DISSERTATION

MANAGING RISK IN COMMERCIAL-OFF-THE-SHELF BASED SPACE HARDWARE SYSTEMS

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2024

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ABSTRACT

MANAGING RISK IN COMMERCIAL-OFF-THE-SHELF BASED SPACE HARDWARE SYSTEMS

The space industry is experiencing a dynamic renaissance. From 2005 to 2021, the industry has exhibited a 265% increase in commercial and government investment [1]. The demand is forecasted to continue its upward trajectory by an added 55% by 2026 [1]. So, the aerospace industry continually seeks innovative space hardware solutions to reduce cost and to shorten orbit insertion schedules.

Using Commercial-Off-the-Shelf (COTS) components to build space-grade hardware is one method that has been proposed to meet these goals. However, using non-space-grade COTS components requires designers to identify and manage risks differently early in the development stages. Once the risks are identified, then sound and robust risk management efforts can be applied. The methods used must verify that the COTS are reliable, resilient, safe, and able to survive rigorous and damaging launch and space environments for the mission's required longevity or that appropriate mitigation measures can be taken. This type of risk management practice must take into consideration form-fit-function requirements, mission objectives, size-weight-and-performance (SWaP) constraints, how the COTS will perform outside of its native applications, manufacturing variability, and lifetime expectations, albeit using a different lens than those traditionally used.

To address these uncertainties associated with COTS the space industry can employ a variety of techniques like performing in-depth component selections, optimizing designs, instituting

robust stress screening, incorporating protective and preventative measures, or subjecting the hardware to various forms of testing to characterize the hardware's capabilities and limitations.

However, industrial accepted guidance to accomplish this does not reside in any standard or guide despite space program policies encouraging COTS use. One reason is because companies do not wish to reveal their proprