5 person-months of astronaut time every year once the ISS reaches its final state, known as "Assembly Complete" [1].

Figure 1.1. Thousands of items are stored in Cargo Transfer Bags (CTBs), which line the walls of ISS.
(image credit: NASA)

A significant portion of this 4.5 person months is due to the nature of the current ISS Inventory Management System (IMS), which is barcode-based. Cargo items aboard ISS are tagged with individual barcodes, as are cargo locations (cargo transfer bags (CTBs), racks, lockers, etc). To track a cargo asset, NASA requires that every time that an item is consumed and/or moved, an astronaut use a handheld barcode scanner and record the barcode of the item, the barcode of the item's origin container, and the barcode of the item's destination container. As an alternative, astronauts can verbally report asset usage and/or moves to Mission Control's Inventory Stowage Officers (ISOs), who in turn enter the changes into the Inventory Management System (IMS) by hand [1].

The accuracy of the current system is quite reasonable; in January of 2008, only 3% of the 13,000 US items on-orbit were designated by NASA as "lost," which one Mission Controller defined as "stuff that we [NASA] really have no idea where it is." However, in an environment as demanding as that of human spaceflight, the loss of even a few items can be quite serious. For example, in early 2006, astronauts were unable to conduct spacewalks for two weeks while they searched for four misplaced lithium-hydroxide canisters that remove CO_2 from the Russian spacesuits [2]. Relatively large items have also been lost at times; in 2005, a Pump Package Assembly - measuring 20" x 20" x 36", roughly the size of a mini-fridge – went missing [3]. The ISS crew conducted multiple searches on-orbit while looking for this item, while an "obscene" amount of engineer-time was spent on the ground spent poring through IMS and brainstorming possibilities in meetings. In the end, the assembly was found in a cavity behind a panel aboard ISS; apparently a former crew had designated that space to be a convenient storage location, but had neglected to update IMS or inform Houston about it [1]. NASA currently has little recourse when the crew does not enter updated asset location and/or consumption data into IMS; in another such instance, a lack of inventory updates in 2004 led to an unexpected depletion of food stocks, forcing the crew to cut back on their meals until the next resupply vehicle arrived [4].

Rule-based analytic Asset Management for Space Exploration Systems (RAMSES)

To better address the challenges of cargo asset management in human spaceflight applications, the Massachusetts Institute of Technology (MIT) and Aurora Flight Sciences have developed Rule-based analytic Asset Management for Space Exploration Systems (RAMSES) over the past three years, via Phase I and Phase II Small-Business Technology Transfer (STTR) contracts with NASA. RAMSES is an automated and wireless system utilizing a modular, layered architecture. It enables automated multi-level asset tracking and management based on state-of-the-art Radio Frequency Identification (RFID) technology. The main advantages of this RAMSES over current bar-code based asset tracking include: (i) significant time savings through automation, (ii) real-time remote status monitoring (via internet, if desired), and (iii) rule-based analytics for proactive asset management. RAMSES has the potential to save a significant portion of the 4.5 person-months per year of on-orbit astronaut time that is budgeted for inventory management aboard ISS (for a six-person crew).

This joint MIT/Aurora effort builds upon previous work regarding asset tracking and supply chain management for human space exploration. Evans et al. (2006) examined NASA's collection of logistics-related "Lessons Learned" from the Space Shuttle, Shuttle-MIR, and International Space Station programs in order to identify potential issues for NASA's new Constellation program. One of the key challenges identified was the large human-in-the-loop component of NASA's previous and existing logistics systems [5]. Galluzzi et al. (2006) studied and advocated that NASA adopt modern, commercial Supply Chain Management best-practices [6]. Finally, de Weck and Simchi-Levi (2006) and Gralla et al. (2005) described an MIT team's extensive field campaign to study human space exploration logistics at the Haughton Mars Base on Devon Island in 2005 [7; 8]. This expedition examined the use of an integrated, comprehensive inventory database and a unified asset classification system to track inventory [9]. Importantly, it also demonstrated that an RFID-based inventory management system (specifically, a first, proof-of-concept version of the RAMSES system) could save significant time compared to a manual barcode tracking system such as that currently used on the International Space Station [10].

1.2. Double-sized ISS CTB retrofit with RAMSES System

Since this demonstration, the RAMSES hardware has continued to evolve. First, the crude demonstration model from the Haughton Mars Base was transformed into a second-generation hard-container with superior systems integration and performance. Then, most recently, the system was integrated into a double-sized NASA Cargo Transfer Bag (CTB) to produce a "smart CTB" (Figure 1.2). There are some 500 CTBs currently on-orbit, and they store most of the small, portable cargo assets on ISS. Integrating the RFID-based RAMSES system into ISS CTBs would offer two key advantages over the current ISS barcode system. For one, it would render certain ISS inventory updates "hands-free", requiring no action on the part of either the flight crew or ground engineers. Every time a bag is opened and closed, the system would automatically initialize and query the passive RFID tags attached to all of the items inside. Any changes in the bag's contents would be instantly transmitted via Station's 802.11b Wi-Fi network to the IMS, as illustrated in Figure 1.3. No longer would astronauts need to take the time to manually scan barcodes every time they consumed or moved an item, nor would flight controllers need to enter it for them on the ground. The other advantage is that NASA would possess greater confidence that the information in IMS – such as the status of food stocks - is entirely up-to-date at every moment, a potentially important safety and mission assurance improvement.

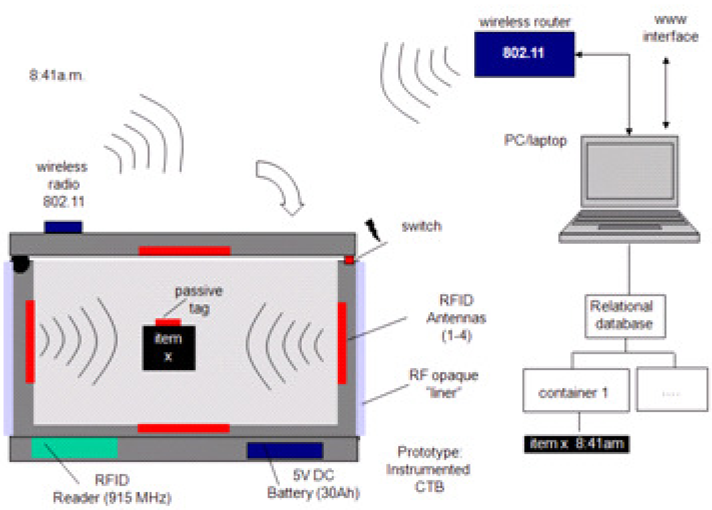

Figure 1.3. Illustration of RAMSES Operational Scenario (Credit: Aurora Flight Sciences)

At its core, RAMSES is an information architecture. As illustrated in Figure 1.4, new information about tracked cargo items flows into the system via one or more physical "sensors" (such as the "smart CTB"). These sensors can be of any hardware type, and different types and/or combinations of sensors can be used to track cargo items across multiple hierarchical layers of specificity (container-level, room-level, city block-level, etc).

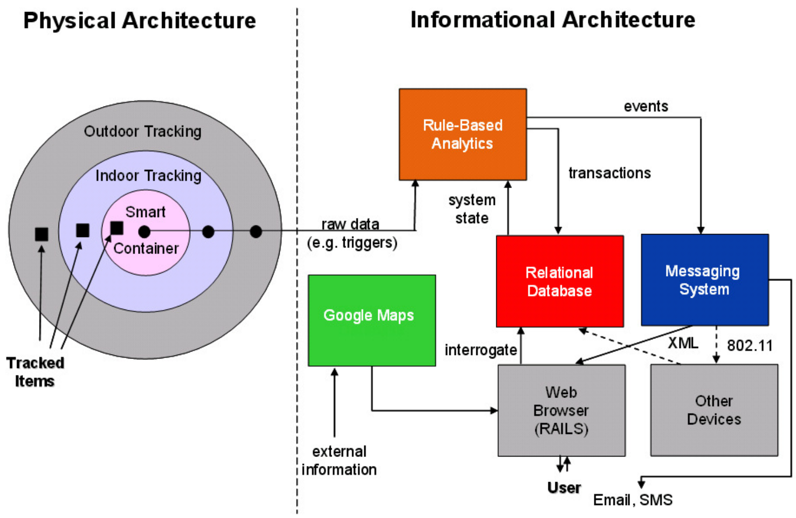

Figure 1.4. RAMSES System Architecture Block Diagram
(Image Credit: Aurora Flight Sciences / O. de Weck)

When a sensor updates, its information is immediately filtered through RAMSES' Rule-Based Analytic algorithms. These user-created algorithms sift through the new and existing data, identifying any inventory changes (i.e., the food supply has run low) or relationships (a high-pressure canister was just placed next to a very sharp object) that are of interest to the user, and updating the status of all items in the Relational Database. When an algorithm finds a match, this "event" causes a notification to be sent to the user(s) via the Messaging System. This notification could be an email, a text message, a special note in the data log, etc. The system currently includes a software interface known as RAILS that can be accessed from any common web-browser. From RAILS, a user can view and search the contents of the Relational Database, can create/edit/delete Rule-Based Analytics, and set the Messaging System. With the proper set of sensors and location, RAILS can also overlay cargo item information on Google Maps.

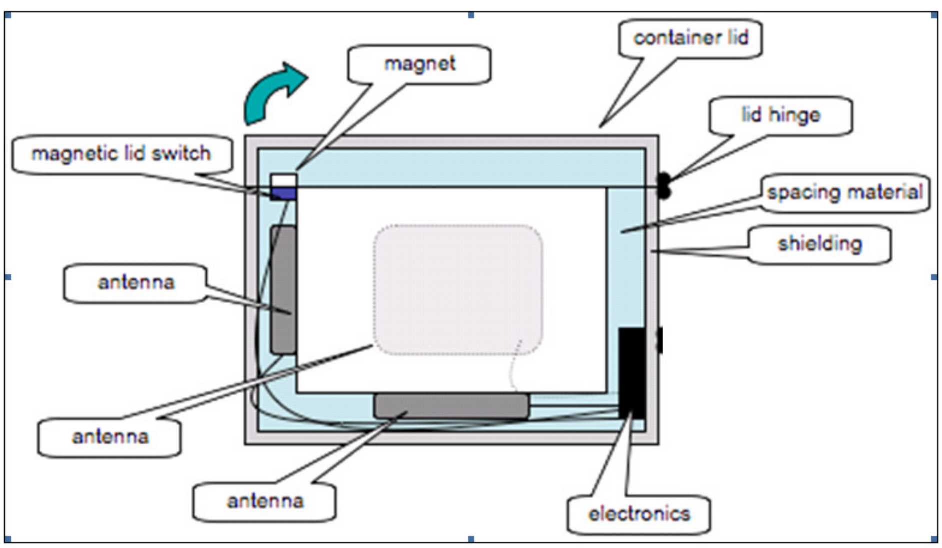

Figure 1.5. "Smart" CTB System Diagram
(Image Credit: Aurora Flight Sciences)

Figure 1.5 illustrates the technical details of the RAMSES Smart CTB prototype. As described above, the idea behind this prototype is to retrofit an existing NASA Cargo Transfer Bag to convert it into a sensor that is connected to the RAMSES information architecture – and eventually, to NASA's own Inventory Management System. The Smart CTB prototype includes multiple Generation II RFID antennas, a compatible RFID reader contained within the Electronics Box, a rechargeable 5V Lithium-Ion battery, a Wi-Fi broadcaster, and a magnetic lid switch that can "wake-up" the system and trigger a scan of the bag's contents whenever the lid is opened and then re-closed. Finally, a fine mesh of copper wire is used to electromagnetically isolate the interior of the bag from its external surroundings, thus preventing the CTB's internal antennas from detecting RFID tags that are outside the bag (and similarly preventing any nearby external antennas from detecting the RFID tags that are within the bag). A complete parts list is included in Appendix F.

Thesis Questions

The first part of this thesis, consisting of Chapters 2-4, examines the value proposition of the RAMSES system and validates initial performance estimates. It tackles two key questions. First, given NASA's current inventory management system and processes, is this RFID system likely to deliver sufficient value to justify the investment necessary to develop, test, and implement it, even with several uncertain parameters? Second, how does the system prototype perform, in both normal (1g) and micro-gravity environments? Can it reliably detect cargo items of various material types, particularly in reduced gravity conditions such as it would encounter on ISS?

To answer the first question – would this system likely deliver positive Net Present Value (NPV) - NASA's existing ISS asset tracking systems and processes were mapped, from initial manifesting through arrival on ISS through end-of-life disposal, as described in Chapter 2. Then, based on this information, a financial model of NASA's existing ISS inventory management architecture was constructed, and Monte Carlo NPV simulations were run to examine the probabilistic net worth of various implementations of the RFID-based inventory system. This work is described in Chapter 3. For the second question – can the RAMSES system reliably detect cargo items of various materials - an extensive series of hardware experiments were conducted in the lab to characterize the real-world performance of the prototype system against several key variables (such as cargo item material composition). Additional experiments were conducted on NASA's reduced-gravity aircraft in order to characterize hardware performance in a simulated space microgravity environment. The results and analysis of these tests are contained in Chapter 4.

However, even if this proposed technological system were demonstrated to be 100% accurate, as well as likely to deliver value in excess of the required initial investment (the questions addressed in Chapters 3 and 4), there remains at least one other critical challenge. How does such a new technology - particularly one developed outside NASA via the Small Business Innovation Research (SBIR) / Small Business Technology Transfer (STTR) program, such as RAMSES – actually get taken up by NASA and "infused" into the agency's own innovation system, and eventually into an operational program such as the International Space Station? The second part of this thesis, Chapter 5, examines this issue.

Continued technological innovation, along many dimensions, is a key enabler for the success of any ambitious spaceflight project, whether it be human or robotic. Multiple technology infusion/development programs exist within NASA, including a few expressly designed to leverage the innovative capacity of entrant firms such as Aurora Flight Sciences of the RAMSES project [11]. Unfortunately, although these programs have been relatively successful in accelerating the development of new "component" technologies, their record of infusion into the overall NASA innovation system is more ambiguous. The Small Business Innovative Research (SBIR) / Small Business Technology Transfer (STTR) program is one such effort, and has some unique characteristics as a mandatory program that Congress imposed on all major Federal Research & Development Agencies in the early 1980's.

Congress articulated four goals for the program, which was first authorized in 1982 by the Small Business Innovation Development Act. These goals are:

1. To stimulate technological innovation.
2. To increase private-sector commercialization of innovations.
3. To use small business to meet federal research and development needs.
4. To foster and encourage participation by minority and disadvantaged persons in technological innovation [12].

Federal law mandates that eleven federal agencies each set aside 2.5% of their extramural research and development program to fund SBIR awards, with an additional 0.3% allocated for STTR awards. Five of these agencies – DOD, Health & Human Services (esp. NIH), NSF, NASA, and DOE – account for 96% of SBIR program awards. NASA's program is the fourth largest, overall, with $103 million in funding distributed in 2005. The SBIR and STTR programs each consist of two phases; the first is meant to be a feasibility assessment of the idea's scientific and technical merit, while the second is a larger-scale research and development push towards realizing an idea's scientific, technical, and commercial promise. At NASA, the typical Phase I award is roughly $60,000 for six months (with a maximum of $100,000), while a typical Phase II award is for a maximum of $600,000 for 2 years [12; 13]. The STTR program is very similar, with the caveats that it must involve a University partner as well as a small business, and its Phase I awards are for 12 months instead of 6 [13].

While Congress has several motivations for the SBIR and STTR programs, it is clearly in the sponsoring agency's interest to maximize the utility it derives from such a mandatory investment. This is particularly true for NASA, which has seen its research and development budgets squeezed significantly in recent years due, in part, to cost-overruns in major programs such as Constellation, the Mars Science Laboratory, and the James Webb Space Telescope. Therefore, when the NRC reports that only 15.9% of NASA SBIR Phase II projects[1] were known to have received some kind of follow-on funding (be it as direct procurement or as further development funding) from NASA [12], one is tempted to ask – can this return on investment be improved? Certainly, a 100% infusion rate should not be the goal, nor even a 50% rate, for such figures would likely indicate that the program was not investing in those inherently risky ideas that might result in radical innovation. However, it seems worthwhile to investigate whether improvements can be made to increase the infusion rate of successful projects while maintaining the risk-tolerance of the program.

[1] 15.9% of 82 that responded to an NRC survey

The SBIR/STTR program has received previous attention in the literature, including [12; 14; 15; 16; 17; 18] among others. The National Research Council convened a symposium on the topic of SBIR/STTR infusion in 2005 [15]; however, this work included participation from all five of the largest federal agencies that sponsor SBIR/STTR, and thus NASA's program (as only the fourth-largest out of five) did not receive significant attention. The differences between the agencies are important; for example, the infusion opportunities at an $18 billion agency such as NASA are more limited than in a $600+ billion agency such as DOD. More recently, Keifer [17] and Anderson & Iacomini [18] shared some general suggestions from their companies' experience in the program, particularly with respect to NASA. However, while interesting anecdotes, both papers focused on successful commercialization of the technology and the need for an appropriate business plan, rather than infusion of the technology into NASA's innovation system. Further, there was no significant discussion of the informal processes which help enable infusion at NASA. Thus, a gap exists in the literature. Preliminary evidence, from the RAMSES project and as well as other companies' NASA SBIR/STTR efforts, indicates that technical success is not enough to guarantee successful infusion. Certain non-technical characteristics and informal processes also seem to have an influence on the outcome.

In Chapter 5, this thesis explores the impact of such non-technical characteristics and informal processes on the infusion of NASA SBIR/STTR projects such as RAMSES into NASA's mainstream innovation. Did those projects which have been successfully infused possess any common non-technical characteristics, and/or utilize any of the same informal processes? If so, what were those characteristics and/or processes? Were such characteristics and processes absent from those projects which were not successfully infused? These questions are examined via six case studies involving several New England small businesses that are active in the SBIR program, as well as via interviews with NASA officials at all levels of the agency who are involved in technology development. A comparative analysis framework was constructed to elicit similarities and differences across the cases – including the RAMSES project - and draw out those common factors which prove significant.

ROADMAP

Before concluding this introduction, it seems appropriate to provide a brief summary of the structure of the remainder of this document.

Chapter 2 provides an overview of NASA's current asset tracking, management, and transportation procedures for all cargo items bound for the International Space Station. This overview describes the processes and procedures from initial manifesting at the Johnson or Kennedy Space Centers, through packing, launch, arrival at ISS, on-orbit storage, and finally waste disposal.

Chapter 3 uses the information from Chapter 2 and other sources to evaluate the likely net present value of the RAMSES RFID system if it were applied to the International Space Station. Monte Carlo techniques are utilized to estimate this value given several uncertain parameters. A sensitivity analysis is conducted to identify the most significant of the uncertain design parameters.

Chapter 4 contains the results and analysis of the extensive testing that was conducted to characterize the performance of the Cargo Transfer Bag prototype of the RAMSES hardware. These tests simulated a wide variety of operating conditions, including a set of trials conducted in reduced gravity conditions.

Chapter 5 conducts a comparative analysis of the RAMSES project and five other NASA SBIR/STTR projects to identify any informal processes and nontechnical characteristics that might be common to successfully-infused SBIR/STTR technologies.

Finally, Chapter 6 combines the results of the three core analyses of this work – the financial, technical, and policy – and draws conclusions regarding the prospects for the RAMSES system to successfully address the ISS logistics challenge, and for it and other SBIR/STTR technologies to be transitioned into the mainstream NASA innovation system and eventually into operational missions.

CHAPTER 2: OVERVIEW OF NASA'S INTERNATIONAL SPACE STATION SUPPLY CHAIN MANAGEMENT SYSTEM

INTRODUCTION

This chapter provides an overview of NASA's current asset tracking, management, and transportation procedures for all cargo items bound for the International Space Station (ISS). This overview describes the processes and procedures from initial manifesting at the Johnson or Kennedy Space Centers, through packing, launch, arrival at ISS, on-orbit storage, and finally waste disposal. The information was gathered via interviews with more than 20 NASA personnel during site visits to the Kennedy and Johnson Space Centers in January of 2008.

INTERNATIONAL SPACE STATION INVENTORY ARCHITECTURE

Overview

The inventory management system for the International Space Station is chiefly based upon barcodes, soft cargo bags and kits (including hard metal kits for food), and a database called the Inventory Management System (IMS). All cargo items[2] are labeled with a barcode which is entered into IMS; thereafter, to update the location and/or status of an item, one can scan the barcode and then enter the appropriate changes into the database. NASA employs a number of engineers at JSC to support the on-orbit crew with inventory management tasks; these engineers are known as Inventory Stowage Officers (ISOs). Four separate copies of the Inventory Management System (IMS) are currently in simultaneous operation, in Houston, Moscow, Baikanour, and onboard ISS. These databases are too large to synchronize by transferring them in their entirety, so every inventory change is tracked in what are called Delta Files. These Delta Files are exchanged once or more per day between all four locations to synchronize the four databases.

Packing Information Flow

As shown in Figure 2.1, there are at least three databases involved in different stages of the ISS cargo manifesting and packing process [3]. The manifest for each flight – the complete list of all hardware that will be flown – is first entered into a database known as MIDAS. Next, the "containment" material – Ziploc bags, packing foam, etc - that will be used to pack and safeguard the hardware is entered into the same database. Following this, the information is uploaded to MAXIMO[4], the database used by the Lockheed Martin Cargo Mission Contract (CMC) organization to generate work-orders and track serial numbers and barcodes. POWER is the name of the front-end interface for MAXIMO, specifically modified for packing operations.

[2] A single "item" is typically defined by packaging; for example, a single spare part that is packaged individually would be considered one item, while a Ziploc bag containing ten screws would also be considered one item. The spare part would have one barcode, while the Ziploc bag would also have one barcode. A package of five shirts would also have a single barcode. However, an item with separable pieces (such as a telephone – base and handset) might have a barcode on each piece.

[3] Figure 1 is simplified, only showing the flow when items are packed and reviewed at KSC, which is the most common path.

[4] Perhaps significantly for RFID applications, MAXIMO and IMS currently can accept input from a handheld barcode scanner.

When the packing of CTBs and other bags is complete, the packing is inspected at a Bench Review held at either KSC or JSC, depending on the packing organization.

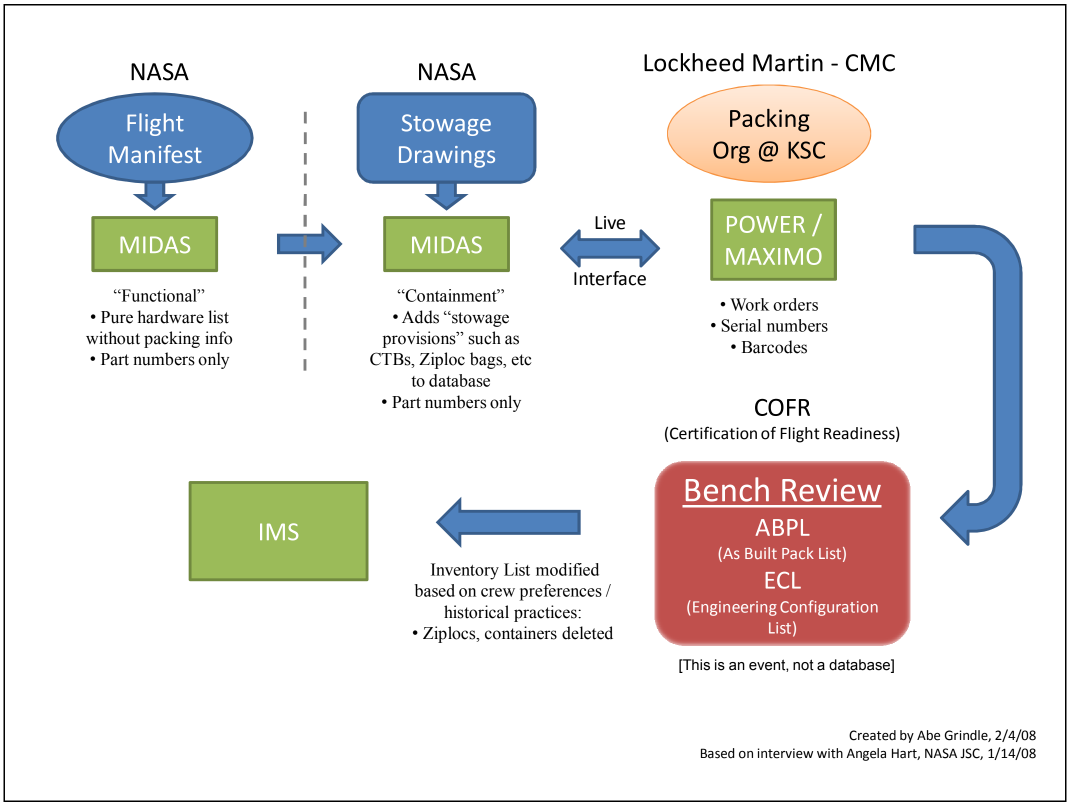

Figure 2.1: ISS United States Packing Information Flow

After the Bench Review and the generation of the As-Built Pack List (ABPL), also called the Engineering Configuration List (ECL), the inventory data is entered into the Inventory Management System (IMS) by the Integration Stowage Officers (ISOs). During this transfer, the ISOs modify the inventory list according to crew preferences and historical practices; in particular, they remove information about item packaging (i.e., Ziploc bags are not listed).

Bags and Kits

There exist several different types of cargo bags, kits, and containers that are used for the ISS Program. These include CTBs, M-bags, mid-deck locker equivalent (MLE) bags, medical kits, and food containers[5]. CTBs serve as a kind of soft, flexible Nomex "suitcase" or duffel bag as shown in Figure 2.2; they were the primary focus of this trip and will be discussed in greater detail in the subsequent section. CTBs come in four sizes: the Half CTB, Single CTB, Double CTB, and Triple CTB. The standard-sized Single CTB measures 19.75" x 16.75" x 9.75"[6], and is used as a unit of measure called a Cargo Transfer Bag Equivalent (CTBE) to describe the capacity (and shape) of some of the other bags.

[5] Note that this is not meant to be a comprehensive list, but rather a list of the most commonly-used.
[6] Ref: Hart, Angela. *Internal Cargo Integration Overview.* Powerpoint Presentation. NASA. Date unknown.

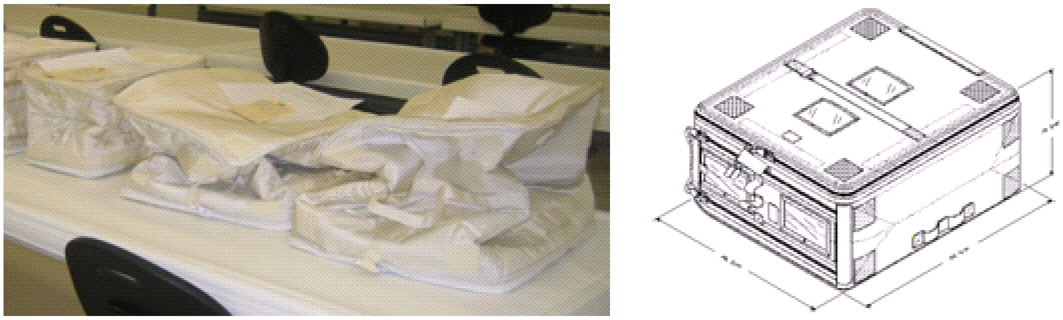

Figure 2.2: Empty Half CTBs (credit: A. Grindle) and Single CTB Engineering Drawing (credit: NASA)

M-bags are soft-bags, larger than CTBs (see Figure 2.3) and available in three variants: M01 (6 CTBEs), M02 (4 CTBEs), and M03 (10 CTBEs). They can be used to help contain CTBs during launch/return or to pack oversize items. Medical kits, similar to CTBs, are made from Nomex and feature removable/adjustable plastic inserts. They are the same size as a Double CTB. MLE bags are specially designed bags that fit into the Orbiter's mid-deck lockers; unlike CTBs, they are not transferred to ISS but instead remain with the Shuttle. Finally, the containers used to transport and store food for ISS are smaller than CTBs and constructed of metal, as shown in Figure 2.4.

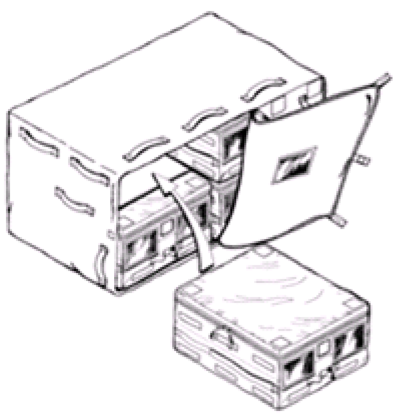

Figure 2.3: MO2 Bag (4 CTBE)
Credit: NASA

Figure 2.4: Food Container
Credit: Angela Hart, NASA

CARGO TRANSFER BAGS

NASA's Cargo Transfer Bags were developed for ISS based upon lessons learned from three previous-generation cargo bags used in the Shuttle-MIR program. As mentioned before, the bags are made from a flame-retardant fabric material known as Nomex, and come in four different sizes. A table with bag dimensions and capacity can be found in Appendix A, along with engineering drawings of each of the four configurations. The most-used bag size is the Half CTB, by a ratio of roughly 2:1 over the Single CTB.

It is estimated that there are approximately 500 CTBs currently onboard ISS. Many of these have remained unopened for years. At Assembly Complete, it is expected that there will be at least 600 CTBs on Station, allocated between several subgroups as follows: the Systems Group will have about 300 CTBEs for their items (consisting of almost entirely metal items, such as spare parts); Payloads will have 100 CTBEs in addition to their racks; Medical will have roughly 50 CTBEs; and Crew Provisions (including clothing, hygiene items, etc., but excluding food and water) will have 200.

Purchase of CTBs

Rothe Industries, of Houston, Texas, is the current manufacturer of the CTBs[7]. Recent bags have cost between $2500 and $5000; the latest Half CTB that was purchased from Rothe cost approximately $3000. The bags are purchased through the Engineering Directorate at NASA JSC. After purchase, ownership is transferred within JSC from Engineering to the OB organization in the Mission Operations Directorate, with JSC's OC organization as the manager. OC, in turn, transfers the bags to Lockheed Martin under the Cargo Mission Contract (CMC), where they are managed in practice by subcontractor MTC Technologies. MTC's CTB group is led by Mr. John Muzzy, and based in the Space Station Processing Facility (SSPF) at KSC. All CTBs are stored at KSC until they are needed.

Figure 2.5: CTBs in 'Pink-Poly' on Storage Shelf at KSC (Credit: A. Grindle)

Storage at KSC

The CTBs in storage at Kennedy Space Center are kept in a climate-controlled environment. They are folded / collapsed upon themselves into a relatively flat configuration, and then sealed in "pink-poly" bags[8]. A large number are stored in the CMC Bag & Tray Room in the SSPF, in an automated storage & retrieval cabinet. Figure 2.5 is a photo of a bag on the automated storage shelf; Figure 6 shows the automated storage and retrieval system.

Packing

In packing the CTBs for flight, available volume is generally the most significant limiting factor, even more so than mass. Whenever possible, the ground tries to pack items that belong together in a single CTB. This allows the crew to simply store the entire bag in the appropriate location when it arrives at the ISS, without any need to spend time unpacking and sorting its contents. Unfortunately, this is not always possible; on Space Shuttle middeck-only flights (no Multi-Purpose Logistics Module, MPLM) available packing volume

Figure 2.6: CTB Automated Storage & Retrieval System (Credit: A. Grindle)

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7 Rothe is also the contractor when any significant repairs to a bag are needed.

8 These pink-polyethylene bags are somewhat analogous to oversize Ziploc bags and anti-static wrap.

is extremely limited, and items must be crammed into every possible space.

As illustrated in Figure 2.7, NASA CTBs are packed at both KSC and JSC. In Houston, JSC's Flight Crew Equipment organization packs CTBs with all items that are designated as "Crew Preference". JSC also packs the CTBs that are shipped to Russia for Progress or Soyuz flights; NASA averages five or six Half CTBs on Progress launches and one or two on Soyuz flights[9]. Additionally, JSC packs food provisions into the metal food containers (Figure 2.4), which are then generally packed into CTBs at KSC. Other hardware and supplies are also shipped to KSC, where they are received, integrated into any additional containment that is specified[10], and packed into CTBs. The bags are generally packed three to five months prior to launch for MPLM missions, as well as for ATV and HTV missions (for which KSC packs), and one month in advance for middeck-only flights.

Bench Review

Before the packing is finalized and the bags passed from CMC to the Next-Level Integrator for loading into the launch module, a Bench Review will be held at the packing location (either KSC or JSC). At this review the flight crew, Integration Stowage Officers (ISOs), various hardware owners, and packing engineers will come together to examine item labeling, containment, grouping of like items, etc. After all outstanding issues have been resolved the bags will be closed and transferred to the Next-Level Integrator (typically Boeing at KSC). If the CTBs undergo a bench review at JSC and are then shipped to KSC for launch, they will not undergo a second Bench Review.

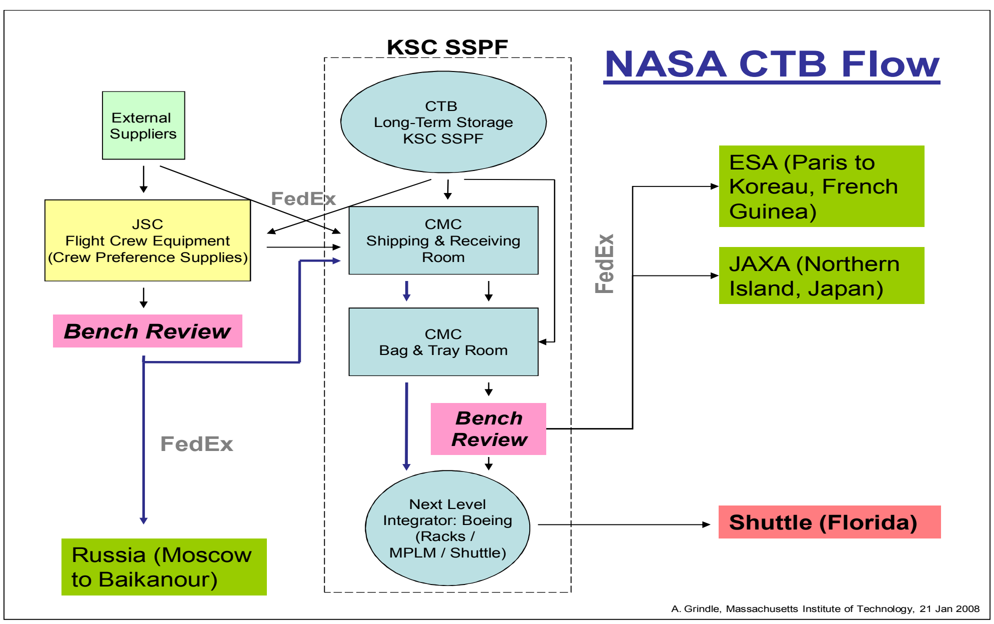

Figure 2.7: CTB Pre-Launch Flow Diagram

[9] Mass IS a significant limiting factor for US cargo on Russian flights; consequently, NASA tries to minimize Half CTB use on these flights (as the bag adds roughly 1 kg) and keep the packed-bag mass under 10 kg.
[10] For example, John Muzzy's group cuts custom foam inserts to protect hardware that is to be packed in CTBs.

Shipping

There are several transportation options that are used to move cargo (both packed and unpacked) between NASA Centers, as well as between NASA and its International Partners. FedEx is frequently used for both domestic and international shipping. In certain situations items are sent via FedEx Custom Critical, for which a FedEx truck dedicated exclusively to the shipment is driven straight from the pick-up site to the delivery location (often JSC to KSC). The truck is temperature- and shock-controlled, and its trailer is locked and sealed such that even the driver cannot open it until arrival at the delivery location. On rare occasions, NASA uses Southwest Airline's Counter-to-Counter service, where items are transported onboard Southwest's passenger jets.

Figure 2.8: HOBOs (Credit: A. Grindle)

For certain types of items, particularly food and medical/life science objects, there is a need to monitor environmental conditions during transport. There is also some concern regarding environmental conditions related to shipping items to the international partners: Russia features many Customs procedures, and shipments are sometimes exposed to low temperatures while waiting to clear; Japan is also anticipated to feature long waits and possible exposure to uncontrolled environments; Europe is generally good about minimizing environmental exposure, although heat and humidity are certainly concerns at Koreau.

A device known as a HOBO (Figure 2.8) is used to record temperature and relative humidity. These monitors, which cost $50 to $100 each, travel in the shipment container. At the destination, they are plugged into CMC's computers and the recorded environmental information is downloaded. If specification conditions are exceeded or any other abnormalities are observed, it is noted on the receiving paperwork[11] for the particular shipment. However, these records are not directly associated with the entries of the affected cargo item in MAXIMO, IMS, or any other database.

Unpacking on ISS

When cargo is delivered to the International Space Station, the crew must spend a significant amount of time unloading and unpacking the Cargo Transfer Bags (CTBs). First, the CTBs must be unloaded – removed - from the newly-arrived spacecraft and transferred to ISS. For shuttle missions, it takes approximately 15 crew-hours to unload a middeck-only flight and 50 crew-hours to unload a Multi-Purpose Logistics Module (MPLM). After the cargo is physically inside the station, more time is required to unpack, sort, and/or store the new cargo. Unpacking generally consumes 10-20 crew-hours for a middeck flight and 20-25 crew-hours for an MPLM mission, with each packed item taking approximately 2 minutes to unpack and store. While the crew is unpacking, Mission Control occasionally requests that they conduct an audit[12] of an

[11] Transportation Form DD-1149 (KSC) or Form 290 (JSC)
[12] Count the contents

incumbent[13] CTB which must be opened anyways to store newly-arrived items. While such audits add to the time required for unpacking, given the current architecture such a "touch-it-once" strategy[14] is the most efficient method to update or verify inventory levels.

When CTBs are emptied on ISS, they are folded down into a flat-like configuration and placed in groups of three or four inside another CTB. Currently, there are between 50 and 60 empty CTBs on-orbit. Occasionally, these bags are used to help package items for return to Earth.

Return & Cleaning

CTBs return to Earth aboard the Shuttle. When the vehicle arrives on the ground, the MPLM (and/or middeck cargo) is transferred to the SSPF. In the SSPF High Bay, the Rack Insertion Device is used to extract the racks from the MPLM. The racks – which "contain" or provide a framework for the CTBs – are transferred to the MTL Technologies/CMC Bag & Tray Room, where the CTBs are removed and unpacked. Returned hardware is wrapped in pink-poly and packaged with foam as appropriate and shipped back to its owners.

Once emptied, the CTBs are inspected and cleaned. Typically, this cleaning is done in-house by CMC; they remove any dirt or foreign fibers with tweezers, tape, and/or alcohol wipes. On rare occasions when a bag is too badly soiled for this process, the group will immerse the CTB in a vat of water and detergent. If a physical repair is needed, the bag will be sent to the manufacturer, Rothe Industries, in Houston.

ISS INVENTORY MANAGEMENT OPERATIONS

As mentioned previously, cargo onboard ISS is currently managed by barcode. All items are labeled with a barcode, either as individual items (such as a spare part) or a package of items (such as a bag of screws). The crew, until recently, used a handheld barcode scanner to associate an item with a particular bag or location in IMS. The scanner was also used to call up an item's entry in IMS on the station's computers and change the status (i.e., to indicate usage). Ostensibly, this barcode reader has been replaced with a PDA that is equipped to read barcodes and connect to IMS via the station's Wi-Fi network[15], but reports indicate that in early 2008 the crew was still using the old barcode scanner. The reason for this was unclear to ground personnel at the time of these interviews. The US provided both the barcode scanners and the PDAs, although both Russian and American crew members use this hardware.

Every day, each ISS crewmember is allocated 20 minutes each in the official mission timeline to update IMS[16]. This is in addition to any of their "personal time" that they might spend performing the function. The 20 minutes is not necessarily intended to be used as a single block, but rather to serve as a placeholder to reflect the amount of time that is spent on the task throughout the day. Once per Flight Increment[17] (twice per year), Mission Control asks the crew to conduct a two-hour audit of particular items in order to update the inventory quantities and usage rates. For example, the crew might be asked to count the number of clean t-shirts that

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[13] "Incumbent" meaning a CTB that is already on-orbit, that has not just arrived in the docked launch vehicle.

[14] Auditing the contents of the CTB while it is out, rather than at another random time.

[15] 802.11b

[16] It should be noted that the ISO in Mission Control often remotely updates IMS for the crew, based on crew updates that are called down.

[17] Typically a flight increment is six months long.

remain (or food, office supplies, etc). The audit process involves taking all of the items out of a particular CTB and counting them as they are placed in another (previously empty) CTB. On average, this takes 20 minutes per bag. Given the very limited nature of available on-orbit crew hours, as one NASA engineer pointed out that, "If we can take that 20 minutes and change it to 20 seconds [or eliminate it], we've done a tremendous amount of work for them."

Ground Support

The crew does receive significant ground support to assist them in maintaining IMS. At NASA JSC, a number of engineers are employed as Integration Stowage Officers (ISOs). ISOs are part of the Mission Operations Directorate; their central responsibility is to serve as the crew's point of contact in Mission Control for inventory/stowage issues. They will answer questions from the crew and also assist in updating IMS (entering changes as the crew calls them down, for example). As of January 2008, there is always an ISO on console while the crew is awake; this requires two ISOs per day each working an eight-hour shift[18] (with one hour overlap for hand-off). In addition, ISOs write stowage notes for on-orbit procedures; these notes describe where the astronauts should find all the necessary items for a particular procedure, in addition to re-stowage and/or disposal instructions (what and where) for the procedure's conclusion.

Supplementing the full-time ISO team is Ms. Ursula Stockdale, a NASA veteran who has worked in the group since 1994 and was involved in the initial development of the CTBs after the Shuttle-MIR program. Ms. Stockdale now works part-time (18 hours per week), and her efforts are focused solely upon ISO Support. She describes her role as the "mother hen" in the background who gets to see the big picture, cleaning up IMS and checking Delta files for errors, watching for inventory trends over time, and leading on-orbit stowage planning for all new US cargo.

Current Inventory Status / Missing Items

At the present time, there are approximately 13000 US items in IMS, spread throughout the station in roughly 500 CTBs (and various other stowage mechanisms). Many of these CTBs remain unopened after years on-orbit; in a typical day, only 10 to 15 CTBs are opened. However, even with a limited number of bags being opened, a large number of inventory transactions still occur – typically, NASA Houston exports two Delta files[19] per day, each containing roughly 400 IMS changes/updates. Occasionally they will export 5 or 6 files in a single day. The Russians on the ground record far fewer transactions; they depend much more heavily on their crew members to enter changes. An average Moscow Delta file will contain about 20 changes – a "big" file will contain 80 or 90. Furthermore, Moscow has generated only about 1400 Delta files, a little more than half as many as Houston or ISS.

Expiration dates are not currently tracked in an active fashion in IMS. As a consequence, occasionally some items have expired on-orbit due to inaccurate usage rate projections. For example, a group of utensil wipes exceeded their approved lifetime while on Station. Some items can be used after their printed expiration dates, but some cannot – the final determination is made by JSC's Engineering Directorate.

[18] The two shifts are 2am – 10am and 9am – 5pm, CST
[19] Recall that Delta files are used to synchronize the four IMS databases in Houston, Moscow, ISS, and Baikanour, and contain only changes – not the entire database.

Of the 13000 US items on-orbit, 3% are presently designated as "lost," meaning "stuff that we [NASA] really have no idea where it is." Again, items are counted at a package level, so if one package is lost which contains five t-shirts, it registers as a single lost item. Over the course of a given year, it is estimated that roughly 10 crew hours are spent searching for some of these lost items, and perhaps twice that effort for ground engineers. However, this can vary depending on the importance of the item(s) misplaced. In one notable incident, a Pump Package Assembly – measuring 20" x 20" x 36", roughly the size of a mini-fridge - was lost on-orbit. Two or three crew hours were devoted to multiple searches, in addition to an "obscene" amount of personnel time on the ground spent looking through IMS, discussing possibilities in meetings, etc. In the end, the assembly was found in a cavity behind a panel aboard ISS; apparently a former crew had deigned this to be a convenient storage location but neglected to update IMS or inform the ground about it.

Trash

Trash on ISS is divided into three categories – Common trash, Russian trash[20], and NASA trash. Common trash accounts for approximately two-thirds of the total trash generated on Station, followed by Russian trash and then NASA trash. The disposal mechanism for almost all trash is for it to be packed into the Progress prior to that vehicle's release from Station for burn-up in the atmosphere. A small amount is also packed into the part of the Soyuz capsule that detaches and burns-up during reentry. The U.S. and Russia split the "cost" of disposing of the Common trash, and each is also responsible for the cost of their individual trash. Since trash is disposed of using Russian vehicles, Russia manages this account and bills NASA for its share of the trash after every disposal.

Common trash largely consists of three types of items, each of which makes approximately an equal contribution to the total mass. These include 1) solid- and (older) liquid-waste containers from the toilets, 2) liquid waste from the toilets, and 3) clothes/towels/hygiene items. The solid waste containers are called KTOs, and are metal containers with a capacity of roughly 11.5 kg each. Liquid waste containers are known as EDVs, and have a capacity of approximately 22 kg each. EDVs are not discarded until they approach their design end-of-life; up to that point, their contents are transferred to the Rodnik tanks[21] that are built into the Progress for disposal. All other common trash – the bulk of which consists of clothes, towels, and hygiene items, but which also includes food wrappers and scraps, used Kleenex, and a variety of other miscellaneous items – is placed in three other types of containers. The KBO-M is a rubberized cloth bag that serves as a common trash waste-receptacle; the Food Waste bag is a small rubberized bag used primarily for small and wet trash such as table scraps; and the Rubber-Lined Bag is a larger rubberized cloth bag that can contain three KBO-Ms or eight Food Waste bags. Appendix B contains pictures of each of the five types of waste containers.

NASA trash and Russian trash consist of items that are more clearly owned by one side or the other, such as old hardware components. The two space agencies have their own independent processes for approving the disposal of such trash; for NASA, the ISO in Mission Control provides direction to the crew regarding what to throw out. Common trash, however, can be disposed of (placed in waste containers) without needing any specific permission from the

[20] Russian trash also includes what is sometimes called "FGB trash"
[21] These tanks are also used to carry water up to the station; they have a capacity on the order of 200-400 kg.

ground. Ground controllers find out about the disposal when the crew updates IMS (or calls down to Houston to ask them to make the update), although this does not necessarily correspond with the physical act of placing the trash in the receptacle. For example, when the crew takes a bag of five t-shirts from the "pantry" and scans the barcode, IMS automatically switches the status of those shirts to "trash" and records them as loaded into the Progress for disposal, even though they are still in use on Station.

Roughly two weeks before the Progress vehicle is scheduled to undock, the Russian Space Agency sends the crew a trash-disposal packing list, based on data from IMS. The crew will then load the specified items and trash containers into the vehicle. There is, however, some ambiguity about what is finally packed, especially when it comes to common trash, because the crew loads both full waste bags (KBO-Ms, etc) and also individual pieces of trash. For example, IMS might show that three packages-worth of t-shirts have been loaded into the vehicle, and the crew themselves report that they have loaded five full KBO-Ms into the Progress; unfortunately, that information alone does not make clear whether the t-shirts were contained within those KBO-Ms or whether they were loaded separately, *in addition* to the five full KBO-Ms[22].

[22] These KBO-Ms could contain other items not so finely tracked within IMS such as used tissues, hygiene products, food scraps, etc.

CHAPTER 3: FINANCIAL ANALYSIS OF THE RAMSES CARGO TRANSFER BAG ON ISS

INTRODUCTION

This chapter develops a model that quantifies the costs and benefits of implementing the RAMSES RFID-based inventory management system aboard the International Space Station, and calculates the probabilistic Net Present Value (NPV) of the investment using Monte Carlo simulations. Other authors have previously conducted cost-benefit analyses for RFID asset tracking / inventory management systems that are applied to different environments. For example, Adenso-Diaz and Gascon (1999) modeled the discounted cash flows associated with the implementation of early-generation RFID tracking technology in a generic commercial warehouse [19] and BearingPoint, Inc (2004) used Monte Carlo simulations to conduct a probabilistic cost-benefit analysis of an RFID-based security and tracking solution for a transoceanic supply chain [20]. Doerr, Gates, and Mutty (2006) analyzed the probable Return-on-Investment (ROI) for a U.S. Department of Defense proposal to monitor ordnance with an RFID/MEMS solution, evaluating quantitative costs and benefits of this proposed public investment with Monte Carlo simulation. They also conducted sensitivity and risk analyses of their results, to discover the probability that the project would generate a positive ROI [21]. The work in this chapter builds most closely upon this last effort, using a similar methodology – Monte Carlo simulation together with sensitivity analyses – but adapted and applied to the unique environment of human spaceflight.

APPROACH

A Net Present Value (NPV) calculation allows the quantitative comparison of costs and benefits that are uncertain and spread over time. Future dollars – costs (*C*) and/or benefits (*B*) that are expected to accrue in *N* future years – are converted into present dollars through the use of a discount rate, *r* (Equation 1). This discount rate typically is chosen to represent the rate of return that would be obtained by investing the required capital into a stock/bond/fund/etc of comparable risk, instead of investing it in the project.

$$NPV = \sum_{i=1}^{N} \frac{B_i - C_i}{(1+r)^i} \qquad [1]$$

For this analysis, a discount rate of 7% was used, as specified by the U.S. Office of Management and Budget (OMB) in Circular No. A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs* for base-case analysis of "public investments". According to OMB, this rate "approximates the marginal pretax rate of return on an average investment in the private sector in recent years." [22]

Also, this analysis was conducted through Fiscal Year 2016, the last year of NASA funding for the Station according to the projections from NASA's 2004 planning document for the Vision for Space Exploration [23]. The 2016 ISS retirement date remains the U.S. Government's baseline as of the time of this work [24].

METHODOLOGY

Figure 3.1, on the following page, summarizes the methodology employed in this analysis and described below.

Simulation of Variables

Three distinct simulation techniques were used to calculate the net present value of the system, and the results were compared. First, a discrete calculation of NPV was performed with input variable values based upon the best information available. A sensitivity analysis was conducted on this discrete scenario, and the results identified those uncertain variables with the most significant impact upon the final net present value. Next, a 3,500-trial Monte Carlo NPV simulation was conducted in which input values for high-impact uncertain variables were randomly generated. These variables were generated with uniform distributions, each with a range intended to span the set of reasonable values and centered near the "best-information" value. Finally, another 3,500-trial Monte Carlo simulation was conducted to iterate the same set of variables, but with normally-distributed input values. In this case, the distribution for each variable was centered at or near the "best-information" value, and the standard deviation was set so that the range of reasonable values would constitute 95% of the total range.

Implementation Scenarios

Two different hardware-implementation scenarios were studied in this work. In the first, the system's net present value was calculated for a "Phase-In" scenario in which the RAMSES RFID-wired CTBs would gradually replace the unwired CTBs on-orbit. This replacement would take place as new, wired CTBs are launched to the ISS as part of already-scheduled logistics missions and displace old, unwired bags already on-orbit.

However, further investigation revealed that – especially given the upcoming Shuttle retirement, scheduled for 2010 – this Phase-In scenario might be unrealistic; the quantity of new CTBs that are scheduled to be launched to ISS is predicted to be rather small [25]. Therefore, a second scenario – the "Modification Kits" Scenario - was developed. In this scenario, modification kits (mod-kits) would be launched all at once to the ISS, and the crew would retrofit CTBs that are already on-orbit with the RAMSES RFID hardware. This analysis assumed that all kits would be launched and installed in FY 2009, and that each kit would require 20 minutes of crew time to install.

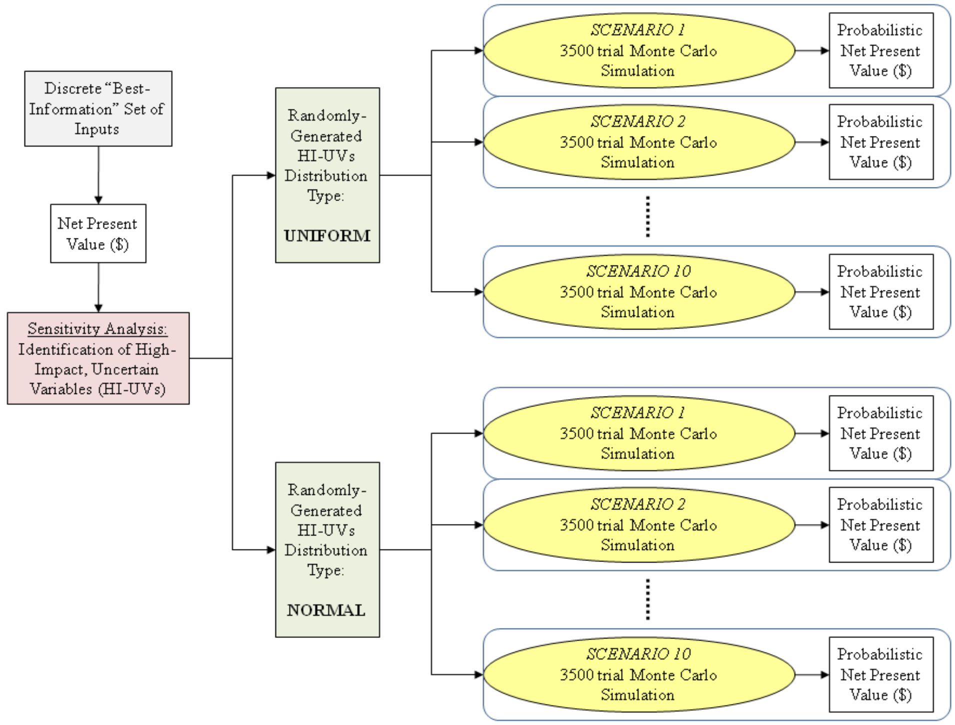

Figure 3.1. Summary of analysis flow for each of the two RAMSES implementation scenarios.

Concentration of Inventory Transactions

Finally, multiple simulations were created to study the combined effects on net present value of: 1) a concentration of inventory transactions[23] in some subset of the bags, and 2) a decision to wire only that subset of the total ISS CTB population. Table 3.1 displays the combinations that were studied. For example, in Scenario 4, the Monte Carlo simulation was conducted as if 50% of the total inventory transactions were concentrated in the 25% of the CTBs which were actually wired. In Scenario 9, 75% of the transactions occurred in the 50% of the CTBs which were wired. Scenarios 1, 3, 6, and 10 assume that transactions are uniformly distributed throughout all CTBs; in 1, 3, and 6 not all bags are wired, despite the absence of any concentration of inventory transactions.

[23] The occurrence of a disproportionate number of inventory transactions within some subset of CTBs, such as those that contain office supplies, food, crew personal items, etc. JSC Engineers indicated that some concentration of this nature does occur, but they do not have the data to quantify the phenomenon.

Table 3.1. Map of inventory transaction concentration scenarios considered.

		Launch Mod Kits (Best Ops Guess); Normally-Distributed Simulations									
		Effective % of CTBs Wired (As determined by concentration of transactions)									
		25%		**33%**		**50%**		**75%**		**100%**	
		Mean NPV / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**
Actual % CTBs Wired	**25%**	Scenario 1		Scenario 2		Scenario 4		Scenario 7		x	x
	33%	x	x	Scenario 3		Scenario 5		Scenario 8		x	x
	50%	x	x	x	x	Scenario 6		Scenario 9		x	x
	100%	x	x	x	x	x	x	x	x	Scenario 10	

Calculating the "Value" of Crew Time and Cargo Launch Volume

Often a cost/benefit analysis will deal with a system in which certain costs and/or benefits are not readily expressed in the common units of value of the analysis. In such situations, one can occasionally find indirect means of converting these elements into the common units of value, although much caution is necessary; the decisions made in such a conversion process can significantly impact the results of the analysis. In this study, it was necessary to convert two key parameters – crew time and cargo volume launch capacity – into present dollars, the common units of value.

"Value" of Crew Time

This analysis required a determination of the "value" of an astronaut's time onboard ISS. The value of such time is an essential component of the analysis, because one of the most substantial benefits of this system is its potential to reduce the amount of time the crew must spend updating and maintaining the Station's inventory database. Such saved time represents a valuable resource that could be invested in value-added activities such as scientific experiments. Time is also a cost; for example, the time which the crew must spend to upgrade the CTBs with modification kits (in one implementation scenario) must be added to the other "costs" associated with the system in order to fairly balance costs against benefits.

Clearly, there are multiple approaches one could use to calculate the value of on-orbit crew time. One could divide the total estimated cost of the Station by the total projected number of crew hours through planned decommissioning in 2016. However, two factors make it difficult to justify attributing the entirety of the total cost of ISS to the value of crew time. First, there are other reasons for constructing the station besides providing a manned orbital laboratory, such as gaining the experience of constructing such a massive structure in space, and doing so with an international team. Second, there is the uncertainty as to whether or not the Station will actually be retired in 2016.

An alternative method for determining this quantity would be to calculate the "productivity value" of crew time, perhaps by dividing the estimated value of the eventual "products" of ISS research by the total active crew time, or by the crew time devoted to experiments. Unfortunately, it is all but impossible to calculate this estimated product value at the present moment; one cannot predict the results of ISS research which might emerge over the next several years. This is particular true because the vast majority of ISS research is "basic" or "fundamental" in nature, and such work generally occurs many years prior to any kind of commercial product or application, although it is foundational to such developments.

Table 3.2. Calculation of value of crew time.

Year:	2009	2010-2016
# Crew:	3	6
Avg. ISS Budget:	$ 3,239,556,135.77	$ 3,501,925,587.47
# "Active" Crew Hours in a Day:	16	16
$ / 'Active' Crew Hr:	$ 184,906.17	$ 99,940.80

Instead, to calculate the value of crew time this analysis took the combined annual ISS Operations budgets[24] for NASA and all the International Partners and divided that by the total number of "active"[25] crew hours per year to arrive at a "$/active crew hour" figure. This figure was calculated both for the current station configuration (current Operations budget divided by active time for three-member crew) through 2009 as well as for the Assembly Complete configuration (average projected annual Operations budgets divided by active time for six-person crew) for 2010-2016. The details of these calculations are shown in Appendix C, with results summarized in Table 3.2.

"Value" of Launch Cargo Volume and Mass

The other significant parameters which required a conversion to the common units of "value" were the volume and mass of launched cargo. Contrary to popular belief, the primary limitation for ISS Cargo is typically not launch *mass,* but rather, launch *volume*; ISS cargo/logistics missions tend to fill the available packing volume before filling the available mass allocation. Consequently, one must account for the "cost" of the cargo launch volume required by RAMSES hardware (in addition to that of its mass) in order to fairly evaluate the net present value.[26]

Table 3.3. Calculation of value of average cargo launch volume.

$ / m³ ('09-'10)	$ 20,272,793.47
$ / m³ ('11-'16)	$ 31,598,719.79

Table 3.4. Calculation of value of average cargo launch mass.

$ / lb ('09-'10)	$ 25,511.96
$ / lb ('11-'16)	$ 35,715.01

To calculate the value of cargo volume, the net variable recurring cost[27] for all cargo missions in a given year was divided by the total available cargo

[24] That is, the ISS Operations budgets of NASA, JAXA, ESA, CSA, and RSA (or at least the best approximations available), including the variable recurring cost of cargo/logistics flights. The cost of construction and construction flights are excluded, as are indirect costs such as the overhead for the Space Shuttle program.

[25] "Active" is defined here as non-sleeping hours. Again, the exact value that should be used for this metric could be debated; should it include the crew's personal time and meal time, or only official "working" hours? Given the grey area associated with the concept of "non-working hours" for a Space Station crew, and to conservatively minimize the value of a unit of crew time, this analysis includes all active (non-sleeping) crew time in the value calculation.

[26] Note that, for the sake of this analysis, it was assumed that the cargo launch volume required by RAMSES hardware could be obtained either by adding an additional cargo flight(s) or by displacing other objects from currently scheduled flights.

[27] The cost of only the cargo mission/spacecraft, not including the overhead associated with any given launch vehicle or program. Put another way, the incremental cost to launch one additional cargo mission. Note that this cost varies substantially by vehicle. Given the uncertainty of international relations and how future developments might impact the choice of vehicle for such an additional mission, an average cost per cargo mission was determined and used, rather than the cost per mission of the lowest-cost vehicle.

volume[28] for such missions, to generate a "$/cubic-meter-of-pressurized-cargo" metric. The ISS logistics flight schedule from 2008 to 2016 gave the necessary information regarding the planned flight schedule and vehicle mix [26]. Also, as detailed in Table 3.3, two values for this quantity were calculated – one for 2009-2010 (prior to Shuttle retirement), and one for 2011-2016 (after Shuttle retirement).

Table 3.5. List of general input variables for Modification Kits Implementation Scenario.

	FY 2009
Cost to Modify 1 CTB for RFID System ($):	$ 3,000.00
Cost of Hardware Components for 1 RFID System ($):	$ 3,000.00
Mass of RFID System (lbs):	4
Volume of Standard CTB (m^3):	0.053
% of Standard CTB Volume required by RFID System:	12%
Time Required for Astronauts to Modify 1 CTB (hr):	1/3
Number of CTBs upgraded by On-Orbit Crew:	600
Cost of 1 NASA Engineer Person-Year (Salary + Overhead):	$ 200,000.00
# NASA Engineer Person-Years for Flight Certification Testing & Review:	7
# NASA Engineer Person-Years for Operational Maintenance (per year):	2
# ISOs Employed to Cover 1 Console Shift / Day, 365 Days / Yr:	6
First Year to Realize Benefits:	2010
Final Year of ISS Operations:	2016
% On-orbit IMS Entries that could be Automated by Wired CTBs:	50%
% of CTB Transactions Accurately Detected by System:	95%
SYSTEM EFFECTIVENESS (%) for those CTBs that are Wired:	48%

The launch cost ($) per unit of cargo mass was calculated similarly to the cost per unit of cargo volume, and is detailed in Table 3.4 and Appendix C.[29] Also, a discussion of the decision to count the cost of both launch mass and volume is included in the final section of this chapter.

General Input Variables

Several other quantities were used in this analysis, as summarized in Table 3.5 for the Modification Kits Implementation Scenario. The estimated cost for the CTB vendor (Rothe Industries, of Houston, Texas) to retrofit and install such hardware in one CTB, or for the developer to build a modification kit for on-orbit installation (both estimated at $3000), was input into the model. Also, the estimated mass and cost ($3000) of one set of RAMSES hardware components - necessary to upgrade one CTB - was entered. The hardware cost is based upon a conservative estimate from the RAMSES development team at Aurora Flight Sciences / Payload Systems, while the installation or modification kit estimate is based upon the cost of a new CTB ($2500 - $5000) [27].

Two other elements included the volume of a standard CTB (0.053 m^3), and the estimated percentage of that volume that would be required by the RAMSES hardware. This percentage was calculated based on extrapolation from current prototype efforts.[30]

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[28] Note that the actual volumetric figure used is "pressurized cargo volume," due to inconsistent reporting of the desired figure-of-merit by International Partners. The actual cargo volume available to be packed is typically less than the pressurized cargo volume, as certain vehicles – such as the ATV, HTV, and MPLM – include space for astronaut ingress and egress. Furthermore, all bags and other packed objects must be secured within the transport vehicle, most commonly within a rack or frame. With the possible exception of the Progress M1, the vehicles are not simply packed to maximum volumetric capacity.

[29] The net recurring launch cost for all cargo flights was divided by the total available cargo mass to determine "$/lb-cargo-mass-launched". This was calculated to be roughly $25,000 per lb prior to Shuttle retirement, and $35,000 per lb after Shuttle retirement. See Appendix C for details.

Still other inputs included the estimated number of CTBs that would be upgraded or replaced on-orbit, and the estimated crew time required to upgrade or replace a single bag (which consists of either installing a modification kit or transferring contents from an old bag to a new, wired bag). This latter estimate – 20 minutes - was based upon the amount of time that it takes the crew to unpack a new CTB that arrives on-orbit containing items that must be distributed among existing CTBs [1].

The total cost (including overhead) of one NASA Engineer-Year was entered as approximately $200,000 [28]. The number of NASA Engineer-Years required for RAMSES flight certification and review was estimated to be 7 (in FY 2009), and for recurring RAMSES operations and maintenance this value was set to 2 (per year, 2009-2016). Also, 12 Engineer-Years are currently devoted to Integration Stowage Officer (ISO) activities.[31]

Finally, a System Effectiveness parameter, β, was created to account for the fact that the system will not automate 100% of all inventory transactions. This is due to two factors: 1) some inventory transactions cannot be automated with the proposed system architecture[32], and 2) the system will have some errors, and will not be able to detect 100% of those transactions which it could automate. Therefore, as shown in Equation 2, the System Effectiveness parameter is merely the product of α, the percentage of inventory transactions which the system *can* automate (best estimate is 50%, as explained in footnote 32) and μ, the percentage of those transactions which the system *does* accurately detect (reasonable estimate is 95%, as detailed in Chapter 4). Therefore, the best estimate value for β is 47.5%.

$$\beta = \alpha \times \mu \qquad (2)$$

RESULTS FROM DISCRETE CALCULATIONS

Table 3.6 shows that, when using "best-information" values for all input variables in the Modification Kits Implementation Scenario, and assuming no concentration of transactions and that 100% of ISS CTBs will be wired, the system has a net present value of almost $15 million. Table 3.7 shows that, by contrast, for the Phase-In Scenario, a discrete calculation of the system's net present value shows a negative NPV of roughly $63 million.

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[30] The initial RAMSES CTB implementation consumes approximately 25% of the total volume of a standard CTB, mostly due to an overly conservative (large) amount of foam insulation used to provide separation from the metallic shielding that lines the CTB and electromagnetically isolates the interior from the outside environment. Further system optimization and use of a more advanced insulation material are projected to reduce this required volume; 12% of the standard CTB volume is chosen as the best estimate value for this variable.

[31] It is estimated that a 100% efficient system of wired CTBs could automate 50% of the inventory transactions onboard Station, which in turn is estimated to be 25% of the ISO workload [25].

[32] Some transactions will "end" - or take place entirely – outside of a wired CTB, where the destination / final-status of the object cannot be detected by the system. For example, an astronaut could remove a new shirt from a wired CTB and take it to his/her living space. The RAMSES system would record the shirt's disappearance from the CTB, but the crew would still have to manually enter the destination of the shirt into the Inventory Management System (IMS) database. This analysis makes the conservative assumption that all transactions follow this pattern (ie, end or begin outside the coverage of a wired CTB), and thus only 50% of transactions can be automated.

However, one must realize that some of these “best-information” values are still quite uncertain. Consequently, the probabilistic Monte Carlo simulations that follow are more reliable indications of value.

Table 3.6. Discrete NPV Simulation for Mod-Kits Implementation Scenario.

Implementation Scenario	NPV - Discrete Simulation
Modification Kits	$ 14,769,006.75

Table 3.7. Discrete NPV Simulation for Phase-In Implementation Scenario.

Implementation Scenario	NPV - Discrete Simulation
Phased-In	$ (63,065,612.21)

VARIABLE SELECTION FOR MONTE CARLO SIMULATIONS

As mentioned previously, a sensitivity analysis was conducted based upon the results of the discrete NPV calculation (which used best-estimate input values for all variables and the modification kit implementation scenario). This analysis determined those variables with the most significant impact upon the calculated net present value. Using Microsoft Excel’s data table feature, each variable – one at a time - was iterated through a range of reasonable values, with a new NPV calculated for each iteration. Then, the sensitivity of NPV to each variable was calculated as the average ratio of the percentage change in NPV to the corresponding percentage change in the iterated variable (*X*), as expressed in Equation 3.

$$\frac{\sum_{i=1}^{n}\left(\frac{|NPV_i - NPV_0|}{NPV_0} \Big/ \frac{|X_i - X_0|}{X_0}\right)}{n} \tag{3}$$

The results of this analysis revealed that seven variables clearly impacted the final NPV result substantially more than the rest. Table 3.8 summarizes this difference in sensitivity for the Modification Kits Scenario. Interestingly, the NPV of the system is most sensitive to the percent of CTB volume which the RAMSES hardware requires (19.63), a physical characteristic of the system, and then to the read-rate accuracy of the hardware (13.39), the key technical performance characteristic.

Of the seven variables with the greatest impact, six were subsequently randomly generated for the Monte Carlo simulations, while the seventh – “# of CTBs On-Orbit that are to be wired” – was iterated via distinct Monte Carlo simulations in conjunction with the concentration of transactions in a subset of CTBs, as previously specified in Table 3.1.

The relative sensitivities of the variables for the Phase-In Scenario (see Appendix C for table) are generally the same as for the Modification Kits Scenario. The most notable exception is that the rate at which CTBs are launched is also a high-impact variable.

Table 3.8. Sensitivity analysis summary.

Sensitivity Analysis Summary	
Variable	*Avg. Norm. % Diff.*
Number of Crew (2010+):	0.69
Avg. ISS Budget (2009-2016):	9.74
# "Active" Crew Hours Per Day:	11.32
RFID System Weight (lbs):	3.99
Cost to Modify 1 CTB for RFID System (add pockets, insulation, install electronics):	0.11
Discount Rate:	3.03
Time Required for Astronauts to Transfer CTB Contents to new CTB (hr):	2.31
Number of CTBs upgraded by On-Orbit Crew:	2.31
# of CTBs On-Orbit that are to be wired:	10.78
% On-orbit IMS Entries that could be Automated by Wired CTBs:	12.96
% of CTB Transactions Accurately Detected by System:	13.39
Percent of Standard CTB volume required for RFID System:	19.63
Volume Cost ($ / m^3):	5.23

CALCULATION OF COSTS

Modification Kits Implementation Scenario

For the implementation scenario which consisted of launching modification kits in FY 2009 to retrofit on-orbit CTBs, there were six non-recurring costs which were calculated for FY 2009. The only recurring cost in this scenario was the NASA Engineer time to support system maintenance and operations, and it was charged for FY 2009 – FY 2016 and discounted as shown in Equation 1. The six non-recurring costs included the real costs or opportunity costs of:

- Hardware components
- Building and preparing the modification kits
- NASA Engineering time for the flight certification testing and approval process
- Launching the system mass
- Launching the system volume
- The crew time needed to install the modification kits on-orbit.

Phase-In Implementation Scenario

In the second implementation scenario, RFID-wired CTBs would gradually replace unwired units as they were launched according to the existing cargo flight schedule. In this scenario, most costs are recurring; the only one-time cost is that of the NASA Engineering time required for RAMSES flight certification testing and review, charged in FY 2009. The recurring charges, spread evenly from FY 2009 to FY 2016 and discounted according to Equation 1, include the real costs or opportunity costs of:

- Hardware components
- Vendor modification of the CTBs and installation of the RAMSES hardware
- NASA Engineering time to support system maintenance and operations
- Launching the system mass (different for pre- and post-Shuttle Retirement)
- Launching the system volume (also different for pre- and post-Shuttle Retirement)
- The crew time needed to transfer contents from old bags to new bags on-orbit (different for crew of 3 in FY 2009 and crew of 6 in FY 2010 – FY 2016).

Calculation of Benefits

Modification Kits Implementation Scenario

All benefits are recurring and appropriately discounted to present value. Furthermore, benefits do not start to accrue until FY 2010, under the assumption that there is some delay time – time required for initial system approval, launch, and set-up – between project initiation and the first realization of benefits. The vast majority of the quantified benefits result from saving crew time that would otherwise be spent on inventory management tasks. These savings include part of the time the crew spends searching for lost items (roughly 10 hours per year), conducting inventory audits[33] (roughly 4 hours per year per crew member), and updating the Station's Inventory Management System (officially scheduled as 20 minutes per day per crew member) [1]. The other benefit derives from saving NASA Engineer time by reducing the workload of the Integration Stowage Officers on the ground at JSC, specifically the time spent assisting the crew with IMS updates [25]. Collectively, these benefits are realized according to the System Effectiveness (β) parameter; for a β of 50%, the benefits credited to the RAMSES system are 50% of the total possible.

Phase-In Implementation Scenario

The only difference between the two implementation scenarios in terms of the calculation of benefits is that with the gradual deployment of CTBs, benefits are realized more slowly. For example, if – starting in FY 2009 - the number of wired CTBs launched every year is equal to 10% of the total ISS CTB population, then in FY 2010 the benefits realized will be 10% of those calculated by the System Effectiveness (β) parameter. In FY 2011, the benefits will be 20% of the β parameter, in FY 2012, they will be 30%. This stands in contrast to the Modification Kits scenario, in which it is assumed that – if all bags are intended to be wired – 100% of the benefits allowed by the β parameter will be realized every year, starting in FY 2010. Note that the benefit calculation method for the Phase-In scenario also assumes that all wired CTBs launched in a given year will not yield benefits until the following year. Due to the uncertainty of launch dates and installation schedules, this conservative assumption was necessary; however, one should recognize that it does cause some loss of present value in the overall analysis for this scenario.

Results of Monte Carlo Simulations

Modification Kits Implementation Scenario

The results from the Monte Carlo normal distribution and Monte Carlo uniform distribution simulations for the Modification Kits Implementation Scenario are summarized on the next page in Tables 3.9 and 3.10.

[33] Counting the numbers of various supplies to verify IMS records

Table 3.9. Summary of probabilistic NPV Monte Carlo simulations for Modification Kits Implementation Scenarios with normally-distributed variables.

		Launch Mod Kits (Best Ops Guess); Normally-Distributed Simulations									
		Effective % of CTBs Wired (As determined by concentration of transactions)									
		25%		**33%**		**50%**		**75%**		**100%**	
		Mean NPV / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**
Actual % CTBs Wired	**25%**	$ (6,028,603.41)	37%	$ 12,484,645.27	71%	$ 49,435,199.17	95%	$ 103,185,422.47	100%	x	x
		$ 19,313,461.96		$ 23,066,435.14		$ 30,550,819.73		$ 44,754,456.13		x	
	33%	x	x	$ (6,035,666.20)	41%	$ 29,780,636.00	82%	$ 85,406,626.04	98%	x	x
		x		$ 25,918,469.55		$ 32,852,633.72		$ 46,558,196.89		x	
	50%	x	x	x	x	$ (7,233,783.26)	43%	$ 46,835,438.82	84%	x	x
		x		x		$ 38,902,427.71		$ 48,677,956.52		x	
	100%	x	x	x	x	x	x	x	x	$ (13,223,978.27)	43%
		x		x		x		x		$ 77,414,934.03	

Table 3.9 illustrates that – from a probabilistic stand-point – the system is slightly more likely to have negative present value than it is to have positive present value, unless there is some concentration of transactions. For example, if 50% of the Station's CTBs are wired in FY 2009 and there is no concentration of transactions (ie, the Effective % of CTBs Wired is also 50%), the system has a *negative* mean NPV of roughly $7.2 million with standard deviation of $38.9 million, and 43% of the 3500 Monte Carlo trials resulted in a positive net present value.

Table 3.10. Summary of probabilistic NPV Monte Carlo simulations for Modification Kits Implementation Scenarios with uniformly-distributed variables.

		Launch Mod Kits (Best Ops Guess); Uniformly-Distributed Simulations									
		Effective % of CTBs Wired (As determined by concentration of transactions)									
		25%		**33%**		**50%**		**75%**		**100%**	
		Mean NPV / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**	**Mean NPV** / **NPV Std. Dev.**	**% NPV > 0**
Actual % CTBs Wired	**25%**	$ (4,988,621.31)	42%	$ 12,821,233.09	69%	$ 49,421,093.27	93%	$ 104,029,505.01	99%	x	x
		$ 22,676,233.15		$ 26,003,258.04		$ 36,047,800.42		$ 50,905,190.09		x	
	33%	x	x	$ (5,532,217.58)	43%	$ 30,897,496.47	80%	$ 84,776,041.88	96%	x	x
		x		$ 29,958,138.37		$ 38,032,301.86		$ 53,581,297.13		x	
	50%	x	x	x	x	$ (5,665,293.53)	45%	$ 48,579,152.53	80%	x	x
		x		x		$ 45,112,372.95		$ 57,779,083.53		x	
	100%	x	x	x	x	x	x	x	x	$ (8,724,286.54)	48%
		x		x		x		x		$ 90,427,908.60	

However, Table 3.9 also shows that a modest concentration of inventory transactions – say, 75% occurring in the 50% of the bags that are wired[34] - results in a positive mean NPV of approximately $46.8 million with standard deviation of $48.7 million, and 84% of the 3500 trials resulting in a positive net present value.

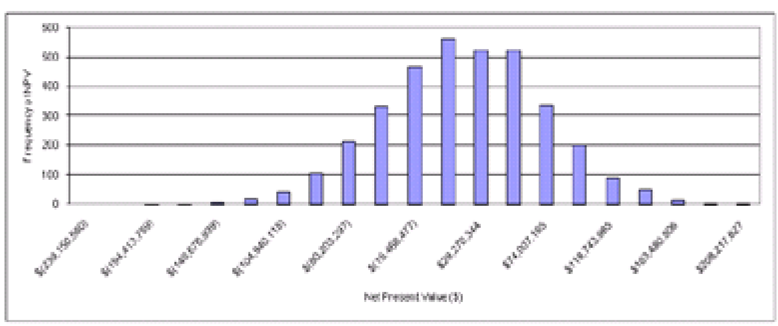

Figure 3.2. Histogram of NPV Monte Carlo simulation (normally-distributed variables) for Modification Kits Scenario with 100% of CTBs wired.

[34] This corresponds to an "Effective % of CTBs Wired" of 75% and "Actual % of CTBs Wired" of 50%.

Table 3.10, mirrors this trend, with values similar to that of Table 3.9. Figure 3.2 shows the results, in histogram form, from the Monte Carlo simulation in which 100% of the CTBs are wired (Scenario 10 in Table 3.1); Figure 3.3 is the cumulative distribution function from the same simulation. Together, these charts illustrate the likelihood of various net present value outcomes.

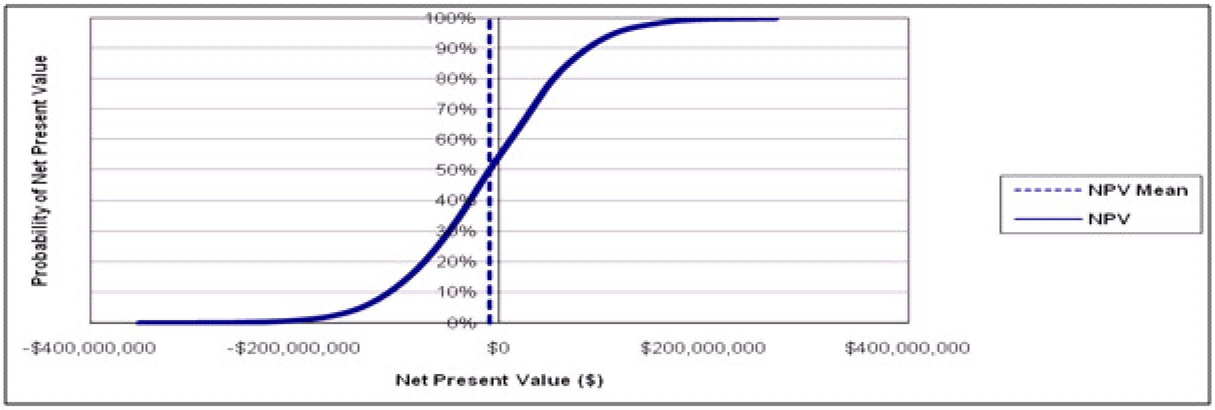

Figure 3.3. Cumulative distribution function of NPV Monte Carlo simulation (normally-distributed variables) for Modification Kits Scenario with 100% of CTBs wired.

Phase-In Implementation Scenario

Results for the Phase-In Implementation Scenario - including the discrete, Monte Carlo normal distribution, and Monte Carlo uniform distribution simulations - are summarized below in Tables 3.11 and 3.12.

Table 3.11. Summary of probabilistic NPV Monte Carlo simulations for Phase-In Implementation Scenarios with normally-distributed variables.

		Phase-In Scenario; Normally-Distributed Simulations									
		Effective % of CTBs Wired (As determined by concentration of transactions)									
		25%		33%		50%		75%		100%	
		Mean NPV / NPV Std. Dev.	% NPV > 0	Mean NPV / NPV Std. Dev.	% NPV > 0	Mean NPV / NPV Std. Dev.	% NPV > 0	Mean NPV / NPV Std. Dev.	% NPV > 0	Mean NPV / NPV Std. Dev.	% NPV > 0
Actual % CTBs Wired	25%	$ (6,803,432.98)	34%	$ 8,526,870.05	65%	$ 39,060,356.68	94%	$ 86,303,025.26	100%	x	x
		$ 17,293,129.40		$ 20,443,046.05		$ 27,083,874.80		$ 40,116,646.79		x	
	33%	x	x	$ (12,184,765.89)	27%	$ 15,862,124.01	71%	$ 59,748,265.88	95%	x	x
		x		$ 21,276,299.13		$ 27,922,136.07		$ 39,447,300.13		x	
	50%	x	x	x	x	$ (27,191,810.76)	16%	$ 8,441,303.93	58%	x	x
		x		x		$ 27,675,522.37		$ 36,598,948.98		x	
	100%	x	x	x	x	x	x	x	x	$ (63,249,144.44)	3%
		x		x		x		x		$ 39,062,347.03	

In Table 3.11, one finds that probabilistic simulations reinforce the early indication of the discrete case; namely, that the Phase-In Implementation Scenario – as modeled in this work – is inferior to the implementation of the system via Modification Kits. Also illustrated in Table 3.11 is the trend of greater value given a concentration of transactions in a subset of CTBs and the decision to equip only those bags. Table 3.12, below, shows that the same patterns hold true when the random Monte Carlo variables are generated with uniform distributions.

Table 3.12. Summary of probabilistic NPV Monte Carlo Simulation for Phase-In Implementation Scenarios with uniformly-distributed variables.

		Phase-In Scenario; Uniformly-Distributed Simulations									
		Effective % of CTBs Wired (As determined by concentration of transactions)									
		25%		33%		50%		75%		100%	
		Mean NPV NPV Std. Dev.	% NPV > 0	Mean NPV NPV Std. Dev.	% NPV > 0	Mean NPV NPV Std. Dev.	% NPV > 0	Mean NPV NPV Std. Dev.	% NPV > 0	Mean NPV NPV Std. Dev.	% NPV > 0
Actual % CTBs Wired	25%	$ (7,134,901.40)	35%	$ 8,086,651.91	63%	$ 39,310,272.91	90%	$ 86,606,752.87	99%	x	x
		$ 19,473,842.81		$ 23,177,847.08		$ 31,333,709.97		$ 45,682,016.38		x	
	33%	x	x	$ (12,751,239.25)	30%	$ 15,601,043.64	68%	$ 58,380,146.70	92%	x	x
		x		$ 24,174,562.15		$ 30,746,874.57		$ 44,146,080.07		x	
	50%	x	x	x	x	$ (27,684,820.39)	19%	$ 7,094,984.10	55%	x	x
		x		x		$ 32,320,417.50		$ 42,237,607.25		x	
	100%	x	x	x	x	x	x	x	x	$ (60,099,581.86)	6%
		x		x		x		x		$ 45,296,435.62	

Conclusions

Based on the best information available and the assumptions detailed above, this analysis suggests that the RAMSES system is likely to yield positive net present value if implemented in International Space Station CTBs via modification kits installed by the crew, provided that inventory transactions are at least somewhat concentrated within the subset of CTBs in which the hardware is installed. As one would expect, the more the inventory transactions are concentrated into a smaller percentage of CTBs, the greater the value delivered by the system (assuming that installation is limited to those bags).

This result is intuitive, given that the largest costs associated with the system are directly tied to the quantity of CTBs that are equipped with RFID. The three largest costs are the opportunity costs for the launch volume (~42% of the total cost for the discrete analysis of the Modification Kits Implementation Scenario), launch mass (~33%)[35], and crew time to install the modification kits[36] (~21%). On the benefits side of the equation, the single term that dominates is the value of the crew time saved that would otherwise be spent on routine updates of the Inventory Management System[37]. The value of this saved time accounts for roughly 94% of the total benefits accrued by the system in the discrete analysis of the Modification Kits Implementation Scenario.

Also intuitive is the fact that the Modification Kits Implementation Scenario performs better than the Phase-In Scenario. This is a result of the fact that the modification kits are modeled as being launched and installed in FY 2009, and thus from FY 2010 – FY 2016 the full, recurring benefits of the system are able to add up and overcome the initial one-time costs associated with launch and installation. If the lifetime of the Station were to be extended – as was recommended in a recent MIT study [29] and favored by the Presidentially-appointed Augustine Commission [30] - the recurring benefits would further accumulate; the net present value of all scenarios would

[35] A discussion of the decision to count the cost of both mass AND volume is included in the next, final section of this chapter.
[36] Or to transfer contents to wired CTBs that are being phased-in.
[37] The official NASA timeline devotes 20 minutes per day per crewmember to this activity, which – for a crew of six – amounts to 730 hours per year (1).

increase, and it would become much more probable that the Phase-In Scenario would result in positive net present value.

It should be understood that at least one potential cost and one potential benefit were not included in this study, as they could not be quantified rationally. The cost of integrating the RAMSES system into the International Space Station's existing Inventory Management System is extremely uncertain. IMS currently has the capability to receive and process input from external devices, such as barcode readers, but the difficulty involved in scaling this capability, or supplementing the current system with a separate RAMSES software module that simply feeds updates to the current, is quite uncertain. There is also a political challenge associated with such modifications, namely to obtain approval from all International Partners.

The unquantifiable benefits of this work include the enhancement of both crew safety and mission assurance. The ability to locate any item (or at least many items and/or any critical items, depending on the extent of implementation) at a moment's notice can potentially make the difference between life and death in an emergency situation. Furthermore, real-time knowledge of stock levels of supplies such as food, medicine, and spare parts can prevent unexpected stock-outs that could jeopardize crew health and/or Station reliability.

Clearly, NASA decision-makers and their international counterparts must carefully weigh all of these factors in their evaluation of this technology. There are substantial benefits associated with this proposed application of RAMSES, but also significant costs, challenges, and uncertainties. Alternative hardware architectures - such as tagging all items but installing a fixed network of RFID readers and antennas rather than wiring and insulating all CTBs – might provide even greater value by requiring less mass and volume, if challenges such as location triangulation and EMF interference could be overcome. At the very least, this analysis demonstrates that an RFID inventory management system merits serious consideration for future human spaceflight applications.

LIMITATIONS, CONSERVATIVE ASSUMPTIONS, AND FUTURE WORK

A brief final note seems appropriate regarding the limitations of this analysis and the conservative assumptions used herein. Two pieces of information proved particularly difficult to locate for this project. First, it was very difficult to obtain any financial information relating to the contributions of the Russian Space Agency to ISS. No reference at all could be found regarding their ISS Operations budget, yet their level of activity in this area is second only to that of NASA. Furthermore, the only cost data that could be obtained for the Progress M1 spacecraft was that NASA's most recent contract with RSA specifies a price of $40.1 million per metric ton for cargo delivery via Progress [31]. This figure was multiplied by the maximum capacity of the vehicle (2230 kg) [32] to arrive at an approximate variable recurring cost per mission of $89.4 million. This figure was then multiplied by the number of missions scheduled (4 in 2008 and 2009) [26] for an annual cargo flight contribution of $360 million (paid in part by NASA). Based on this, a figure of $550 million was used as the total annual ISS Operations financial contribution of RSA, but there is no solid basis for this figure. The actual value could be substantially higher, which would result in a positive increase of net present value for all implementations of the system.[38] It seems unlikely that the actual figure is lower than that used here. Thus, the assumption made to compensate for this limitation was conservative in nature.

Second, the ISS Operations budgets for all other International Partners (IPs) proved almost as elusive. However, in the ISS Program's document entitled *Cost Analysis Requirements Description* (CARD), the negotiated percentage contributions of each Partner to the Common Systems Operations (CSO) Costs[39] - "the costs to operate the ISS" - were detailed [33]. NASA agreed to pay 76.6% of CSO Costs, JAXA - 12.8%, ESA - 8.3%, and CSA – 2.3%. (As for the Russians, the document only said that "Russian support of their segment and their crewmembers would equal their CSO Costs obligations [34].") Unfortunately, no dollar amount was provided for any one of these percent contributions. Thus, to calculate each Partner's budget, it was assumed that NASA's ISS Operations budget – as detailed in the agency's FY 2009 Budget Request [35] - represented NASA's 76.6% share of the CSO Costs. This assumption, in turn, allowed calculation of the total CSO Costs, including the specific dollar contributions of all other Partners. However, these figures seem likely to be overly conservative; the NASA ISS Operations budget does not account for the costs associated with launching crew members via the Space Shuttle, and therefore the actual value of NASA's percentage contribution to CSO Costs might be moderately to significantly higher than simply the NASA ISS Operations budget line (of roughly $2.06 billion in FY 2009 [35]). Again, if the actual combined ISS Operations costs are greater than those values used in this analysis, the consequence would be an increased value for crew time, and thus an increased likelihood of greater positive net present value for the RAMSES system – in either implementation scenario. Therefore, as with the previous assumption, this one is also conservative.

Finally, there could be a legitimate debate regarding the method used in this paper to calculate the opportunity cost of cargo launch volume and mass. One could argue that this method imposes a "double" cost for any launched object, by dividing the total (non-recurring) vehicle cost among its payload mass capacity to calculate a "$ / lb" figure, and then again dividing the total vehicle cost among its pressurized payload volumetric capacity to calculate a "$ / m^3" figure. Each launched object is then charged for both. Some might suggest that the vehicle cost should instead be split between the two characteristics, or distributed between them in some other manner, because the utilized method would charge twice the actual cost of the vehicle if applied to a single launch that is at maximum capacity for both mass and volume. However, this method was the most conservative of the many options available, and thus places the greatest value upon minimizing hardware volume and mass. It protects against scenarios in which opportunity costs might be under-represented; for example, if a vehicle is packed to its volumetric capacity with large but low-mass objects, a different accounting method could result in the net opportunity cost of launching those objects coming to only a portion of the actual non-recurring cost of the vehicle. The conservative approach adopted here is consistent with that utilized throughout this work.

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[38] An increase of the total annual ISS Operations Cost results in an increase in the calculated value of crew time, according to the method used here; this, in turn, increases the Net Present Value of the overall system because crew time makes up ~94% of the system's recurring benefits and only 21% of the (non-recurring) cost.

[39] Include costs to transport and return crew and common supplies ("crew members, food, clothing, air, water, health care items, propellant," etc), and ground operations costs ("integrated planning, mission control, integrated L&M, POIC (Payload Operations & Integration Control?), and launch processing for CSO Cost cargo") [33].

There exist numerous opportunities for future work that builds upon this analysis. It would certainly be useful to re-examine the results if one or both of the missing pieces of data, mentioned above, could be obtained. Also, it would be interesting to apply this analysis to other proposed automated inventory management architectures for ISS, and very straightforward to do so. Additional work could also be done to clarify the technical and political integration challenges associated with implementing such a system on Station, particularly those related to the Inventory Management System. This last is perhaps the most significant cost uncertainty inherent in this work. On the benefits side, however, one could also attempt to quantify the amount and value of enhanced crew safety and mission assurance that would result from this kind of asset management system. As another direction for future research, this cost benefit analysis framework could also possibly be extended and applied more generally to other types of technology infusion problems. Finally, there also is room for continued technology development work in regards to both the RAMSES system itself, and the more general passive RFID tag environment, especially in regards to improving detection rates for tags affixed to or near metal and/or liquid objects.

CHAPTER 4: PERFORMANCE TESTING OF THE RAMSES CTB PROTOTYPE IN NORMAL- AND REDUCED-GRAVITY

INTRODUCTION

In Chapter 3, we quantitatively examined the value proposition of the RAMSES RFID-based inventory management system. A model was constructed that quantified the costs and benefits of deploying RAMSES "smart CTBs" aboard the International Space Station, and also calculated the probabilistic Net Present Value for the investment using Monte Carlo simulations. The analysis determined that, for ISS, the key to realizing a positive return-on-investment was to implement the system in a targeted manner that would capture the greatest number of inventory transactions with the smallest deployment of the RFID system, while also minimizing system volume and mass and maximizing performance [36].

This chapter describes the results and implications of extensive testing of the RAMSES CTB prototype. Experiments were conducted to characterize the system's performance over a wide range of operational scenarios, both on the ground and in a reduced gravity environment (~.02 g). The reduced gravity testing in particular raised the system TRL to Level 6 and provided crucial information regarding the bounds of system performance for MIT/Aurora/NASA evaluation efforts and Phase III development work. In addition to gravity, other experimental variables included the material composition of the simulated cargo items (paper, metal, or liquid), the number of cargo items within the container at one time, the orientation of the cargo items, and the method by which the passive RFID tags were attached to the cargo items.

EXPERIMENTAL SETUPS

Three different types of experiments were conducted in this effort to characterize the performance of the RAMSES Double-CTB prototype, as summarized in Table 4.1. Experiment 1, conducted in standard laboratory conditions at 1g, tested the system performance while the reader was in "snapshot" mode – that is, it conducted a single scan of the contents of the CTB, and reported those tags detected by that single scan. This first set of tests also examined the effect of tag orientation on reader accuracy, consisted of the largest number of trials, and used only Alien™ Gen II passive RFID tags (both as packaged and with supplemental foam backings). Experiment 2 was ground-based, consisting of 1g replications of the test sequence that would subsequently be repeated in micro-gravity. These 1g simulations were conducted with the RFID reader scanning the CTB contents continuously for 20 seconds, and then reporting the total number of unique tags that had been detected during that period. All test articles had been placed into the CTB in "random" orientations, and both Alien and Omni-ID™ tags were tested. Finally, Experiment 3 replicated the test matrix of Experiment 2, but in micro-gravity conditions aboard the ZeroG Corporation / NASA Reduced Gravity Office 727 parabolic flight campaign of August 2009. Across all three tests, the common variables included both the number and material-type of the RFID-tagged test articles that were placed into the CTB.

Table 4.1. Variables across experiment setups.

	Gravity	Reader Mode	Tag Types	Tag Orientations (to CTB base)
Experiment 1	1g	"Snapshot"	Alien	3(parallel, perpendicular, random)
Experiment 2	1g	20s continuous	Alien, Omni-ID	1 (random)
Experiment 3	~.02 g	20s continuous	Alien, Omni-ID	1 (random)

Results

Experiment 1

As described above, Experiment 1 was conducted in standard laboratory conditions at 1g, and included the most comprehensive set of tests with five trials conducted for each unique combination of variables. Four different independent variables were examined over the course of the experiment, including:

- **Material** of tagged objects (paper, liquid, metal, and an equal mix of the three)
- **Number** of tagged objects within the CTB at one time (6, 12, 18, 24, 30)
- **Orientation** of tagged objects within the CTB (tags parallel, perpendicular, or randomly oriented with respect to the floor panel of the CTB)
- **Tag mounting** scheme (directly on the object, directly on a plastic bag that contained the object, or mounted on a roughly ¼-inch-thick piece of foam which was then attached to a plastic bag containing the object.

Figures 4.1, 4.2, and 4.3 illustrate the various test articles and tag mounting schemes.

Figure 4.1. Tissue, bag & foam tag mount.

Figure 4.2 Metal can, direct mount.

Figure 4.3. Water, bag mount.

The macro-level results from this testing were several, and are illustrated in Figures 4.4-4.8. First, all other factors equal, paper objects were the easiest to read, and in most cases metals were easier to read than liquids. Second, in general, as the number of tagged objects in the CTB increased, the percentage of objects that were "missed" by the reader also increased. Third, among the three tag orientations tested, randomized (chaotic) orientations of the tags within the CTB generally produced the highest read accuracy. (This result prompted the idea of characterizing performance in reduced-gravity.) Fourth, the impact of the tag mounting scheme varied significantly with the material of the test article. For paper, each of the three tag mounting approaches worked equally well. However, for metals and liquids, only the foam and bag mounting approach (as shown in Figure 4.1) generated read rates of 75% or better (18 test articles or less, random orientation). Directly-tagged metal objects (Figure 4.2) did not read at all, and metals and liquids with tags mounted directly on the plastic bags (Figure 4.3) saw read rates of between 25-70%, depending on the material and number of objects.

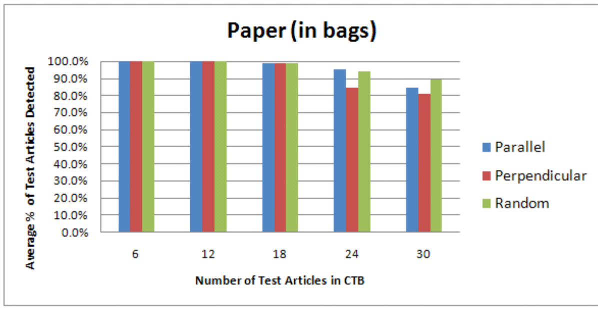

Figure 4.4. Experiment 1 results for paper objects.

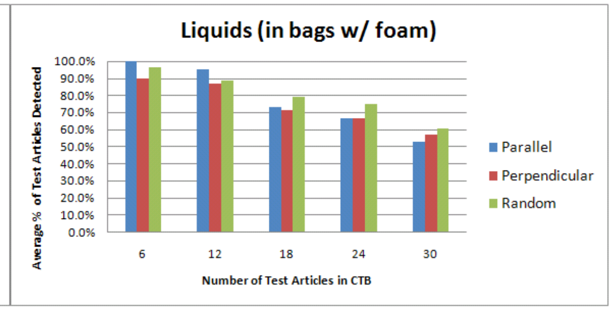

Figure 4.5. Experiment 1 results for liquid objects.

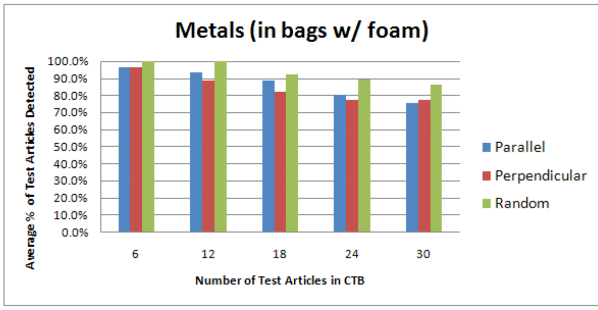

Figure 4.6. Experiment 1 results for metal objects.

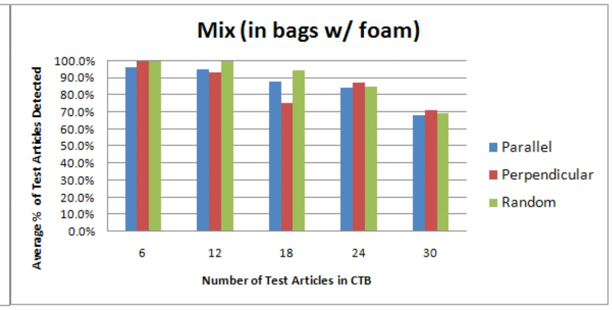

Figure 4.7. Experiment 1 results, equal mix of objects.

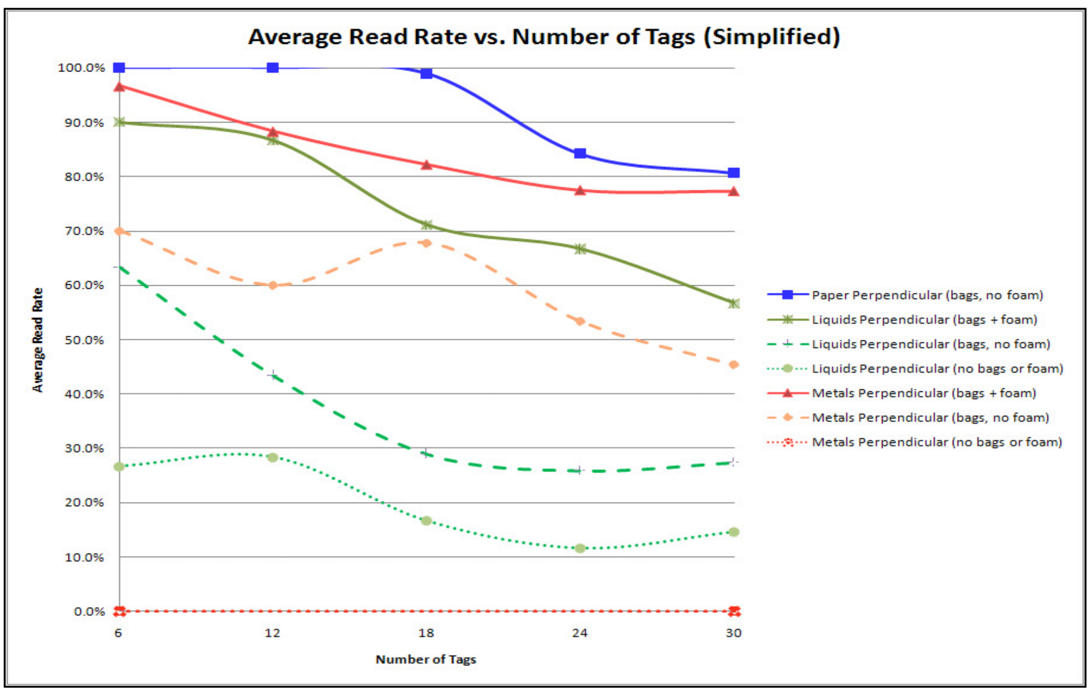

Figure 4.8. Experiment 1 results show the effects of material, number of tags, and tag mounting strategy (noted in parentheses) on the average percentage of tags that were read correctly. All results displayed in this chart were for trials in which cargo items were loaded into the CTB such that the RFID tags were oriented perpendicular to the bottom of the CTB.

Experiments 2 and 3

Experiment 2 was a ground-truth baseline for the reduced-gravity Experiment 3. The chief limitation of these experiments was the modest amount of data points that could be collected; only 64 trials were able to be performed across the two flight days (compared to more than 350 that were performed in Experiment 1). Consequently, Experiments 2 and 3 were designed to focus on the most important variables –material type (of the test articles), number, and RFID tag type. All tests were conducted in the "random" orientation. Still, given the limited number of trials available, only one data point for each unique set of variables was obtained. The other significant difference between these experiments (particularly Experiment 2) and Experiment 1 is that, as summarized in Table 3.1, Experiments 2 and 3 were conducted with the RFID reader in "continuous read mode" for 20 seconds and reporting the total number of unique tags detected during that period, whereas for Experiment 1 the reader was in "snapshot" mode and reported only those tags detected during a single scan of the CTB.

Figure 4.9. Omni-ID Prox™ tag on metal can.

The "RFID tag type" variable used for these experiments merits further explanation. This variable differs from the "tag mounting scheme" category from Experiment 1. The "tag mounting scheme" variable in Experiment 1 examined three different mounting schemes for attaching the Alien tags to test articles[40], whereas the "RFID tag type" variable in Experiments 2 and 3 refers to the use of Alien tags (with the best-performing mounting schemes from Experiment 1) vs. Omni-ID Prox™ tags. It must be emphasized that the comparison was not directly-mounted Alien tags vs. directly-mounted Omni tags, but rather Alien tags mounted on plastic bags for tissue (scheme shown in Figure 4.3) and on foam and plastic bags for metals and liquids (scheme shown in Figure 4.1) vs. Omni tags that were directly mounted upon the test articles (Figure 4.9). The choice to use the best-performing Alien tag mounting scheme for Experiments 2 and 3 was made because the primary goal of these experiments was to characterize the effects of reduced gravity on system performance. Therefore, all non-essential performance-drags (such as directly mounting the Alien tags to metal test articles, which resulted in zero reads in Experiment 1, as shown in Figure 4.8), were eliminated to the extent possible. By comparison, the Omni tags were not available to the team during Experiment 1, and so no optimum mounting scheme had been developed for them; additionally, the manufacturer's website claimed that the tags were "ideal for inventory control or location monitoring for high-value metal or liquid assets" and had "ultimate reliability and accuracy on any material in any environment" [37]. If these claims were accurate, the team wanted to demonstrate them with the RAMSES system; the tiny form-factor of the Omni tags (Figure 4.9) renders them significantly more appealing for real-world use than any of the foam-based tag mounting schemes developed for the Alien tests of Experiment 1.

[40] The three tag mounting schemes tested were: 1) tag mounted directly on the test article, 2) tag mounted on a plastic bag that contains the test article, and 3) tag mounted on a piece of foam attached to a plastic bag that contains the test article.

The results of Experiments 2 and 3, including comparisons to Experiment 1[41], are detailed in Figures 4.10-4.13. In general, it can be seen that, for the same type of tag and material, the RAMSES system performs no worse - and often performs better - in reduced gravity than it does in 1g. Figures 4.10 and 4.11 particularly illustrate this; in both, the trials with Alien tags in reduced gravity always yielded at least as high a read rate as the Alien tags in 1g, and the same for the Omni tags. The results in Figure 4.12, from the trials for liquid objects, are a bit more mixed; while the Omni tags were always better in reduced gravity than in 1g, the Alien tags at low concentrations actually tested better in 1g. However, given the sharp reversal and divergence of this pattern at the higher concentrations (24 and 30 test articles in the CTB), as well as the general trend seen across all reduced gravity tests, it seems likely that this low-concentration result is attributable to fluctuations in system performance over a very small sample size. Figure 4.13, showing the results for the tests using an equal mix of each type of material (ie, 6 items = 2 metal, 2 liquid, and 2 paper), illustrates results similar to those of Figure 4.12. Again, there is a clear and consistent divergence in the performance of the Omni tags, with the reduced gravity tests always out-performing the 1g equivalents. Also, while there are mixed results for the Alien tags at low concentrations (of test articles in the CTB), as the number of items increase beyond 30 there is a clear and lasting divergence, where the tests conducted in reduced gravity always read a higher percentage of the tags than the corresponding tests in 1g.

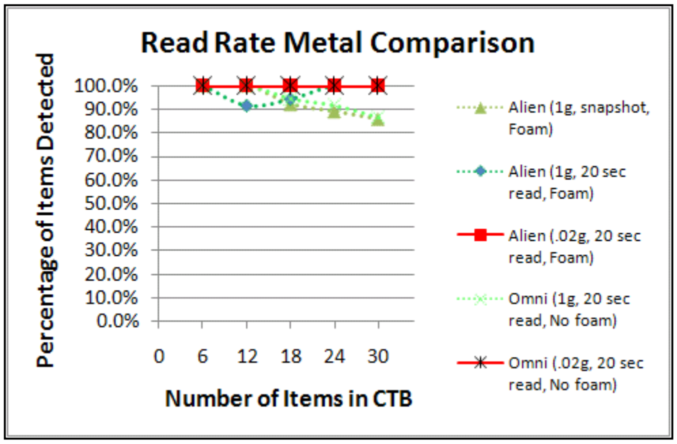

Figure 4.10. Metal objects, effect of reduced gravity.

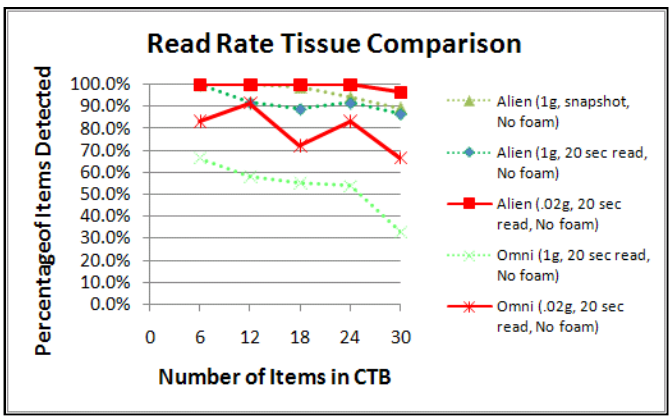

Figure 4.11. Paper objects, effect of reduced gravity

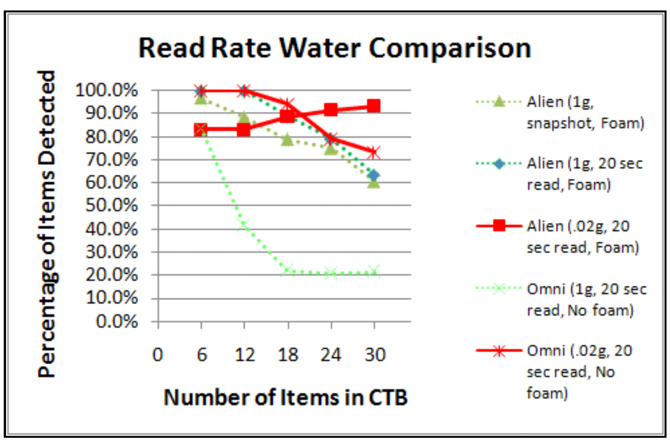

Figure 4.12. Liquid objects, effect of reduced gravity.

[41] Experiment 1 results in Figures 10-13 are labeled "Alien (1g, snapshot, ….)".

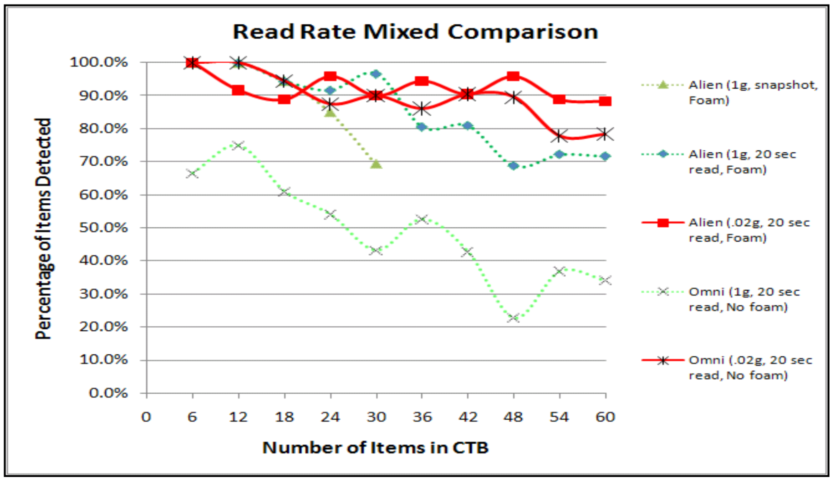

Figure 4.13. Equal mix of objects, effect of reduced gravity.

It bears repeating that the data points shown in Figures 4.10-4.13, for Experiments 2 and 3, each represent a single test. Again, this lack of repetition was due to the very limited number of tests that could be conducted in reduced gravity conditions. In the team's opinion, the experiments that were conducted represented the best compromise between breadth of variables examined and reliability of results. Establishing qualitative trends across the key variables, such as were described above, was deemed a more valuable use of the limited reduced gravity tests than collecting a limited number (2-4) of repeated points for a reduced set of variables.

CONCLUSION

These experiments revealed several important characteristics of the performance of the RAMSES Cargo Transfer Bag prototype. A number of these characteristics are relevant for any potential implementations of a next-generation RAMSES system on the International Space Station, within the Constellation Program, or even here on Earth. First, read rates of 100% for at least 30 metallic objects[42] were obtained in reduced gravity conditions using the RAMSES system and commercial-off-the-shelf (COTS) tags (Omni-ID Prox™) with a small form-factor. This is an important milestone for any potential NASA implementation, as metallic cargo items – such as many spare parts – are quite common in human spaceflight environments. A Gen II passive tag with a small form factor, that is effective on metallic objects, is a key requirement. Secondly, these experiments demonstrated that at least one Gen II COTS passive tag, the Alien Squiggle®, could achieve read rates of 96% or greater in reduced gravity conditions in the RAMSES prototype when mounted on paper (ie, non-metallic and non-liquid) objects. Such non-metallic / non-liquid items represent perhaps the greatest percentage of cargo items that NASA would like to tag and track with RFID in the immediate future.

Such results reinforce the conclusions established in Chapter 3. The finding of that chapter was that a narrow, targeted implementation of the RAMSES system would very likely generate a significant positive return-on-investment for NASA. The read rate accuracy of the RAMSES

[42] At least for those metallic objects tested here, empty aluminum soda cans.

system was one of the key uncertain input parameters that went into that calculation, and we see now that the values used in the calculation were quite conservative. In the Monte Carlo simulations, the system accuracy value was allowed to range between 80% and 100%,[43] but as just demonstrated, in a realistic environment RAMSES can actually achieve read rate accuracies of 100% for metal and at least 96% and 93% for paper and liquid objects, respectively. Therefore, the true probability of the system generating a significant positive return-on-investment is perhaps even greater than outlined in Chapter 3.

[43] For the Monte Carlo scenarios which varied the inputs assuming a normal distribution of each input, the system accuracy variable was set to mean = 90% and standard deviation = 5%. Therefore, a 95% system accuracy value would fall in the upper quartile of that range. See Tables C.7 and C.8, in Appendix C, for complete details.

CHAPTER 5: IMPORTANT FACTORS FOR SUCCESSFUL INFUSION OF SMALL-BUSINESS (SBIR/STTR) TECHNOLOGY INTO NASA'S MAINSTREAM INNOVATION SYSTEM

INTRODUCTION

In Chapter 2, we learned about NASA's current asset tracking system for the International Space Station. In Chapters 3 and 4, we examined the financial and technical performance of the RAMSES system, an RFID-based solution that proposes to automate a significant portion of the ISS inventory management process. This technology, funded largely via NASA's Small Business Innovation Research (SBIR) / Small Business Technology Transfer (STTR) program, appears to have significant merit.

However, at least one serious challenge remains. RAMSES must cross the so-called "valley of death" [15] for new technologies, and make the transition from the end of its STTR Phase II contract to infusion into the mainstream NASA innovation system. This chapter compares RAMSES and several other SBIR/STTR projects in an initial attempt to better understand how SBIR/STTR projects are or are not infused at NASA. Particular attention will be paid to identifying those informal processes and non-technical characteristics which may be common to successfully-infused projects.

DATA COLLECTION

Six case studies of SBIR/STTR projects are described in this chapter. Of these six, two of the projects (Cases B and C) are from a single company, while the other four are each from a different company. Companies were asked to participate via an open invitation emailed to a consortium of New England-area small-business technology firms. Interviews were arranged with every company with NASA SBIR/STTR experience that responded. At each company, interviews were conducted with at least one senior manager and at least one senior member of the technical staff with SBIR/STTR experience.

In addition to these company-based case studies, 22 interviews were conducted with NASA engineers and managers at three field centers (Goddard, JPL, and JSC) and Headquarters. These interviews were part of a larger research effort to understand NASA's macro-level innovation architecture, and the processes and programs by which an idea is developed and perhaps eventually incorporated into a flight project. COTRs (Contracting Officer's Technical Representative) and technologists, SBIR/STTR program staff, and technology development leadership were interviewed at the theme, center, mission directorate, and agency levels.

All interviews in this effort were of a semi-structured format. In the interviews of SBIR/STTR company employees and NASA COTRs and technologists, the initial question for each interview subject was to describe a "successful" SBIR/STTR project that s/he had worked on, as well as an "unsuccessful" such project.[44] As the interview progressed, follow-up questions were asked as

[44] The definition of "successful" and "unsuccessful" was initially left to the discretion of the interview subject. If requested, however, the interviewer defined "successful" as the project's final product having been "infused" or "taken up" by NASA. It is important to note that not all interview subjects were able to give examples of each.

necessary (and as time allowed) in several key areas to supplement the initial description of the project provided by the interview subject. These follow-up questions examined the technology of the project, the characteristics of the company's project team, the characteristics of the NASA COTR (Contracting Officer's Technical Representative), the characteristics of the company itself, the nature of the communication between the company team and NASA, the internal dynamics of NASA itself at the time, and the origin of the project idea and proposal.

For the foundational case, Case A, interviews were conducted with both the small business team and the NASA COTR. The other five cases were based upon interviews with either the company or the NASA COTR; the missing side could not be reached in time for inclusion in this effort. The six cases contained in this work were not chosen to be representative of the many kinds of SBIR/STTR companies and projects, but rather as an initial dataset to identify potential factors which later work could examine in greater detail.

METHODOLOGY

The six case studies to be described in this paper will be examined across several intervals of the SBIR/STTR lifecycle. The lifecycle is divided as shown in Figure 5.1.

Figure 5.1. SBIR/STTR Project Lifecycle

In Figure 5.1, the various stages of an SBIR/STTR project are split into six different segments:

1) Initial brainstorming. (How did the company come up with the idea for the proposal?)
2) Experience of SBIR/STTR Phase I.
3) Transition from Phase I to Phase II.
4) Experience of SBIR/STTR Phase II.
5) Post-Phase II funding from NASA.
6) Infusion into NASA flight project.

Most SBIR/STTR projects will not survive to see all six stages, but many that are proven to be technically feasible will proceed to the end of Stage 4. After Stage 4, there is no longer any Congressionally-mandated funding (indicated by the dotted box) set aside for the SBIR/STTR programs. One of the key questions to be answered is how a technically-successful project is able to make the leap from Stage 4 to Stages 5 & 6.

DATA

SBIR/STTR Projects – Case A

Case A is the first and most comprehensive of the six SBIR/STTR projects that will be described in this paper. Case A is unique among the six because it is the only one to both attract Post-

SBIR Phase II funding (Stage 5 in Figure 5.1) and be chosen for a current flight-project (Stage 6). Furthermore, for Case A, key players from both the small business and NASA were interviewed.

The story of Case A begins with failure. Company A is a very small business (less than 10 full-time employees) that was spun out from a larger corporation in the early part of this decade to focus exclusively on a specific technology. When the commercial market for this technology started to tighten up, the company reluctantly[45] turned to the SBIR program to supplement its other business. The company had early success with the DOD SBIR program, winning several Phase I awards and every Phase II which they applied for. However, this same success did not translate to its proposals to NASA; during this same time period, the company submitted three "blind"[46] proposals to NASA for Phase I SBIRs, and all three were rejected.

For roughly 15 years prior to this, a certain NASA technologist and several government colleagues had been working on this technology for space-based remote sensing applications. The technologist's efforts were initially funded by a $50,000 award from his Center's "Director's Discretionary Fund" (DDF), and then ramped up substantially by two subsequent grants (each 3 years in duration) from the relevant theme technology office in NASA's Science Mission Directorate.

Then, by coincidence, the CEO of Company A and this key NASA technologist met while both were attending a technical review meeting for the particular technology in question. The CEO and the NASA technologist talked about their work on this technology, and the technologist encouraged the CEO to submit another Phase I proposal to NASA. As it happened, the relevant NASA Phase I SBIR sub-topic manager was a colleague of the technologist and worked just down the hall, so the technologist told the sub-topic manager to expect the proposal and requested the opportunity to help review it. When the proposal came in, the technologist and his colleague were very pleased with its quality, and recommended it for SBIR funding. The technologist also volunteered to serve as the COTR (Contracting Officer's Technical Representative, the key NASA point-of-contact and technical advisor for the contract – an <u>unfunded</u> responsibility) if the project were to be receive an SBIR award. (All of this occurred in what is denoted "Stage 1" of Figure 5.1, above.)

The project was indeed chosen for a Phase I SBIR award, and the technologist was appointed the COTR. Company A performed very well throughout Phase I (Stage 2 of Figure 5.1). The company and technologist communicated regularly over the duration of the six-month contract, and the company thoroughly impressed the technologist by delivering working hardware by the end of the contract.[47]

Company A then submitted a proposal (Stage 3 in Figure 5.1) for a SBIR Phase II award. The technologist strongly supported this proposal, and recommended it for funding. Much to his

[45] The company was reluctant to do business with the government because it did not want to deal with the changes to its accounting system required by government cost-plus-fee contracts. It vastly preferred firm-fixed contracts.
[46] A "blind" proposal is defined as one that was submitted without any prior consultation (pre-solicitation release) with interested NASA parties.
[47] Typically a Phase I contract is simply a "feasibility study" which results in little or no hardware.

surprise, however, the proposal was not funded. The technologist vigorously protested to the relevant NASA SBIR theme office, which happened to be located at his Center at the time. The technologist felt that Company A deserved such advocacy given the outstanding work which they had done during Phase I, and he felt that the technology held significant potential for NASA applications related to his own efforts. The technologist convinced the relevant SBIR program official that it was a mistake to reject Company A's Phase II proposal, and the official was motivated enough to dig up some SBIR money that had gone unclaimed in order to continue the project for 18 months. Roughly simultaneous to this protest, the NASA technologist also submitted a proposal to his Center's IRAD (Internal Research and Development) fund, but this proposal was not successful.

Nevertheless, the cobbled-together SBIR funding kept the project going, and as it continued to progress, an opportunity for true infusion began to develop. About this time, technical difficulties arose in the construction of a satellite of critical national importance. The NASA technologist working with Company A felt that the company's technology could help this mission overcome its challenges.

As the 18 months of quasi-Phase II funding came to an end, the NASA technologist again applied for IRAD funding to keep the work going, and this time he was successful. Thus, the project reached Stage 5 on the lifecycle diagram of Figure 5.1. Simultaneously, the technologist had also been talking with the flight project mentioned above, and finally convinced them to adopt Company A's technology.[48] Consequently, after only a few months of IRAD funding, the technology was picked up and robustly funded by the flight project (Stage 6 of Figure 5.1). Asked to comment as to the SBIR's impact on the flight project's decision to adopt the technology, the NASA technologist stated, "Having a commercial company building these, actually, I think, added some level of credibility for it to be considered for a flight mission."

SBIR/STTR Projects – Case B

Case B is the first of two cases which deal with the same small business, denoted here at Company BC. This company, for the entirety of Cases B and the majority of Case C, was a space technology development firm with less than 15 employees. During the final year of its Phase II work in Case C, the company was acquired by a larger aerospace-focused small business with a few hundred employees. Before this acquisition, a majority of Company BC's revenue came from NASA SBIR and STTR awards.

Case B bears some striking similarities to Case A. Described by the CEO of Company BC as the 'best NASA SBIR that we've done', the Case B project started with a conversation about NASA's needs and Company BC's technological expertise and ideas. The CEO of Company BC spent several years at NASA before his time at BC – including experience in the mission area relevant to the eventual proposal - and the conversation was with a former colleague who had become a manager in one of NASA's science technology development offices. During the conversation, the CEO and the NASA manager came up with an idea for an SBIR based upon a product that BC had previously developed. Both company and customer were excited about the

[48] This task was no doubt made considerably easier by the political pressure to accomplish the particular science objective.

proposal, and the company subsequently proposed and won a Phase I award. Thus, again, the brainstorming in Stage 1 successfully transitioned to Stage 2.

This Phase I SBIR was assigned to the NASA science technology office which the CEO's former colleague managed, and this manager assigned as COTR a technologist who was "the" person at NASA working on exactly the technical area at which the SBIR was targeted. The CEO described this COTR as being very interested and engaged throughout the project. Never did more than 2 weeks pass between contact. The CEO reported that this helped the team to establish very firm and specific requirements early in the process. It also gave the company some additional motivation, the CEO reported. He knew that the COTR was going to thoroughly read all the reports that were generated, to the extent of calling to ask about a specific point on a particular page if he (the COTR) didn't understand or agree with it. More importantly, the CEO stated that what gets Company BC's team "out of bed" is the chance to "fly things in space", and so having such clear interest from NASA was a significant motivation for them.

Phase I was very successful, and a Phase II contract was awarded. The CEO reported that his team "cranked out a lot more than $600k" worth of work for the Phase II, due to the convergence of factors described above. The NASA COTR and his manager were pleased with the work, and at the end of Phase II, their office funded a "Phase III" effort[49], equivalent to Stage 5 from Figure 5.1. For the Phase III, Company BC and their NASA counterparts flew the project on NASA's reduced-gravity aircraft to collect data in that gravity regime. This too was successful. However, because the relevant flight project was delayed significantly into the future, no further work has been done with the project's results. The CEO is confident that, given the positive results, Company BC will be a "major player" when it comes time to develop the relevant system for the flight project. Still, given the likely 10-15 year wait, Stage 6 infusion remains an open question.

SBIR/STTR Projects – Case C

Case C deals with another SBIR project that was conducted by Company BC. This project is an interesting contrast with Case B, because although it builds on exactly the same previously-developed core technology as the Case B project, a few key characteristics of the project were different – as was the final result.

In Case C, Company BC submitted a "blind" Phase I proposal to a NASA SBIR solicitation that looked promising. There was no prior contact between the company and any relevant individuals at NASA. The proposal was accepted for a Phase I contract, but Company BC felt the assigned COTR was not a good match. The company believed that the project was only loosely related to the COTR's daily responsibilities, and that he did not seem to be intellectually interested in the technology that Company BC was developing. Furthermore, at the time, NASA was still defining its own relevant plans in the technology area of the SBIR proposal. Thus, the company found it very difficult to formulate fixed requirements in a timely fashion, and felt very much on its own. The CEO felt that the COTR's view was that Company BC could do whatever it wanted; the CEO believed that the COTR did not have strong input or feelings about the end

[49] A "Phase III" award refers to a contract which an SBIR-funding agency can award as a follow-on to a Phase II, and which is exempt from the normal full and open competition requirements of the Federal Acquisition Regulations.

results generated by the SBIR work. Also, the CEO noted that his team began to write the bare minimum for the required status reports, because unlike in Case B, they saw no evidence that this COTR was carefully reading nor interested in the reports.

Company BC was able to win a Phase II award for the project, but problems continued. Eventually, due to technical troubles and a continued lack of engagement from any customer, the CEO down-scoped the project in order to prevent Company BC from taking a loss on the endeavor.

SBIR/STTR Projects – Case D

Case D illustrates the importance of maintaining technical continuity and buy-in for a particular project on the small business side of a project. The project was conducted by Company D, a firm of approximately 15 people that is focused on the development of the specific technology of Case D.

Stage 1 of Case D proceeded much the same as with Cases A and B. The key technical person for Company D met a relevant NASA technologist through prior relationships with the technologist's colleagues. This technical person and his company had done several previous SBIRs related to the technology in question, and he and the NASA technologist brainstormed some SBIR ideas based on the technologist's/NASA's needs and the company's interests and capabilities. The NASA technologist described his role as describing NASA's needs to the Company D representative, reporting that he told the representative, "If it did this, we could really use it, and here's the real application for it, so you gotta worry about this, this, this, and this. So I did not tell them how to build it or anything like that, it was more like a […] what do we want to do with it, and what does it have to be able to do for us to really use it." In the end, the two came up with a project that would combine, in a new way useful to NASA, several different things that the company had previously developed.

When Company D's Phase I SBIR proposal was accepted, the NASA technologist volunteered to serve as the COTR. He was keenly interested in the project, which was very relevant to his NASA responsibilities. As he explained, what the company had proposed to do was something that his NASA lab did not have the capability – nor the funding - to do: "We [were] definitely leveraging their ability." Furthermore, he noted, "we [NASA] want to be able to buy these later anyway."

The Phase I SBIR went well, and the NASA technologist endorsed the company's proposal for a Phase II contract. This was awarded, and the technologist reported that things proceeded well until the key Company D employee, who had been working on the project originally, took a job somewhere else. After that, the technologist reported that he didn't hear from the company very often, and that they did not meet his expectations for finishing the Phase II. The NASA technologist reported that he had not seen a Phase III proposal from the company, and would probably not recommend them for such a proposal if it were to be forthcoming.

SBIR/STTR Projects – Case E

In Case E, we briefly explore another example of a project with some promise which was doomed by problems on the company side. This project was proposed by Company E, a brandnew start-up company that included only a few employees. Furthermore, when this company started work on the Phase I contract, the company was not particularly close to being able to fabricate anything.

Still, the Phase I proposal was awarded, and the same NASA technologist as for Case D was tapped to serve as COTR. According to the technologist, this company did some good work early in Phase I, but then proceeded to "self-destruct". The Phase I project was not completed, and no Phase II was awarded or proposed. The company folded.

SBIR/STTR Projects – RAMSES

The final case study is RAMSES. This project was a Small-Business Technology Transfer (STTR) partnership between Aurora Flight Sciences (formerly Payload Sciences, Inc.) and the Massachusetts Institute of Technology. This case is an interesting contrast to the first three cases – the other cases which were not disrupted by internal company dynamics - because it shares characteristics with both the "successes" (Cases A and B) and the "failure" (Case C). RAMSES managed a small Stage 5 effort (August 2009) after the end of Phase II (May 2009), but has not achieved actual infusion into NASA (Stage 6).

RAMSES was a blind proposal, with no prior relevant contact between the company and NASA, and was accepted for a Phase I STTR.[50] The NASA employee who was assigned as the COTR for the project was the person who had written the original solicitation. The team's accepted project was not what the COTR had originally intended, but the team reported that he willingly engaged with the project nonetheless.

Phase I went well and a Phase II proposal was accepted. However, about this time, the NASA COTR left the agency for a different job. Also, as Phase II began, the RAMSES team started to narrow the focus of the project to the NASA application for which the technology seemed most suited. This application was asset tracking and management for human spaceflight applications, especially the International Space Station and Constellation programs. Unfortunately, this area of application was the expertise of a different NASA Center than the one out of which the project was managed.

The technical work proceeded well, but maintaining NASA engagement proved quite difficult. The "replacement" COTR was not a member of the mainstream NASA technical staff. Despite repeated attempts, the Phase II project team was unable to establish contact with the COTR until the end of the Phase II contract, when it was time to arrange delivery of the hardware and final report. Thus, the primary NASA customer contact that occurred during the two-year Phase II was not with or through the COTR, but rather the project team's own network of contacts at NASA. Through these contacts, intermittent customer outreach was achieved. Part of this outreach included an in-depth study of the relevant NASA program by the project team, in order to understand the customer's needs and guide the development of the prototype as well as the business case.

[50] Note that the primary difference between an SBIR and STTR is that the latter must include a University partner in addition to the small business. The length of the Phase I award is also 12 months instead of 6, and the program may be somewhat less competitive, but for all intents and purposes it is very similar to the SBIR program.

The project team successfully completed the Phase II work, and through its own efforts found an opportunity and wrote a proposal to conduct tests under a special program for a parabolic flight campaign with NASA's Reduced Gravity Office. This proposal was successful (thus a quasi-Stage 5 was achieved), as was the parabolic flight test campaign, and these combined results generated moderate interest from relevant NASA technical and programmatic officials. In October of 2009, discussions occurred with ISS Program officials regarding a potential flight opportunity and the production of additional prototype systems. However, these discussions had not resulted in a clear infusion opportunity as of the publication of this thesis.

COMPARATIVE ANALYSIS OF SBIR/STTR CASE STUDIES

Table 5.1, on the next page, summarizes the six different cases, according to the lifecycle stages of Figure 5.1. From Table 5.1 and the preceding discussion of the cases, three important themes emerge with respect to successful SBIR infusion.

First, these cases seem to indicate the *value of pre-proposal (Stage 1) contact between the companies and potential NASA customers*. It is important to point out that three of the six cases studied here were Phase I proposals that were accepted with no such prior consultation; therefore, this work does not suggest that any kind of "favoritism" exists with respect to Phase I awards. However, it does appear that such pre-proposal contact can play a significant role in facilitating the company's understanding of NASA's potential needs and requirements; Company A, despite enjoying very high SBIR proposal acceptance rates with the DOD, went 0 for 3 on its first three proposals to NASA. Furthermore, pre-proposal contact seems to promote the matching of a project with an interested and relevant COTR. Of the six cases described in this paper, all three (Cases A, B, and E) which featured pre-proposal contact between the company and NASA were matched with strong COTRs, while all three which did not feature such pre-proposal contact were matched with COTRs who the companies felt had less relevant experience and/or less interest in the particular project. It is worth noting that the DOD explicitly encourages such pre-proposal contact in its SBIR program[51] [14].

Relevant to this last point, a second theme that can be noted from these cases is the *importance of a relevant, interested, and engaged COTR*. In Cases A, B, and E, the companies felt that there was good alignment between the COTR's work, experience, and interests and the particular SBIR project. One can argue that two of these three Cases (specifically A and B) represent the most successful projects of the six, as both were taken up by the relevant NASA organizations for additional, post-Phase II development (Stages 5 and 6). While impossible to say with certainty, the third, Case D, seemed to be moving in that same direction until a disruption occurred at the project company.

[51] DOD provides a post-solicitation-release period for questions and answers as well as a specific point-of-contact for each topic, with all questions and answers posted publicly.

Table 5.1: Comparison of six SBIR/STTR projects.

	Case A	Case B	Case C	Case D	Case E	RAMSES
Stage 1	3 blind Phase I's rejected, Brainstormed w/ NASA technologist (eventual COTR) prior to successful Phase I application	Brainstormed w/ NASA technology manager prior to Phase I application. Add-on to previous work.	Blind proposal, Add-on to previous work.	Brainstormed w/ NASA technologist, eventual COTR, prior to Phase I application. Add-on to previous work.	Blind proposal	Blind proposal, no prior experience with technology.
Stage 2	Matched with very interested and relevant COTR, excellent results.	Matched with very interested and relevant COTR, very clear requirements provided, good results.	Matched with uninterested and irrelevant COTR, no req's provided, host program in flux.	Matched w/ very interested and relevant COTR, clear requirements and good results.	Company did good work, but was a start-up that folded.	Project not exactly what COTR intended, but he is interested and semi- engaged. Good results.
Stage 3	Phase II denied; COTR appeals and wins partial funding	Phase II awarded	Phase II awarded	Phase II awarded	None.	Phase II awarded
Stage 4	"Phase II" goes well, same COTR	Phase II goes well, produced "much more than $600k" of work	Phase II struggles, and team eventually de-scopes to avoid cost overruns. COTR remains disengaged.	Good progress until key technical person left company, then sharp fall-off.	None.	COTR leaves, is replaced by non-technical staff member who is busy and not in contact. Wrong center for this work. Technology works well.
Stage 5	COTR secures IRAD funds, but only needed for very short time	COTR / Technology manager provide Phase III funding for parabolic flight tests	None.	None.	N/A	NASA FAST program, and team, funds parabolic flight tests.
Stage 6	Technology chosen to help technically-troubled, priority flight project	Technology on shelf until the relevant flight project gets approved (5 to 10+ yrs)	N/A	N/A	N/A	Large effort by team to contact relevant people at relevant center for potential Phase III. As of publication, no clear success.

The COTRs supported these projects in multiple ways. They provided information about NASA's needs and requirements, they provided technical guidance and suggestions, motivation, and when necessary they served as an internal-to-NASA advocate for the technology. The technology developed in Case A in particular – which was eventually infused into a priority flight project - would have been shelved with the rejection of the SBIR Phase II application if the COTR had not intervened and persistently advocated for continued funding. Critically, the COTRs for Cases A and B also identified and secured Stage 5 (post-SBIR Phase II) funding; and for Case A also indentified the Stage 6 (flight-project infusion) opportunity, which Company A could not have done on its own. This support for the post-Phase II infusion process was notably lacking for RAMSES; if not for the RAMSES team's pre-existing set of NASA contacts, the project would likely have been shelved from lack of internal NASA visibility at the end of Phase II. Finally, anecdotes suggest that an active and interested COTR can also serve as a motivator to help ensure that NASA receives maximum value from its awards. For example, the CEO of Company BC noted that Company BC put much more effort into the reports for Case B than they did for Case C and produced "much more than $600k" worth of work for that Phase II, simply because they knew that the Case B NASA COTR would carefully read each report and follow-up, whereas the Case C COTR did not.

A third theme that emerges from this work is the *importance of a Stage 6 infusion opportunity*, in order for any project to be fully integrated into the mainstream NASA technology system. In Case A, the SBIR project was very fortunate to have a flight mission opportunity come along just as the technology was finishing its development period. The existence of this opportunity stands in contrast to the experiences of Case B and RAMSES, the only other projects to successfully move into Stage 5. For Case B, the fundamental challenge to continued work is that the flight mission for which the technology is designed will not occur for another 10-15 years. Thus, while NASA gained valuable information for future design work from the SBIR effort, it may not be able to leverage the expertise of the Company BC team when it comes time to actually build the flight system. In 10 to 15 years, people at Company BC may have moved to other jobs at other companies, and/or simply not remember many of the details of the completed work.

Of course, there must also be funding to support the final development and testing necessary for such infusion. For RAMSES, unlike Case B, a relevant flight mission (the International Space Station) does currently exists. Unfortunately, there seems to be very little NASA funding available to support the final development and certification of the technology in order to fly it.

Furthermore, for these cases it also seems important that such a flight project has some incentive for providing a flight opportunity to a new technology. Case A was fortunate that its particular flight mission was one of national importance and had a critical need for the technology developed in Case A. The criticality of the need appeared to be an incentive for the adoption of the new technology. By comparison, the relevant flight mission for RAMSES does not have as critical a need for the technology RAMSES provides, and thus is under no special pressure to provide a flight opportunity for it.

CONCLUSION

This chapter described the comparative analysis of six different NASA SBIR/STTR projects – including the RAMSES project - in an attempt to identify any non-technical characteristics and/or informal processes which might be important for successful technology infusion. Within this set of cases, three key observations emerged. First, in all cases for which there were pre-proposal conversations between potential companies and NASA customers, the accepted SBIR project was subsequently well-matched to an interested and relevant NASA COTR. Second, in these cases, an interested and relevant COTR appeared to be an important advocate, motivator and enabler of infusion. Third, the existence of an opportunity for infusion – and the funding and incentives to support it – was important to achieving final "spin-in" to a flight project for the cases examined here.

These observations may explain at least some of the difficulty that the RAMSES team has experienced when it comes to achieving NASA infusion. The RAMSES project was a blind proposal without any pre-submission conversations between the team and NASA, and although NASA chose to accept the proposal and fund it, the team's idea was not what the assigned COTR had imagined when he proposed the sub-topic. Thus, the project was not well-aligned with the daily responsibilities of the COTR or the competencies of his NASA center. This mis-alignment was exacerbated when the original COTR left NASA after Phase I, and another NASA employee outside the relevant technical area had to assume the role. The RAMSES team drew on its own network of contacts at NASA in order to gain some level of insight into NASA's likely desires and requirements for the system. However, in light of the cases examined in this chapter, the lack of an appropriate internal "champion" from the start - who could have guided development from Day 1, advocated for the system within NASA, and identified the funding sources required to support final infusion – may be a significant reason that RAMSES has not yet escaped the "valley of death" and passed into the mainstream NASA innovation system. The current budget pressure and programmatic uncertainty in NASA's human spaceflight program is likely also a contributing factor.

Finally, it should be noted that the questions explored in this chapter seem particularly ripe for further study. A more comprehensive effort to study a larger number and more diverse selection of companies and technologies could help to develop a truly comprehensive understanding of those non-technical characteristics and informal processes which help enable infusion of SBIR/STTR (and other) innovations at NASA.

Chapter 6: Conclusions

This thesis has employed engineering, management, and social science methodologies to analyze the prospects for the RAMSES technology development project to achieve infusion into the mainstream NASA innovation system. As Figure 6.1 and this work illustrates, infusion is only possible when the Technical, Financial, and Program/Policy elements of a project all come together. The questions which this thesis developed and pursued as it investigated those elements for RAMSES can be utilized by any other development project that wishes to determine its prospects for infusion. Admittedly, achieving infusion is a very complex process, and neither this nor any other analysis conducted *a priori* will be able to perfectly predict the final outcome. However, a careful and holistic consideration of all three key factors – Technical, Financial and Program/Policy – should serve as a useful guide.

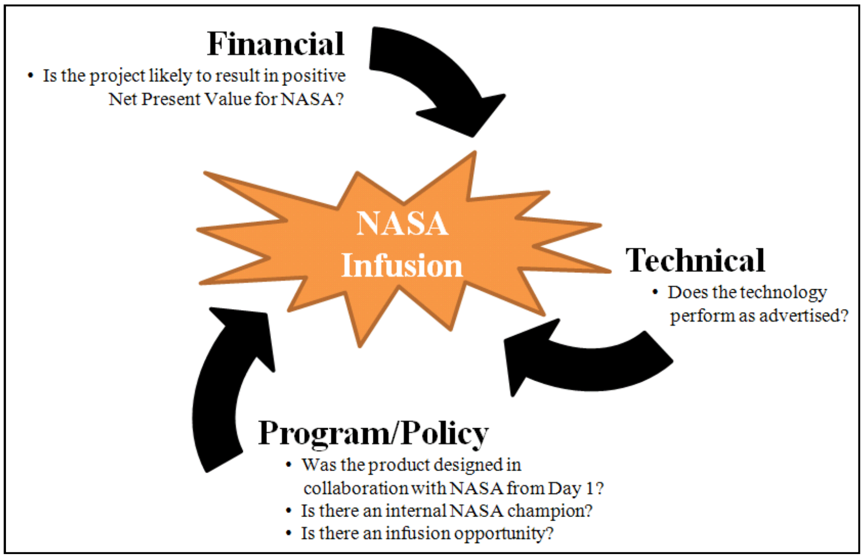

Figure 6.1 SBIR/STTR Infusion depends upon Technical, Financial, and Program/Policy Factors.

Summary

The Massachusetts Institute of Technology and Aurora Flight Sciences developed RAMSES (Rule-based analytic Asset Management for Space Exploration System) via NASA Small-Business Technology Transfer (STTR) Phase I and Phase II contracts. RAMSES leverages Generation II passive Radio Frequency Identification (RFID) technology to address the challenges of efficient asset tracking and management in human spaceflight applications. In particular, RAMSES aims to automate the tracking the tens of thousands of small, portable cargo assets that are currently stored onboard the International Space Station (ISS).

Chapter 2 detailed NASA's current inventory tracking and management processes and systems for the International Space Station Program. Maintaining an accurate record of the quantities and locations of the tens of thousands of assets is a significant task, scheduled to consume some 4.5 person-months of crew time every year at ISS Assembly Complete.

Chapter 3 applied this information to calculate the probabilistic Net Present Value (NPV) of the application of RAMSES system to the International Space Station's Cargo Transfer Bags (CTBs). Quantities such as crew time, cargo launch volume, and cargo launch mass were monetized to allow comparison of costs and benefits, and several different implementation scenarios were evaluated. The analysis found that the application is likely to have significant positive value for NASA when inventory transactions are concentrated in a subset of the total cargo transfer bag population, and/or if ISS Operations are continued into 2018/2020. It is demonstrated that a modest concentration of inventory transactions – for example, 75% of transactions occurring in the 50% of the bags that are RFID equipped - results in a positive mean NPV of approximately $46.8 million, and an 84% probability of a positive NPV, even with a ISS retirement date of 2015. A sensitivity analysis revealed that the volume, mass, and accuracy of the RAMSES system have a significant impact upon the estimated NPV. Of course, this model could not capture all the relevant parameters, particularly the costs for International Partner approval and software integration, nor the benefits of improved crew safety and mission assurance.

Given this promising financial analysis, Chapter 4 examined the technical performance of a prototype RAMSES Cargo Transfer Bag (CTB) in both standard and reduced gravity conditions. In addition to gravity, other experimental variables included the material of the test articles (paper, metal, or liquid) and the number of articles within the container at one time. As predicted by ground test results, the best read rates were observed during reduced-gravity flight, with metals detected at 100% accuracy, paper at 96%, and water at roughly 93%, when tests were conducted with 30 articles of the material in the "smart CTB" and optimum RFID-tagging strategies. These results, while still at the prototype level, demonstrate that the system holds significant potential for future flight implementation on ISS and future human spaceflight outposts.

Finally, in Chapter 5 a comparative analysis of RAMSES and five other NASA Small-Business Innovation Research (SBIR) / Small-Business Technology Transfer (STTR) projects was conducted. This analysis worked to identify any non-technical characteristics and/or informal processes that might be unique to SBIR/STTR projects that are successfully infused into the mainstream NASA innovation system, and thus important to that transition. For the cases studied herein, it seems that three characteristics were important: pre-proposal knowledge exchanges between companies and NASA, strong matching of a project with a relevant NASA COTR, and the availability of an actual infusion opportunity. (Of course, these characteristics are only relevant if the small business executes the project and the technology proves feasible and financially viable.) The RAMSES project lacked the first two of these characteristics, and has yet to connect with an opportunity for final infusion.

CONCLUSIONS AND RECOMMENDATIONS

When the results of these three analyses – Technical, Financial, and Program/Policy - are brought together, a clear and complete picture begins to emerge. In the case of RAMSES, the financial models show that an ISS implementation of RAMSES would likely be worth the required initial investment of financial resources and allocations of launch volume and mass, particularly if ISS is extended until 2018 or 2020. The technical evaluation reveals that the "smart CTB" prototype actually functions best in a reduced-gravity environment, and can attain accuracy rates in excess of 93% with simulated cargo items. Therefore, the RAMSES system is certainly a reasonable candidate for infusion into the mainstream NASA innovation system.

However, we see that a strong technical and financial case is not necessarily sufficient; if certain other non-technical characteristics and informal processes are not also aligned, a technology can easily fall victim to the "valley of death" and wither away on a forgotten lab bench gathering dust. For RAMSES to avoid this fate, an infusion opportunity must be identified and/or created, whether by a change in agency funding and/or priorities, a late-coming NASA "champion", and/or the persistence and diligence of the project team itself.

As for NASA itself, the agency should continue to work towards ensuring that all SBIR/STTR projects are given the support and connections necessary to enable infusion, when the technology and small-business partner successfully meet expectations. Certainly, NASA faces tremendous budgetary and scheduling pressure in all of its work, and is currently in a state of considerable uncertainty regarding its future direction in human spaceflight. Nevertheless, the agency must continue to struggle with the paradox that - particularly when technology development funding is so scarce – NASA cannot afford to let promising ideas go to waste. Further efforts to facilitate pre-proposal contacts, appropriate matching of projects with COTRs, and wide communication of infusion opportunities might all serve as low-cost, high-reward initiatives in this struggle.

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List of Appendices

Appendix A: Acronyms

Acronym	Phrase or name
COTR	Contracting Officer’s Technical Representative
CTB	Cargo Transfer Bag
CTBE	Cargo Transfer Bag Equivalent
HI-UV	High-Impact Uncertain Variable
IMS	Inventory Management System
JSC	NASA Johnson Space Center
KSC	NASA Kennedy Space Center
ISS	International Space Station
NASA	National Aeronautics and Space Administration
NPV	Net Present Value
NRC	National Research Council
RFID	Radio Frequency Identification
US	United States

Appendix B: Additional Figures and Diagrams from Chapter 2

CTB Dimensions & Drawings

Table B.1 - CTB Dimensions (Hart, *Internal Cargo)*

CTB	Approximate Size (external dimensions) L x W x H [cm (in.)]
SEG33111836 Half (1/2x)	24.8 cm x 42.5 cm x 23.5 cm (9 .75 ” x 16.75” x 9.25”)
SEG33111837/838 Single (1x)	50.2 cm x 42.5 cm x 24.8 cm (19.75” x 16.75” x 9.75”)
SEG33111839 Double (2x)	50.2 cm x 42.5 cm x 50.2 cm (19.75” x 16.75” x 19.75”)
SEG33111840 Triple (3x)	74.9 cm x 42.5 cm x 50.2 cm (29.5” x 16.75” x 19.75”)

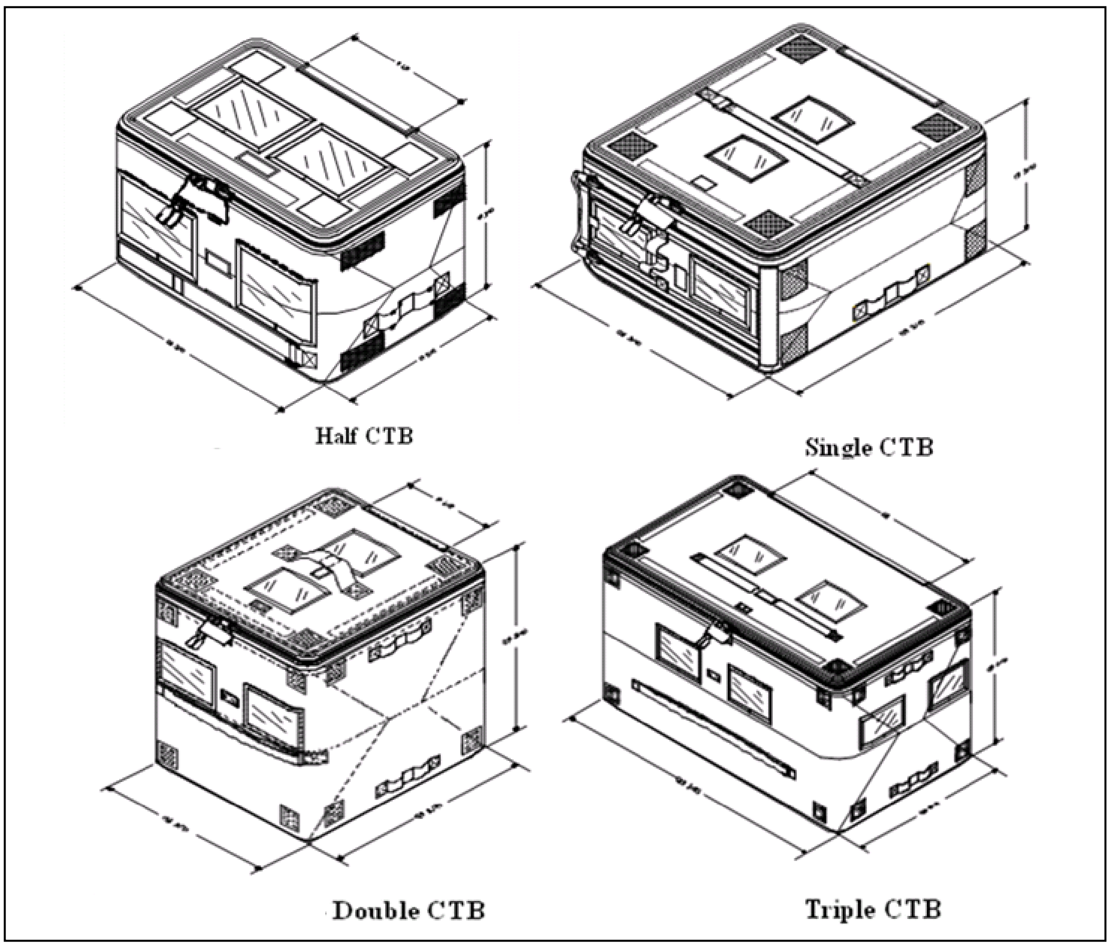


Figure B.1. NASA Cargo Transfer Bag Diagrams (Image Credit: NASA)

<u>**TRASH RECEPTACLES**</u>

(Image Credit: Hart, NASA; from *Internal Cargo Integration Overview* presentation)

**Figure B.2 – EDV buckets (left) and lid (right)
(Liquid Biological Waste Container)**

Figure B.3 – KTO (Solid Biological Waste Container)

Figure B.4 – Food Waste Bag

Figure B.5 – KBO-M (Common trash receptacle)

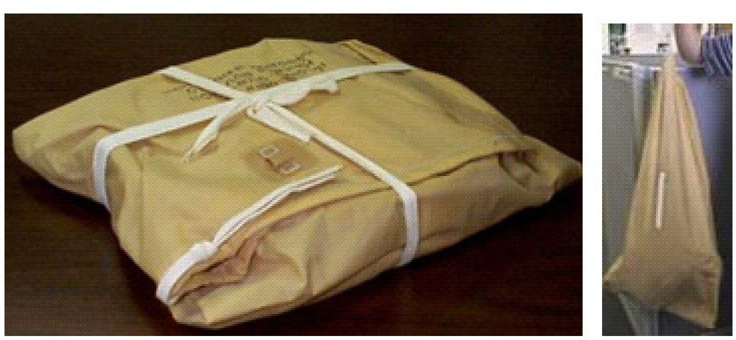
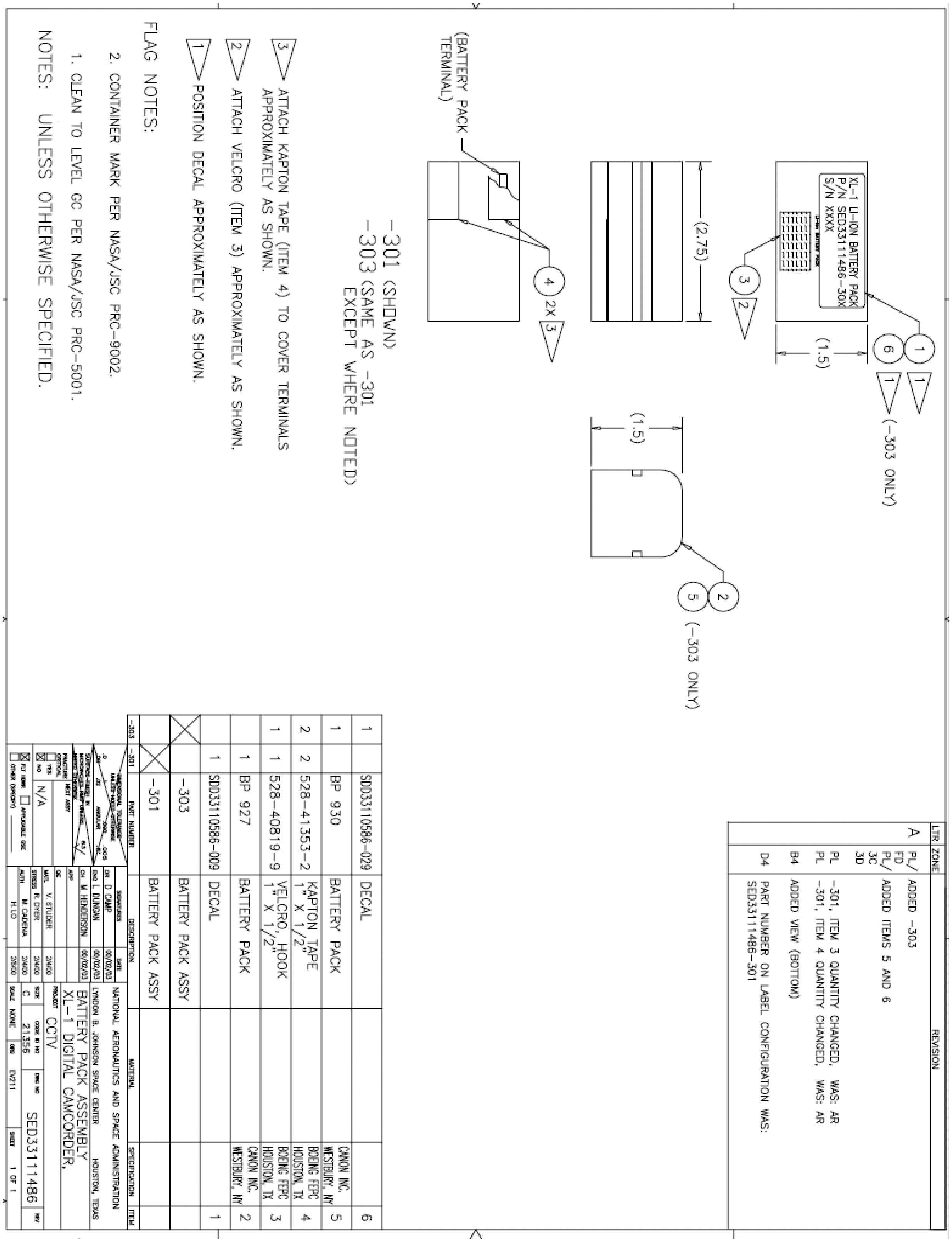


Figure B.6 – Rubber-Lined Bag

RF SAW SDTO BATTERY (IMAGE CREDIT: NASA)



APPENDIX C: ADDITIONAL CALCULATIONS AND RESULTS FROM CHAPTER 3.

DETAILED CALCULATIONS OF VALUE OF CREW TIME

Table C.1 – Estimated Annual ISS Operations Budget (Common Systems Operations Cost)

ISS Ops Budget:	2009	2010-2016
US	$ 2,060,200,000	$ 2,261,175,000
RSA	$ 550,000,000	$ 550,000,000
JAXA	$ 344,263,185	$ 377,846,475
ESA	$ 223,233,159	$ 245,009,824
CSA	$ 61,859,791	$ 67,894,289
Total:	***$ 3,239,556,136***	***$ 3,501,925,587***

Sample Calculations:
US = $2,060,200,000 [35]
*Common Systems Operations Costs = (1/.766) * US = $2,689,556,136* [33]
*JAXA = (.128)*Common Systems Operations Costs = $344,263,185* [33]
*ESA = (.083)*Common Systems Operations Costs =$223,233,159* [33]
*CSA = (.023)*Common Systems Operations Costs = $61,859,791* [33]

Note:
1) Value of $550 million for RSA is an educated guess; see detailed explanation above in Limitations, Conservative Assumptions, and Future Work, Chapter 3.

Table C.2 – Calculation of Value of Crew Time

Year:	2009	2010-2016
# Crew:	3	6
Avg. ISS Budget:	$ 3,239,556,135.77	$ 3,501,925,587.47
# "Active" Crew Hours in a Day:	16	16
$ / 'Active' Crew Hr:	$ 184,906.17	$ 99,940.80

Note:
1) "# Active Crew Hours in a Day" is per crew member.
2) See discussion regarding definition of "Active" Crew Hours in "Value" of Crew Time, Chapter 3.

DETAILED CALCULATIONS OF VALUE OF CARGO LAUNCH VOLUME AND CARGO LAUNCH MASS

Table C.3 – Data Related to Cargo/Logistics Flights

	Cost Per Mission (Variable Recurring Cost)	Max Cargo Capacity (kg)	Max Dry Cargo Mass (kg)	Available Dry Cargo Volume (m^3)	Cost Per Cubic Meter of Dry Cargo Volume
Shuttle MPLM	$ 400,000,000	9400	9400	31	$ 12,903,225.81
Progress M1	$ 89,423,000	2230	1800	6.6	$ 13,548,939.39
ATV	$ 500,000,000	7667	5500	13.8	$ 36,231,884.06
HTV	$ 500,000,000	6000	5500	14	$ 35,714,285.71

Calculations:
Cost Per Cubic Meter of Dry Cargo Volume = Cost Per Mission / Available Dry Cargo Volume

Notes:
1) Assumed for Shuttle MPLM missions that all cargo capacity is located in MPLM.
2) All "Cost Per Mission" values should be regarded as rough approximations.

References:
Cost Per Mission [38].

Table C.4 - Launch Schedule and Calculation of \$ / lb and \$ / m^3.

	2008	2009	2010	2011	2012	2013	2014	2015
Shuttle	3	3	1					
Shuttle MPLM	1	2	0					
Orion	0	0	0	0	0	0	0	1
Soyuz TMA	2	3	4	4	4	4	3	2
Progress M1	4	4	3	3	3	3	3	3
ATV	1	1	0	1	1	1		
HTV	0	1	1	1	1	1	1	1
Max Cargo Mass (kg)	25987	41387	12690	20357	20357	20357	12690	12690
Available Dry Cargo Volume (m^3)	71.2	116.2	33.8	47.6	47.6	47.6	33.8	33.8
Net Variable Recurring Costs	$ 1,417,692,000	$ 2,397,692,000	$ 1,088,269,000	$ 1,588,269,000	$ 1,588,269,000	$ 1,588,269,000	$ 1,008,269,000	$ 928,269,000
Avg. Cost Per Cubic Meter Dry Cargo Volume	$ 19,911,404.49	$ 20,634,182.44	$ 32,197,307.69	$ 33,366,995.80	$ 33,366,995.80	$ 33,366,995.80	$ 29,830,443.79	$ 27,463,579.88
Avg. Cost Per Kilogram of Cargo Mass *(kg)*	$ 54,553.89	$ 57,933.46	$ 85,758.00	$ 78,020.78	$ 78,020.78	$ 78,020.78	$ 79,453.82	$ 73,149.65
Avg. Cost Per Pound of Cargo Mass *(lbs)*	$ 24,745.48	$ 26,278.44	$ 38,899.57	$ 35,389.99	$ 35,389.99	$ 35,389.99	$ 36,040.02	$ 33,180.46
		Average Cost Per lb of Cargo			**Average Cost Per m^3 of Cargo**			
		$/lb ('09-'10)	$ 25,511.96		**$ / m^3 ('09-'10)**	$ 20,272,793.47		
		$/lb ('11-'16)	$ 35,715.01		**$ / m^3 ('11-'16)**	$ 31,598,719.79		

Max Cargo - Shuttle MPLM [38], Progress M1 [32], ATV [39], HTV [40].
Max Dry Cargo Mass - Shuttle MPLM [38], Progress M1 [32], ATV [39], HTV [38].
Available Dry Cargo Volume – Shuttle MPLM [38], Progress M1 [41], ATV [42], HTV [38].

SENSITIVITY ANALYSIS RESULTS FOR PHASE-IN IMPLEMENTATION SCENARIO

Table C.5 – Sensitivity Analysis of Input Variables for Discrete Simulations of Phase-In Implementation Scenario. In comparison to the sensitivities for the Mod-Kits Scenario in Table 3.8, the magnitudes of the sensitivities here are much smaller, but the pattern of relative magnitudes remains fairly similar. The reason for the difference in magnitudes is that, for Table 3.8, the reference NPV (NPV_0) was ~$+14 million, while for the Phase-In table it was ~$-65 million, and so for the Phase-In scenario for the same changes in input variables and similar magnitude changes in output values, you get smaller % changes in output.

Sensitivity Analysis Summary	
Variable	*Avg. Norm. % Diff.*
Number of Crew (2010+)	0.07
Avg. ISS Budget (2009-2016)	1.15
# "Active" Crew Hours Per Day:	1.31
RFID System Weight	0.76
Cost to Modify 1 CTB for RFID System (add pockets, insulation, install electronics):	0.02
Discount Rate	0.02
Time Required for Astronauts to Transfer CTB Contents to new CTB (hr):	0.27
Number of CTBs Contents Transferred to Wired CTB On-Orbit:	0.00
# of CTBs On-Orbit that are to be wired:	2.22
Wired CTB Launch Rate (% of Total ISS Population):	0.71
% On-orbit IMS Entries that could be Automated by Wired CTBs:	1.51
% of CTB Transactions Accurately Detected by System:	1.56
Percent of Standard CTB volume required for RFID System:	1.37
Volume Cost ($ / m^3):	0.32

DETAILS OF DISCRETE SIMULATION FOR MODIFICATION KITS IMPLEMENTATION SCENARIO

Table C.6 - General Inputs (Part I).

Year:	**2009**	**2010-2016**
# Crew:	3	6
Avg. ISS Budget:	$ 3,239,556,135.77	$ 3,501,925,587.47
# "Active" Crew Hours in a Day:	16	16
$ / 'Active' Crew Hr:	$ 184,906.17	$ 99,940.80
RFID System Weight (lbs):	4	4
Launch Cost ($ / lb):	$ 25,511.96	$ 35,715.01
$ / System:	$ 102,047.85	$ 142,860.02
Discount Rate:	7%	7%
Volume of Standard CTB (m^3):	0.053	0.053
Percent of Standard CTB volume required for RFID System:	12%	12%
Volume Cost ($ / m^3):	$ 20,272,793.47	$ 31,598,719.79
$ / System:	$ 128,717.97	$ 200,629.63

Note:

1) "Launch Cost ($/lb)" and "Volume Cost ($/m^3)" both have different values for Pre- and Post-Shuttle Retirement. For convenience, these values are listed under "2009" and "2010-2016" respectively, even though the Shuttle will not retire until the end of 2010. All calculations are performed using the correct retirement date.

NORMALLY-DISTRIBUTED RANDOM VARIABLES FOR MONTE CARLO SIMULATIONS

Table C.7 - Randomly Generated Variables for Modification Kits Implementation Scenario.

	Lower 95% Bound	*Upper 95% Bound*	*Mean*	*Std Dev*	**2009-2010**	**2011-2016**
Avg. Total ISS Budget:	$3,100,000,000	$3,650,000,000	$ 3,375,000,000	$ 137,500,000	$ 3,168,583,748	$ 3,365,681,107
# "Active" Crew Hours in a Day:	10	18	14	2	12	
% On-orbit IMS Entries that could be Automated by Wired CTBs:	30%	70%	50%	10%	45%	
% of CTB Transactions Accurately Detected by System:	80%	100%	90%	5%	92%	
$ / m^3 of Cargo Up-Volume:	$ 10,000,000	$50,000,000	$ 30,000,000	$ 10,000,000	$ 35,979,362	$ 28,675,797
Percent of Standard CTB volume required for RFID System:	4%	20%	12%	4%	8%	

Table C.8 - Randomly Generated Variables for Phase-In Implementation Scenario.

	Lower 95% Bound	*Upper 95% Bound*	*Mean*	*Std Dev*	**2009-2010**	**2011-2016**
Avg. Total ISS Budget:	$3,100,000,000	$3,650,000,000	$3,375,000,000	$137,500,000	$3,188,222,430	$3,524,480,947
# "Active" Crew Hours in a Day:	10	18	14	2	13	
% On-orbit IMS Entries that could be Automated by Wired CTBs:	30%	70%	50%	10%	48%	
% of CTB Transactions Accurately Detected by System:	80%	100%	90%	5%	96%	
$ / m^3 of Cargo Up-Volume:	$ 10,000,000	$50,000,000	$ 30,000,000	$ 10,000,000	$ 39,046,734	$ 41,051,962
Percent of Standard CTB volume required for RFID System:	4%	20%	12.0%	4.0%	14%	
Wired CTB Launch Rate (% of Total ISS Population):	5%	15%	10.0%	2.5%	11%	

Sample Calculation:
(From Table C.7, using Microsoft Excel 2007 functions) [43]
2009-2010 Random Value for "# Active Crew Hours in a Day" =
INT(NORMINV(RAND(), Mean $_{\#\ Active}$, Std Dev$_{\#\ Active}$)) = 12

Note:

1) The appropriate General Input variables are set equal to the randomly-generated variables (Columns "2009-2010" and "2011-2016"), and an Excel Data Table is used to create the 3500 point simulation. This calculates the net present value using 3500 combinations of the randomly-generated variables.
2) A variable does not have a value listed under "2011-2016" if the "2009-2010" variable is used for both time periods.

UNIFORMLY-DISTRIBUTED RANDOM VARIABLES FOR MONTE CARLO SIMULATIONS

Table C.9 - Uniformly-Generated Variables for Modification Kits Implementation Scenario.

	Lower Bound	*Upper Bound*	**2009-2010**	**2011-2016**
Avg. Total ISS Budget:	$ 3,100,000,000	$ 3,650,000,000	$ 3,145,265,355	$ 3,363,132,171
# "Active" Crew Hours in a Day:	10	18	10	
% On-orbit IMS Entries that could be Automated by Wired CTBs:	30%	70%	41%	
% of CTB Transactions Accurately Detected by System:	80%	100%	97%	
$ / m^3 of Cargo Up-Volume:	$ 10,000,000	$50,000,000	$ 11,549,377	$ 49,555,001
Percent of Standard CTB volume required for RFID System:	4%	20%	4%	

Table C.10 - Uniformly-Generated Variables for Phase-In Implementation Scenario.

	Lower Bound	*Upper Bound*	**2009-2010**	**2011-2016**
Avg. Total ISS Budget:	$ 3,100,000,000	$ 3,650,000,000	$ 3,357,339,623	$ 3,490,240,955
# "Active" Crew Hours in a Day:	10	18	13	
% On-orbit IMS Entries that could be Automated by Wired CTBs:	30%	70%	50%	
% of CTB Transactions Accurately Detected by System:	80%	100%	85%	
$ / m^3 of Cargo Up-Volume:	$ 10,000,000	$50,000,000	$ 15,565,849	$ 43,202,514
Percent of Standard CTB volume required for RFID System:	4%	20%	13%	
Wired CTB Launch Rate (% of Total ISS Population):	5%	15%	6%	

Sample Calculation:
(From Table C.9, using Microsoft Excel 2007 functions) [44]
2009-2010 Random Value for "# Active Crew Hours in a Day" =
INT(RAND()(Upper Bound* $_{\# Active}$ *– Lower Bound* $_{\# Active}$*)+Lower Bound* $_{\# Active}$*) = 10*

Note:

1) The appropriate General Input variables are set equal to the randomly-generated variables (Columns "2009-2010" and "2011-2016"), and an Excel Data Table is used to create the 3500 point simulation. This calculates the net present value using 3500 combinations of the randomly-generated variables.
2) A variable does not have a value listed under "2011-2016" if the "2009-2010" variable is used for both time periods.

<u>Appendix D: Additional Results from Chapter 4</u>

<u>Additional Results from Experiment 1 – Ground Tests in Standard Laboratory Conditions</u>

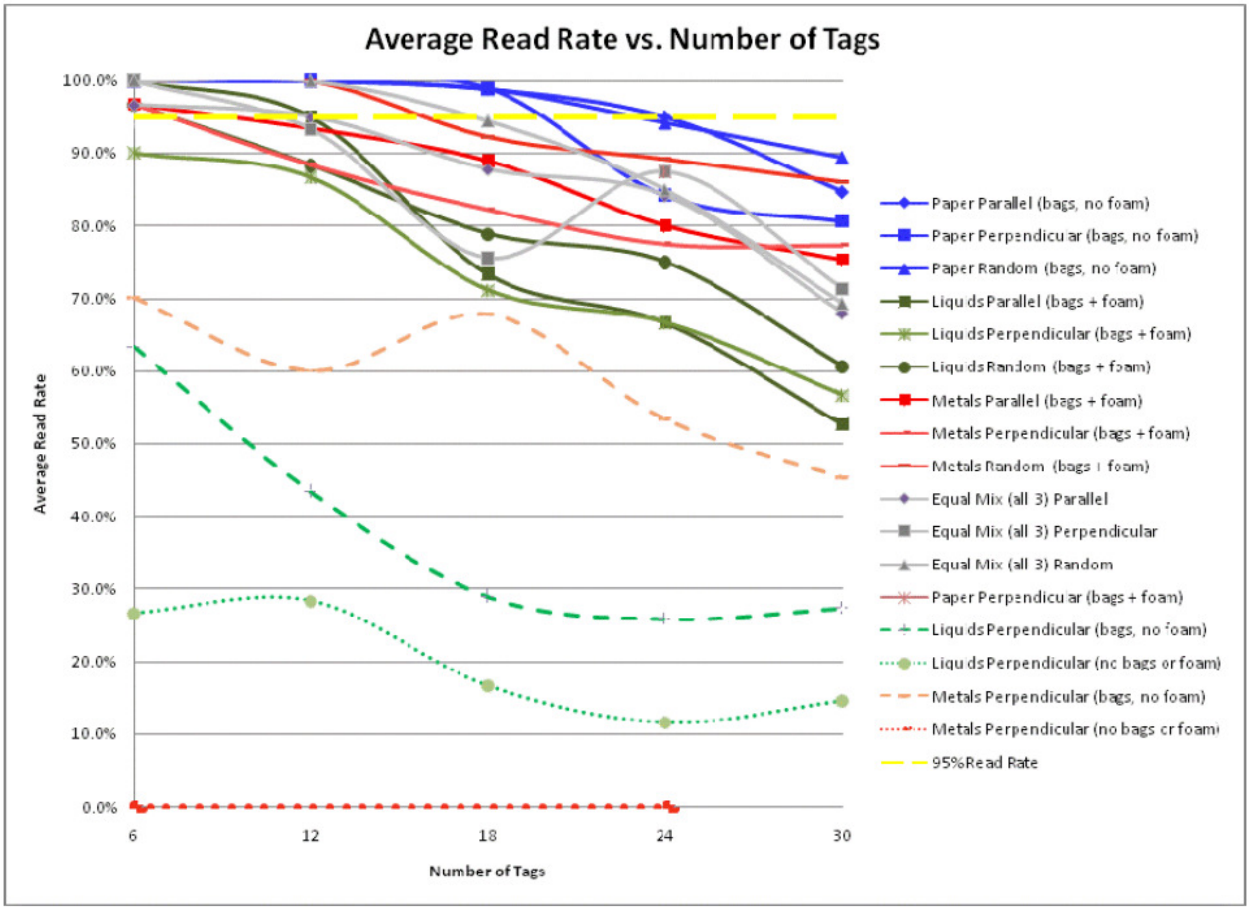


Figure D.1 - Complete dataset from Experiment 1, showing results from all scenarios tested. One can clearly see that the metal and liquid test articles suffered significant drop-off in read rates when the Alien tag was not "insulated" from the articles via a foam cutout (case with insulation shown in Figure 3.3). Also, one notices that the random-orientation cases seem to perform best, all other factors equal.

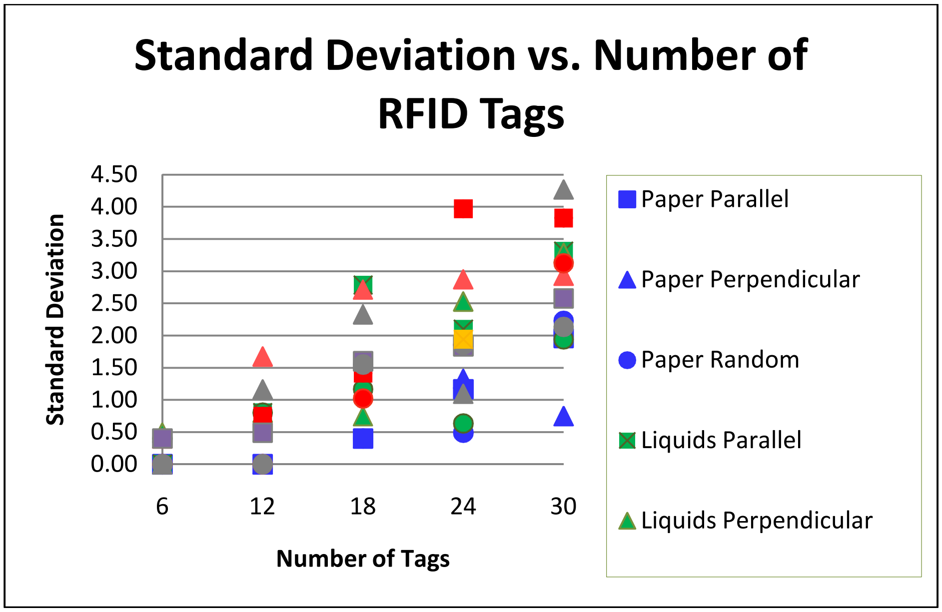


Figure D.2 - Illustration of standard deviation, as calculated for each case shown in Figure D.1.

Table D.1 - Results of all individual trials for Paper, nominal mounting scheme (tags on plastic bags without foam.)

Test Case A (Paper, Parallel, in Bags)										
# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
6	6	6	6	6	6	*6.00*	*0.00*	*0.00*	*0.0%*	100.0%
12	12	12	12	12	12	*12.00*	*0.00*	*0.00*	*0.0%*	100.0%
18	18	17	18	18	18	*17.80*	*0.40*	*0.20*	*1.1%*	98.9%
24	23	21	22	24	24	*22.80*	*1.17*	*1.20*	*5.0%*	95.0%
30	28	26	25	22	26	*25.40*	*1.96*	*4.60*	*15.3%*	84.7%

Test Case B (Paper, Perp, in Bags)										
# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
6	6	6	6	6	6	*6.00*	*0.00*	*0.00*	*0.0%*	100.0%
12	12	12	12	12	12	*12.00*	*0.00*	*0.00*	*0.0%*	100.0%
18	18	18	17	18	18	*17.80*	*0.40*	*0.20*	*1.1%*	98.9%
24	22	20	21	20	18	*20.20*	*1.33*	*3.80*	*15.8%*	84.2%
30	24	25	24	25	23	*24.20*	*0.75*	*5.80*	*19.3%*	80.7%

Test Case C (Paper, Random, in Bags)										
# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
6	6	6	6	6	6	*6.00*	*0.00*	*0.00*	*0.0%*	100.0%
12	12	12	12	12	12	*12.00*	*0.00*	*0.00*	*0.0%*	100.0%
18	18	18	18	17	18	*17.80*	*0.40*	*0.20*	*1.1%*	98.9%
24	22	23	23	22	23	*22.60*	*0.49*	*1.40*	*5.8%*	94.2%
30	29	26	29	27	23	*26.80*	*2.23*	*3.20*	*10.7%*	89.3%

Table D.2 - Results of all individual trials for Liquids, nominal mounting scheme (tags on foam on plastic bags.)

Test Case D (Liquids, Parallel, Foam + Bags)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	6	6	6.00	0.00	0.00	0.0%	100.0%
12	11	10	12	12	12	11.40	0.80	0.60	5.0%	95.0%
18	8	14	16	13	15	13.20	2.79	4.80	26.7%	73.3%
24	12	18	17	16	17	16.00	2.10	8.00	33.3%	66.7%
30	21	16	11	17	14	15.80	3.31	14.20	47.3%	52.7%

Test Case E (Liquids, Perp, Foam + Bags)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	5	6	5	6	5	5.40	0.49	0.60	10.0%	90.0%
12	10	11	11	11	9	10.40	0.80	1.60	13.3%	86.7%
18	13	12	12	14	13	12.80	0.75	5.20	28.9%	71.1%
24	18	17	11	17	17	16.00	2.53	8.00	33.3%	66.7%
30	16	13	23	17	16	17.00	3.29	13.00	43.3%	56.7%

Test Case F (Liquids, Random, Foam + Bags)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	6	5	5.80	0.40	0.20	3.3%	96.7%
12	11	11	11	9	11	10.60	0.80	1.40	11.7%	88.3%
18	15	13	16	13	14	14.20	1.17	3.80	21.1%	78.9%
24	19	18	18	18	17	18.00	0.63	6.00	25.0%	75.0%
30	15	20	17	20	19	18.20	1.94	11.80	39.3%	60.7%

Table D.3 - Results of all individual trials for Metals, nominal mounting scheme (tags on foam on plastic bags.)

Test Case G (Metals, Parallel, Foam + Bags)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	5	6	5.80	0.40	0.20	3.3%	96.7%
12	12	12	10	11	11	11.20	0.75	0.80	6.7%	93.3%
18	16	18	17	15	14	16.00	1.41	2.00	11.1%	88.9%
24	22	13	22	23	16	19.20	3.97	4.80	20.0%	80.0%
30	22	17	23	22	29	22.60	3.83	7.40	24.7%	75.3%

Test Case H (Metals, Perp, Foam + Bags)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	6	5	5.80	0.40	0.20	3.3%	96.7%
12	12	11	13	8	11	11.00	1.67	1.40	11.7%	88.3%
18	10	16	14	16	18	14.80	2.71	3.20	17.8%	82.2%
24	15	23	19	20	16	18.60	2.87	5.40	22.5%	77.5%
30	23	24	24	18	27	23.20	2.93	6.80	22.7%	77.3%

Test Case I (Metals, Random, Foam + Bags)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	6	6	6.00	0.00	0.00	0.0%	100.0%
12	12	12	12	12	12	12.00	0.00	0.00	0.0%	100.0%
18	16	18	15	17	17	16.60	1.02	1.40	7.8%	92.2%
24	22	21	23	23	18	21.40	1.85	2.60	10.8%	89.2%
30	26	29	28	20	26	25.80	3.12	4.20	14.0%	86.0%

Table D.4 - Results of all individual trials for Equal Mix of test articles (X paper, X liquid, X metals), nominal mounting scheme for each (tags on foam on plastic bags for liquids and metals, tags on plastic bags without foam for paper.)

Test Case J (Equal Mix, Parallel, Foam + Bags for Metal & Lqd, Bags for Paper)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	5	6	*5.80*	*0.40*	*0.20*	*3.3%*	96.7%
12	12	12	11	11	11	*11.40*	*0.49*	*0.60*	*5.0%*	95.0%
18	18	16	17	14	14	*15.80*	*1.60*	*2.20*	*12.2%*	87.8%
24	21	22	18	18	22	*20.20*	*1.83*	*3.80*	*15.8%*	84.2%
30	20	25	20	17	20	*20.40*	*2.58*	*9.60*	*32.0%*	68.0%

Test Case K (Equal Mix, Perp, Foam + Bags for Metal & Lqd, Bags for Paper)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	6	6	*6.00*	*0.00*	*0.00*	*0.0%*	100.0%
12	12	12	11	12	9	*11.20*	*1.17*	*0.80*	*6.7%*	93.3%
18	16	10	12	16	14	*13.60*	*2.33*	*4.40*	*24.4%*	75.6%
24	20	20	21	23	21	*21.00*	*1.10*	*3.00*	*12.5%*	87.5%
30	27	15	19	21	25	*21.40*	*4.27*	*8.60*	*28.7%*	71.3%

Test Case L (Equal Mix, Random, Foam + Bags for Metal & Lqd, Bags for Paper)										
# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
6	6	6	6	6	6	*6.00*	*0.00*	*0.00*	*0.0%*	100.0%
12	12	12	12	12	12	*12.00*	*0.00*	*0.00*	*0.0%*	100.0%
18	18	18	17	14	18	*17.00*	*1.55*	*1.00*	*5.6%*	94.4%
24	22	20	22	21	17	*20.40*	*1.85*	*3.60*	*15.0%*	85.0%
30	19	21	24	18	22	*20.80*	*2.14*	*9.20*	*30.7%*	69.3%

Table D.5 - Results of off-nominal mounting schemes for liquid and metallic objects.

Test Case O (Liquids, Tags directly on Bottles, Perp)										
# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
6	2	3	1	0	2	*1.60*	*1.02*	*4.40*	*73.3%*	26.7%
12	3	2	6	4	2	*3.40*	*1.50*	*8.60*	*71.7%*	28.3%
18	2	4	2	5	2	*3.00*	*1.26*	*15.00*	*83.3%*	16.7%
24	2	3	3	4	2	*2.80*	*0.75*	*21.20*	*88.3%*	11.7%
30	3	4	3	5	7	*4.40*	*1.50*	*25.60*	*85.3%*	14.7%

Test Case P (Liquids, Bag withOUT Foam, perp)										
# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
6	2	3	6	6	2	*3.80*	*1.83*	*2.20*	*36.7%*	63.3%
12	6	5	4	7	4	*5.20*	*1.17*	*6.80*	*56.7%*	43.3%
18	6	4	5	6	5	*5.20*	*0.75*	*12.80*	*71.1%*	28.9%
24	6	7	9	3	6	*6.20*	*1.94*	*17.80*	*74.2%*	25.8%
30	9	5	7	11	9	*8.20*	*2.04*	*21.80*	*72.7%*	27.3%

Test Case Q (Metals, Tags directly on Cans, Perp)										
# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
6	0	0	0	0	0	*0.00*	*0.00*	*6.00*	*100.0%*	0.0%
12	0	0	0	0	0	*0.00*	*0.00*	*12.00*	*100.0%*	0.0%
24	0	0	0	0	0	*0.00*	*0.00*	*24.00*	*100.0%*	0.0%
24	0	0	0	0	0	*0.00*	*0.00*	*24.00*	*100.0%*	0.0%
30	0	0	0	0	0	*0.00*	*0.00*	*30.00*	*100.0%*	0.0%

Test Case R (Metals, Bag withOUT Foam, perp)										
# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
6	5	4	5	3	4	*4.20*	*0.75*	*1.80*	*30.0%*	70.0%
12	10	8	7	4	7	*7.20*	*1.94*	*4.80*	*40.0%*	60.0%
18	14	9	13	16	9	*12.20*	*2.79*	*5.80*	*32.2%*	67.8%
24	16	15	16	9	8	*12.80*	*3.54*	*11.20*	*46.7%*	53.3%
30	12	19	18	9	10	*13.60*	*4.13*	*16.40*	*54.7%*	45.3%

Table D.6 - Results of intensive orientation tests for Paper test articles, with tags mounted in the nominal configuration for paper (on plastic bags). Each row consists of 10 individual "snapshot" reads of the exact same configuration and orientation of test articles (24) within the container. For example, the "Unstress Parallel Repeat (10)" row consists of 10 trials of the same "easy" parallel configuration, where all tags were orientated downwards toward the reader in the floor of the CTB, and no two tags were directly touching one another. Similarly, in the "stress" cases, tags were oriented as much as possible away from the readers and touching other tags, with test articles positioned between the tags and as many readers as possible.

	Stress Test Cases (Paper, Bags) - Same Configuration for each test's 10 trials															
	# of Tags in CTB	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 6**	**Trial 7**	**Trial 8**	**Trial 9**	**Trial 10**	**Mean**	**Std Dev**	**Avg. Absolute Error**	**Avg. % Error**	**Avg. Read Rate**
Unstress Parallel Repeat (10)	**24**	21	22	21	24	23	19	23	24	21	22	*22.00*	*1.48*	*2.00*	*8.3%*	91.7%
Stress Parallel Repeat (10)	**24**	21	22	23	23	22	23	21	22	19	22	*21.80*	*1.17*	*2.20*	*9.2%*	90.8%
Unstress Perp Repeat (10)	**24**	19	18	20	18	19	22	20	23	22	21	*20.20*	*1.66*	*3.80*	*15.8%*	84.2%
Stress Perp Repeat (10)	**24**	14	20	15	20	19	12	21	14	16	19	*17.00*	*3.00*	*7.00*	*29.2%*	70.8%
Random Repeat (10)	**24**	23	20	22	23	24	23	24	23	24	23	*22.90*	*1.14*	*1.10*	*4.6%*	95.4%

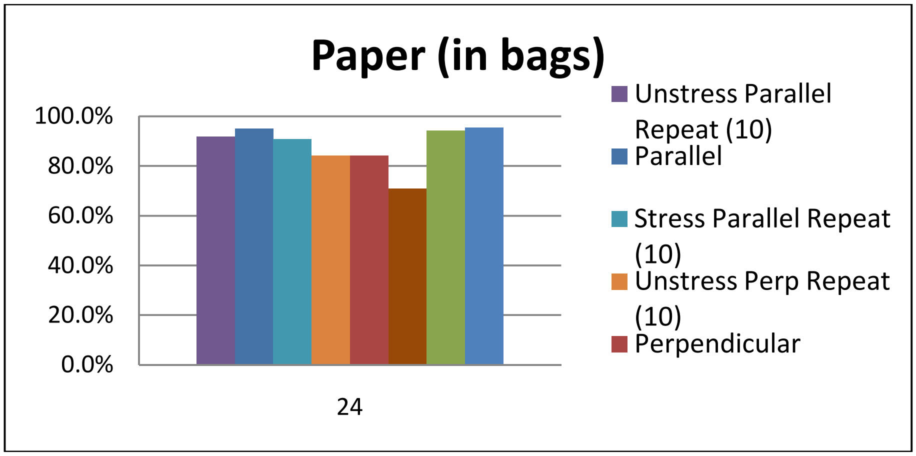


Figure D.3 - Shows the average read rates for the tests listed in Table D.6.

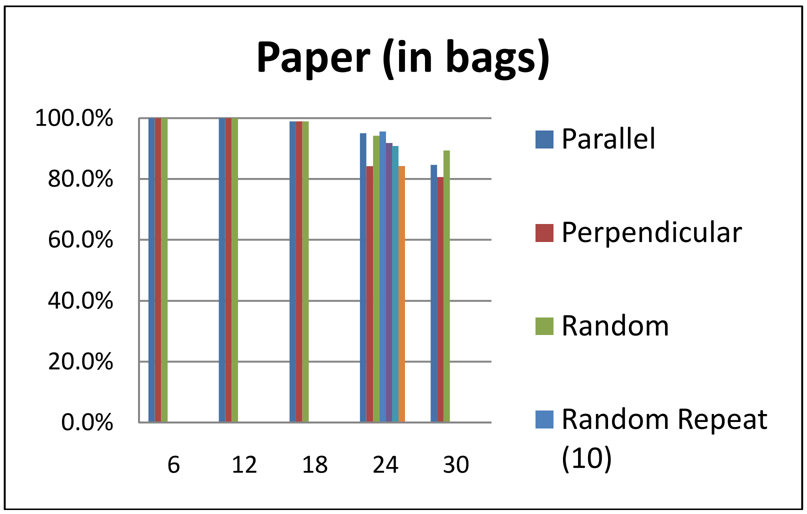


Figure D.4 - Shows the average read rates for tests listed in Table D.6 as well as the nominal tests for that material from Test Case A of Table D.1.

Table D.7 - Similar to Table D.6, shows results of intensive orientation tests for Liquid test articles with tags mounted in the nominal configuration for liquid and metallic objects (on foam on plastic bags).

	Stress Test Cases (Liquids, Bags + Foam) - Same Configuration for each test's 10 trials															
	# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
Unstress Parallel Repeat (10)	**24**	17	14	18	19	15	19	17	19	18	19	*17.50*	*1.69*	*6.50*	*27.1%*	72.9%
Stress Parallel Repeat (10)	**24**	12	14	8	10	8	13	11	9	10	8	*10.30*	*2.05*	*13.70*	*57.1%*	42.9%
Unstress Perp Repeat (10)	**24**	17	13	20	14	18	17	16	15	18	19	*16.70*	*2.10*	*7.30*	*30.4%*	69.6%
Stress Perp Repeat (10)	**24**	11	13	11	10	13	17	15	13	12	13	*12.80*	*1.94*	*11.20*	*46.7%*	53.3%
Random Repeat (10)	**24**	19	15	18	16	17	15	14	15	12	16	*15.70*	*1.90*	*8.30*	*34.6%*	65.4%

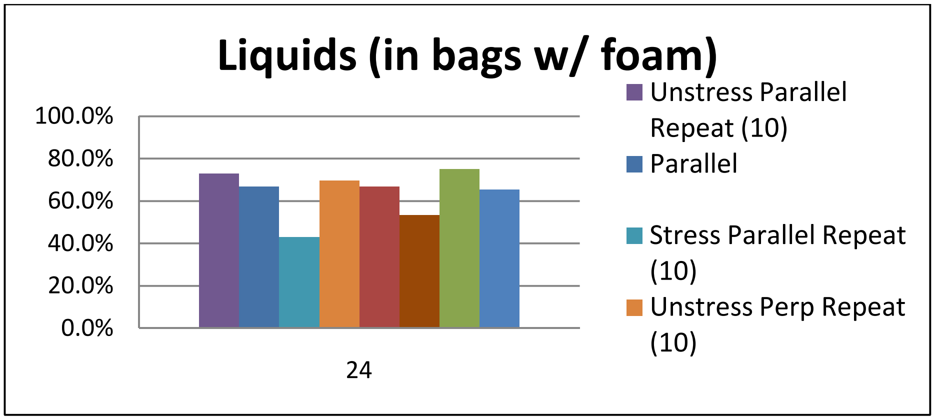


Figure D.5. Shows the average read rates for the tests listed in Table D.7.

Table D.8. Similar to Table D.6, shows results of intensive orientation tests for Metal test articles with tags mounted in the nominal configuration for liquid and metallic objects (on foam on plastic bags).

	Stress Test Cases (Metals, Bags + Foam) - Same Configuration for each test's 10 trials															
	# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
Unstress Parallel Repeat (10)	**24**	22	10	17	23	24	21	23	22	19	16	*19.70*	*4.10*	*4.30*	*17.9%*	82.1%
Stress Parallel Repeat (10)	**24**	13	9	11	21	19	18	21	17	19	18	*16.60*	*3.95*	*7.40*	*30.8%*	69.2%
Unstress Perp Repeat (10)	**24**	24	19	23	20	24	19	20	23	20	18	*21.00*	*2.14*	*3.00*	*12.5%*	87.5%
Stress Perp Repeat (10)	**24**	16	23	17	19	21	17	14	20	18	22	*18.70*	*2.69*	*5.30*	*22.1%*	77.9%
Random Repeat (10)	**24**	22	18	23	16	19	15	21	19	17	21	*19.10*	*2.51*	*4.90*	*20.4%*	79.6%

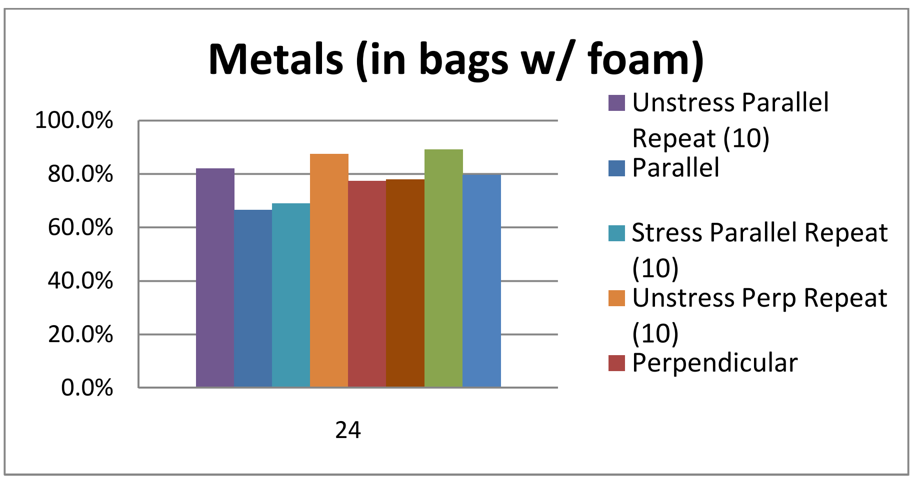


Figure D.6. Shows the average read rates for the tests listed in Table D.8.

Table D.9. Similar to Table D.6, shows results of intensive orientation tests for an Equal Mix of test articles with tags mounted in the nominal configuration each material type.

	Stress Test Cases (Equal Mix, Bags + Foam) - Same Configuration for each test's 10 trials															
	# of Tags in CTB	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10	Mean	Std Dev	Avg. Absolute Error	Avg. % Error	Avg. Read Rate
Unstress Parallel Repeat (10)	**24**	22	20	21	22	21	18	22	22	20	22	*21.00*	*1.26*	*3.00*	*12.5%*	87.5%
Stress Parallel Repeat (10)	**24**	21	16	22	19	20	22	23	20	21	22	*20.60*	*1.91*	*3.40*	*14.2%*	85.8%
Unstress Perp Repeat (10)	**24**	21	20	22	21	19	21	19	20	21	18	*20.20*	*1.17*	*3.80*	*15.8%*	84.2%
Stress Perp Repeat (10)	**24**	21	22	20	19	21	19	21	17	21	19	*20.00*	*1.41*	*4.00*	*16.7%*	83.3%
Random Repeat (10)	**24**	17	23	23	19	20	21	20	21	19	23	*20.60*	*1.91*	*3.40*	*14.2%*	85.8%

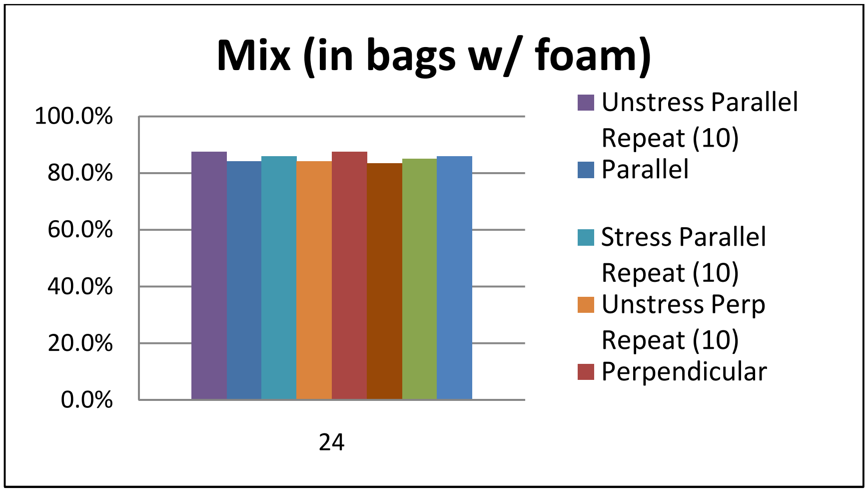
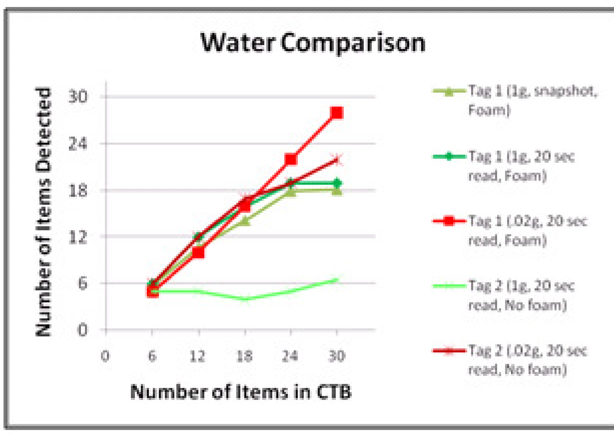
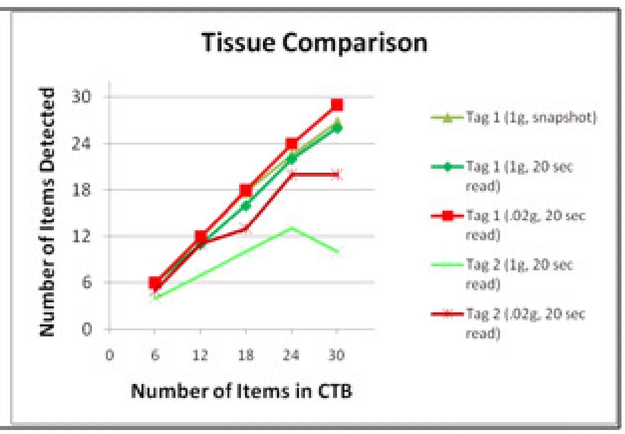


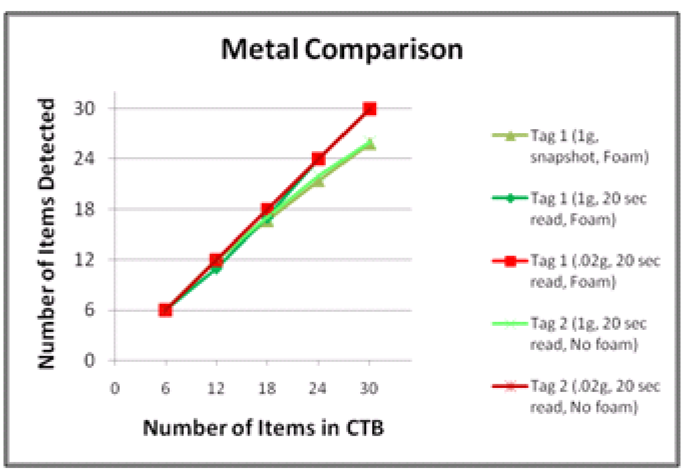
Figure D.7. Shows the average read rates for the tests listed in Table D.9.

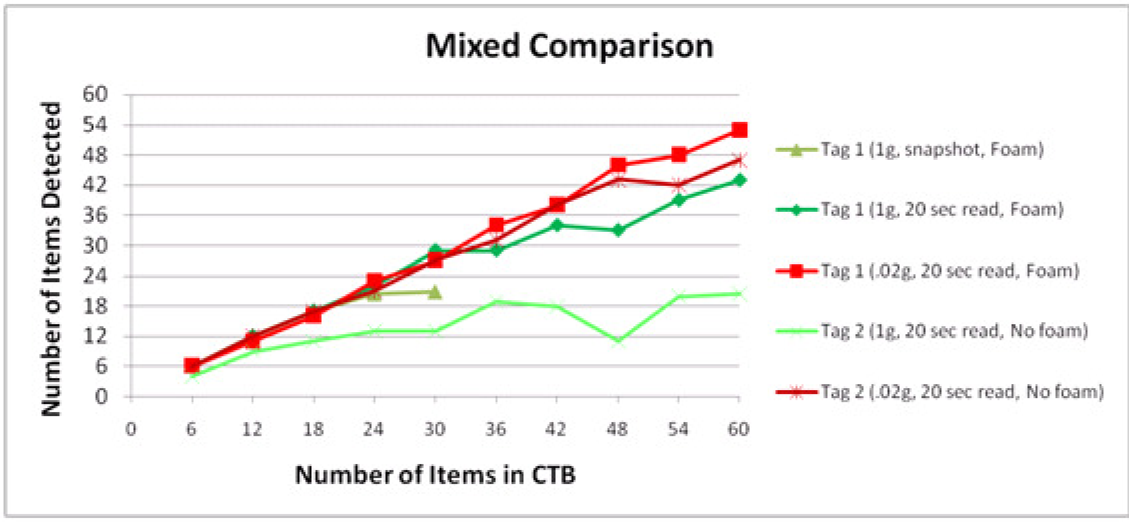
<u>ALTERNATIVE REPRESENTATION OF RESULTS FROM EXPERIMENTS 2 & 3</u>

Note: "Tag 1" denotes Alien Squiggle® tags with the specified mounting scheme (foam backing or no foam, as per the nominal for that material type from Experiment 1), and "Tag 2" denotes Omni-ID Prox™ tags directly affixed to test articles.








Mixed Comparison
Number of Items Detected
60
54
48
42
36
30
24
18
12
6
0
0
6
12
18
24
30
36
42
48
54
60
Number of Items in CTB
Tag 1 (1g, snapshot, Foam)
Tag 1 (1g, 20 sec read, Foam)
Tag 1 (.02g, 20 sec read, Foam)
Tag 2 (1g, 20 sec read, No foam)
Tag 2 (.02g, 20 sec read, No foam)

Appendix E: Additional Information Regarding Inventory Management for Human Spaceflight at NASA

Space Shuttle Logistics at Kennedy Space Center (KSC)

Kennedy Space Center is currently holding hundreds of thousands of spare parts in their warehouse facilities. They have roughly 110,000 non-flight ground facility line-items in their inventory database, and some 95,000 flight hardware line-items. According to KSC Shuttle Logistics engineers, tens of thousands of these parts have not been used in 15 years or more. However, the vast majority of these items have more than one end-user (the "next-higher-assembly") – some have hundreds. As long as there remains one such "next-higher-assembly" still in operation, NASA requires that the item be retained. Also, some 26,000 of the items being held have National Stock Numbers, which means they can readily be purchased via established government suppliers; these parts would be good candidates for a Just-In-Time logistics strategy, but continue to be held in stock by KSC. The result of these two policies is that KSC is currently running a 50,000-square-foot deficit on warehouse space, during a period in which they are also trying to find space for new items for Constellation.

Within the main warehouse, KSC has a robotic retrieval system – dubbed Mini-Loads – that allows efficient storage of smaller parts, those roughly 4 inches or less. This system consists of a group of six shelves of drawers that are stacked 45 high; upon command, a robotic retriever picks up the specified drawer and delivers it to the operator, who kits (packs) the item(s) and enters the transaction into the inventory database. Mini-Loads contains approximately 84,000 (of the 110,000) non-flight ground facility line-items, and roughly 650 (of the 95,000) flight hardware line-items. Flight hardware is kept in environmentally-controlled sections of the warehouse, both in Mini-Loads and outside of it.

The Shuttle Logistics organization tracks parts in a database known as PeopleSoft. PeopleSoft came online in 2002 and is the largest parts database at KSC. Parts typically have a barcode that is used to reference them in the system, although for smaller items, sometimes the bags or bins that contain them are barcoded instead. PeopleSoft does not contain entries with item dimensions – to get an idea of size, an experienced operator can look at the listed warehouse storage location and infer an approximate item size based on his/her knowledge of the sizes of different storage spaces. Every year, the logistics group reviews a list of all stocked items that have had no activity for the last ten years, checking each part for any active "next-higher-assemblies". If none exist and a part can be excessed, it is added to a "Retention Review" database which automatically goes out and talks to three other databases, giving potentially interested parties one last chance to stop its divestment.

Finally, there is a company known as the National Shuttle Logistics Depot (NSLD) that makes hardware parts that KSC needs but can no longer order from other outside commercial companies. NSLD is located off-center, in Cape Canaveral.

Boeing KSC Pilot in SSPF High Bay

Introduction

In early 2008, KSC's Space Station Processing Facility (SSPF), Boeing CAPPS / Payload Services brought online a rather impressive RFID asset tracking pilot program. The program was overseen by Phil Lintereur, the manager of the Boeing CAPPS / Payload Services Fluids and Propulsion Group, and the vendor was RFID Global Solution. The work was motivated by several factors, including an incident in which someone accidentally threw away a small piece of equipment valued at roughly $1 million. Another key factor was an estimate that the system would render at least two full-time positions unnecessary.

Hardware & System Architecture

The system is built around very small, "2D" active Gen II tags. Some of the tags are the size of a dime; others are as small as the punch-out from a hole-punch. They broadcast in the 6-8.5 GHz range, and cost approximately $25 each. The tags are either mounted directly on the objects or on lanyards that are already attached to objects (for example, tools) for barcodes. Some of the tags are specially encapsulated to resist impact damage such as might occur if a tool is dropped. Approximately 1,000 tags are currently involved in Phase I of the pilot; of these, 200 feature replaceable batteries. The other 800 have permanent batteries and are configured to broadcast every seven seconds, the longest delay possible with the chosen hardware. Given this setting, the tags are expected to have a lifetime of 10 years.

The system features a fine-location option; the vendor claims that it can locate a tag within 12 inches of its actual position through the use of triangulation algorithms. The tags are detected via readers that are hard-mounted throughout the relevant rooms in the facility, and also with hand-held readers for certain mobile applications such as the equipment vans used to service payloads at the launch pad. The mounted readers feature a 600-foot read-range, while the hand-held readers feature a read-range of approximately 10 feet. Also, the system does not seem to be impacted by modest amounts of metal – for example, it can read through a closed metal cart to detect the tools stored inside. The vendor's proprietary middleware, GlobalView™, powers the system's data collection and analysis activities.

Current and Future Objectives

Phase I of the project is currently underway. Its objective is to track high-value assets (> $100k) as well as Multi-Use Mission Support Equipment (MMSE), and also to implement the system in a set of special vans and a flatbed truck that are used to service payloads at the launch pad. Additionally, some tags will be used to assist Boeing's Multiflow Schedule Assessment Team (MSAT), the group that monitors usage of floor space in the SSPF High Bay. This team maps the floor configuration of the entire high bay once per week; up until now, this has been a completely manual process. The tags are being used on a trial basis to automatically track the movement of all items in a certain portion of the high bay, to determine their usefulness for facilitating MSAT's mapping work.

Phase II, which will be considered for funding depending on the results of Phase I, would extend the number and type of assets tracked. It would include the tools and other contents of the SSPF Instrument Library; a manual inventory of this repository currently requires some 160 person-hours to complete. Additionally, other Ground Support and Fluids equipment would be tracked, with things such as serial numbers and calibration information stored on the tags.

Lessons Learned from Approval Process

The Boeing manager reported that the greatest challenge in obtaining approval for the RFID system was helping reviewers (from Safety / EM / Facilities) understand that the tags' modulation frequency would not interfere with the Wi-Fi network in the High Bay.

PROJECT CONSTELLATION

CCSDS Wireless Working Group

The Consultative Committee for Space Data Systems (CCSDS) is an international working group which strives to promote interoperability by developing agreed-upon standards for information systems. NASA, ESA, and CSA are core partners in this effort, but other national space agencies (such as the Russian Space Agency) are also involved. Historically, these efforts have focused on interoperability in point-to-point communication/information relay systems such as TDRSS[52] and the Deep Space Network, but over the last several years the committee's efforts have broadened. Of particular note, the Wireless Working Group[53] is now focused upon intra-vehicle/habitat information systems, and it is looking to set standards for inventory management systems. In this working group, RFID technology has come up with regards to its potential for inventory tracking, as well as (to a lesser degree) for sensor interrogation.

CEV/Orion & Lunar Habitat

The two main crewed components for Constellation include the CEV[54] and the Lunar Habitat. Generally speaking, the CEV is the more constrained of the two – mass is an enormous challenge for that team right now, and current designs indicate that there will be very little margin available. Furthermore, the volumetric signature of the CEV backplane may not allow that vehicle to carry CTBs; they simply might not fit. Smaller, individual Ziplocs and other bags will be used instead, although cargo in general will be very limited aboard CEV. CEV is designed to be a "taxi", and therefore won't be carrying much cargo in the first place. Also, the transmission power of some Gen II systems could be a concern due to the vehicle's pyrotechnics. As for the

[52] Tracking and Data Relay Satellite System

[53] JSC is represented on this working group by Patrick Fink and Richard Barton, both of whom were interviewed for this report.

[54] Crew Exploration Vehicle, now officially named "Orion"

Lunar Habitat, it will clearly contain lots of items that will need to be tracked; however, many design details remain undefined, as it is still 12 years down the road in terms of its development. This can be both an opportunity and a challenge for developing any inventory management architecture.

Other Constellation Work

VerdaSee Solutions Contract

Patrick Fink, Evan Yagoda, and team oversaw a Project Constellation contract with VerdaSee Solutions, Inc, to take a fresh look at RFID options. In particular, Constellation was interested in reviewing Gen II tags in light of the significant technological progress that had been made in recent years. If the hardware can perform, among other characteristics it offers the advantage of being the industry standard. The contract called for VerdaSee to complete its work by October of 2008.

Extended Range SAW-Based Tag Antenna

In January of 2008, Patrick Fink had some seed funding to develop an "extended range SAW-based tag antenna". He was partnering with KSC on this work to examine potential test facility applications; Emilio Valencia was his main point-of-contact at Kennedy.

INTERNATIONAL SPACE STATION PROGRAM

RF SAW Station Development Test Objective (SDTO)

History

The RF SAW Station Development Test Objective (SDTO) was a NASA JSC effort, led by Tim Brown and Amy Schellhase, to run a small demonstration of inventory management on Station using RF SAW technology. The project was the result of a number of efforts over the last several years. Initial investigations of RFID indicated that the Gen I technology was not sufficiently mature for NASA applications. However, a couple of years later, in 2004, NASA commissioned the University of Nebraska at Lincoln (UNL) to do an RFID market study and take another look. The recommendation from that study was to build a system around a PDA that featured a PC-card RFID reader; unfortunately, that particular implementation did not perform adequately – specifically, the team could not get the tag read-range which they desired. As Tim explained, for 95% or better read-accuracy, which "has always been our [group's] requirement," the PDA had to be within a few inches of the target tag, very similar to a barcode. A year or so after this, Tim heard about RF SAW technology at a conference and subsequently set up a demonstration with a U. S. vendor, RF SAW Inc. In this demonstration, the company achieved read-ranges of 30 to 40 feet; Tim and his group were impressed, as this was the first RFID technology they had seen which ostensibly could address ISS inventory tracking needs.

Hardware

Tim and Amy decided to move forward with the RF SAW technology and developed a small-scale demonstration testing aboard the International Space Station. The culmination of this work was the RF SAW SDTO, which was tested onboard ISS in 2008[55]. The SDTO consisted of a number of RF SAW-tagged Crew Provision items which were launched on Progress flights 27 and 28[56]; these were either placed into a few CTBs on-orbit or launched pre-packed in CTB's, and then read with a custom-built "handheld" reader. The operational scenario for the test was for a crew member to hold the reader and then spin a CTB (with tagged contents) in front of it, at a fairly short distance (roughly a couple of feet). Crew Provision items (office supplies, clothing, etc) were tagged for testing because that organization was very interested in the potential for a system that could help improve inventory tracking and management. Additionally, since crew provisions are consumable items, they are replenished on a regular basis thus enabling the ground to tag the items for the SDTO, rather than having the crew tag items already on ISS. Tagging of food was considered, however the organization responsible for food was not enthusiastic about such a use of RFID; they felt that their current tracking system - which is based on consumption rates - was sufficient. Furthermore, all food is packed in metal food kits (Figure 4), and reading tags through a metallic container was not practical.

Flight Certification & Export Control

The hardware for the SDTO - particularly the reader - had to go through the typical NASA certification testing in order to fly. The reader was handed over to JSC's Engineering organization, which subjected it to "touch", material (outgassing), EMI (Electromagnetic Interference), and radiation[57] testing. Angela Olstead served as the point-of-contact for the effort. A few minor issues were reported from those tests:

1. The tags initially failed the material tests due to excessive alcohol outgassing; further investigation revealed that this was a result of the vendor cleaning the tags with alcohol prior to human-readable label application and tag delivery to NASA. This was resolved by "baking out" the alcohol from the tags.

2. The radiation testing actually somewhat *improved* the performance of the tags, apparently by "cleaning out" some of the etchings.

3. The reader initially failed the EMI test because of an electromagnetic "leak" coming from where the antenna connector emerged from the aluminum body case. The vendor provided a solution to this problem and thus resolved the issue.

[55] Assuming that the reader is delivered without incident by the first flight of ESA's ATV.
[56] These flights are referred to as 27P and 28P by NASA.
[57] Does it still work after exposure to a heightened radiation environment?

Additionally, the reader had to clear ITAR / Export Control requirements, but did so without incident. The tags did not have to be reviewed in this manner because they were categorized as "labeling", not "hardware".

Challenges

In the process of developing this SDTO, Tim indicated that his team encountered significant problems with the RF SAW tags. The original plan was to start tagging items on flights 27 and 28P and possibly continue to do so for all future flights, but the team is evaluating the forward work plan due to hardware problems. Two problems were discovered that did not appear during testing. First, the tags appeared to be more "brittle" than expected, with several tags breaking at the antennae during packing operations. Second, the adhesive used to attach the tags to items did not hold as well as it did during testing. Due to these two problems, it was decided to not continue tagging operations beyond that needed to support the SDTO until the vendor could address the issues. Furthermore, the reader itself was larger than what was desired for an operational system. NASA had asked the vendor to use as the reader's power source a camcorder battery[58] that was already approved for flight; originally, the vendor believed that they would need to use three such batteries in order to achieve three hours of lifetime for the reader, and so sized the reader box accordingly, which made it quite large. The vendor later discovered that they could make do with only one battery, but the shell for the box had already been built and apparently it was not feasible to resize it given time and/or budget constraints. While the reader size does not preclude its future use, the team planned to address the reader size after completing the SDTO to determine whether it is cost effective to pursue a smaller reader.

Ideas for other Use Cases for RAMSES and/or other RFID Technology

Trash

A number of NASA employees who were interviewed for this effort independently suggested that an RFID inventory management system could be useful to track trash. One NASA Engineer, who works waste-disposal issues for JSC MOD, suggested two possible benefits that could be realized by tagging items and installing readers at the airlock hatches where the Shuttle, Soyuz, Progress, and (soon) ATV and HTV dock. The idea is that such readers could track and verify the movement of tagged objects as they are placed into a vehicle for return or disposal. One clear benefit of such a system would be to prevent the accidental disposal of items; for example, it is not unheard of for small items such as memory cards to be lost in such a manner. Of equal or greater importance, however, would be the system's potential to eliminate the "double-counting" problem that currently exists. As mentioned in an earlier section, it is

[58] Lithium-Ion, Canon Battery Pack BP-930 (alt. -927), NASA part # SED33111486-303; http://estore.usa.canon.com/images/accessories/DV_DVD_Camcorders/Batteries/D85-0962-201_l.jpg; See Appendix C for NASA engineering drawing.

sometimes unclear how much trash is actually loaded into the vehicle. For example, say that the crew reports to Mission Control that they have loaded four Rubber-Lined bags of Common trash into the Progress. Common trash does not require pre-approval prior to being placed in a waste receptacle, so the ground does not know the specific contents of these bags (just that it generally contains "Common trash" – tissues, food scraps, used office supplies, clothing, etc). At the same time, IMS lists several pieces of used clothing as "trash," and automatically assumes that they have been transferred into the Progress. The problem is that, unless the crew specifically tells the ground how they have disposed of the clothing, it is unclear whether the clothing was loaded into the vehicle *inside* the four Rubber-Lined bags, or *in addition* to them. This "double-counting" introduces uncertainty into both the mass properties of the vehicle[59] as well as the post-disposal bill that Russia generates and sends to NASA. Brian estimates that he spends five to ten hours per flight on post-flight billing reconciliation, trying to determine exactly how much trash was loaded and thus how much the US bill should actually be.

There is certainly interest within NASA in this application; however, it seems to present a significant challenge in that it would be very difficult to tag every individual item. For example, under the current system a package of five new t-shirts contains one barcode on the package itself. The individual t-shirts are not barcoded. Therefore, as the application of passive RFID tags would likely mirror that of barcodes, unless the shirts are put back into their original (or an equivalent) package for disposal, they would not be tagged and a hatch reader would still be unable to detect their movement.

Middeck Lockers

According to another NASA Engineer, a member of NASA KSC's Space Station / Payloads Processing Mechanical Engineering Group, the shuttle middeck lockers could be a very useful application for a RAMSES-type system. Astronauts on-orbit are supposed to pack these lockers according to specific instructions and lists that Mission Control sends up, but the crew often deviates - they try to cram as much as possible into the lockers (which will be returning to Earth, rather than being disposed of), they put items into the wrong lockers, etc. The result is that it is very difficult for Mattingly's group to sort things out post-flight and return items to their proper owners.

The most obvious downside of this application is that the Shuttle Program is scheduled to end in 2010, and therefore would not have any significant opportunity to see a return on such an investment.

Crew Health and Experiments (CHEX)

This JSC group deals with many biological-related items such as drugs, medical samples, and life science experiments. They expressed interest in two potential applications for RAMSES. First, they are interested in tracking their items through terrestrial shipping and launch

[59] A potentially significant concern for ESA's ATV, based on reports that it has very little fuel margin.

preparation, especially if they could fuse the inventory information with geographic location and environmental conditions. Secondly, they would like to be able to track small items on ISS such as cotton balls, pills, etc., in order to better understand consumption rates (both overall and for specific crew members) and thus improve their resupply planning and crew health profiles.

The first application seems potentially feasible given the current development direction of RAMSES; such a system could replace the use of HOBOs to monitor environmentally-sensitive shipments. The second idea is much more challenging, as these are items that cannot really be tagged at this time. Perhaps steps could be made in that direction, though – for instance, one could install some kind of "smart medical 'cabinet'" on ISS which requires the crew to gain access using an RFID badge and also record which medicine bottle (an object that could be tagged) they remove; thus, the system could associate a crew member with a certain supply, even if the actual count of items consumed could not be determined. Of course, there might also be privacy concerns with such a system.

Module / Vehicle Hatches

Several NASA Engineers suggested mounting RFID readers at all vehicle and ISS module hatches, similar to the trash-tracking concept but with other purposes. In particular, one thought that this strategy might be very beneficial for CEV, in order to track the flow of items to and from the Lunar Lander. Due to the mass constraints on CEV, a large amount of CEV cargo will need to be launched in the lander and then transferred to CEV once the two vehicles dock on-orbit; it will be essential to make sure that all this cargo gets where it needs to go.

A KSC Engineer suggested a different use for the same system; he thought that it could be useful to prevent Foreign Object Debris (FOD) from tools or other ground support equipment that gets accidentally left inside the a vehicle (shuttle, CEV, or the Lunar Lander) after maintenance operations. The system would register an alert if all of the tools that it tracked entering the vehicle were not also detected exiting it.

Both of these concepts hold some potential; some have raised objections to the second, noting that it would not address FOD from other (non-taggable) sources such as eyeglasses, but this does not alter the fact that it could help to mitigate as least some sources of FOD. Furthermore, if the tools are already tagged – as is happening with Boeing's SSPF RFID pilot program – the only additional (albeit nontrivial) task would be to mount a few readers on the vehicles themselves.

Tracking/ Auditing Ground Assets

Another suggestion was that an RFID system could be used to facilitate the tracking and auditing of NASA's terrestrial assets, ranging from tools and expensive servicing equipment to office computers and TVs. A NASA manager explained that this could significantly reduce the effort required to conduct these audits, which are mandatory for the entire center at least once per year.

The Boeing SSPF pilot is moving somewhat in this direction, but at a much smaller scale than envisioned by this manager. Clearly, the major obstacle to a wider implementation would be the enormous capital cost that would be required.

Tracking People in Hazardous Locations

Finally, it was also suggested that RFID could be used to track employees in hazardous locations, such as the high bays or the launch pad. Currently, KSC uses a system in which an employee must leave a copy of his or her picture badge on a board outside the hazardous location; in the event of an emergency, this badge board serves as the reference for who is inside the hazardous area. Also, an employee must swipe his/her badge through a card reader in order to gain ingress or egress from the area, an action which allows the creation of an electronic reference list. If some kind of RFID system (probably using active tags similar to those in Boeing's SSPF pilot) could track more precisely the location of all employees within a hazardous area, this could be a useful aid for rescue workers in the event of an emergency. However, such a concept would have nontrivial privacy implications as well as technical challenges[60].

[60] For example, on the launch pad there would be a great deal of metallic interference, and also potential concerns about the transmission power due to pyrotechnics on the vehicle.

APPENDIX F: ADDITIONAL INFORMATION REGARDING THE RAMSES CTB PROTOTYPE

Table F.1 Parts List for RAMSES Prototype Modification Kit

Item #	Qty	Item	Part Number	Manufacturer
1	1	Directed 8601 Magnetic Switch		Radio Shack
2	2	BP6-915 RCP Right hand circular antennas		Mobile Mark
3	2	BP6-915 LCP Left hand circular antennas		Mobile Mark
4	1	Slimcab Desktop Cabinet	CS-11221-s	RS Electronics
5	1	Skyetek M9 Reader	SM-M9-MH-UF-V30	Skyetek, Inc.
6	1	Skyetek Interface Board	SP-IB-CB-00	Skyetek, Inc.
7	1	SkyePlus MXU 860-960 MHz antenna multiplexer (4 port)	SP-MX-04-UF-M9	Skyetek, Inc.
8	1	Verdex-Pro XM4-bt	XM4-bt	Gumstix, Inc.
9	1	ConsoleLCD-vx	ConsoleLCD-vx	Gumstix, Inc.
10	1	Netpro-vx	Netpro-vx	Gumstix, Inc.
11	1	WiFi Module FCC for Netpro-vx		Gumstix, Inc.
12	1	Screws & Spacers Kit		Gumstix, Inc.
13	1	Power Module, RAMSES Power Switch (Custom Made)		Aurora Flight Sciences
14	1	Conn ADT SMA Jack/MMCX Plug	ACX1352-ND	Digikey
15	6	SMA Bulkhead Connectors Jack to Jack ($14.12each)	530-142-0901-401	Mouser Electronics
16	1	LED (Front Panel)		
17	1	Power Switch (2-position)		
18	3	SMA Cable Assemblies STRT Plugs 316 6" ($12.08 Each)	530-415-0029-006	Mouser Electronics
19	2	SMA Cable Assemblies STRT Plugs 316 12" ($11.00 Each)	530-415-0029-012	Mouser Electronics
20	1	Mini USB V2.0 Cable: TypeB Male to Mini 5 pin Male	70-8033	Willy's Electronics
21	1	USB Battery Cable (5V Pocket-Size Lithium Battery Pack)		BIXComputers
22	10	Aluminum Spacer Male-Female 1/4" length 2-56 Screw ($0.36 each)	93505A211	McMaster-Carr
23	10	Aluminum Spacer Male-Female 1/2" length 2-56 Screw ($0.36 each)	93505A213	McMaster-Carr
24	10	Aluminum Spacer Male-Female 3/4" length 2-56 Screw ($0.39 each)	93505A215	McMaster-Carr
25	1	18-8 SS PanHead Phillips Machine Screw 0-80 thread 1" length. Pack of 50	91772A102	McMaster-Carr
26	1	Brass Miniature Machine Screw Nut Thread Size 0-80. Pack of 25.		McMaster-Carr
27	1	Pan Head Phillips Machine Screw 2-56 Thread 1" length. Pack of 100.		McMaster-Carr
28	1	zinc-plated Steel Machine Screw Hex Nut 2-56 Thread Size. 3/16" Width. 1/16" Height		McMaster-Carr
29	1	Zinc-plated Steel Pan Head Phillips Machine Screw 2-56 Thread, 3/16" Length. Pack of 100.		McMaster-Carr
30	3.5 m^2	Copper Wire Mesh (16 Mesh Copper .011" Wire Dia.)	016X016C0110W48T	TWP, Inc.
31	3.5 m^2	Foam spacing material (1.25" thick)		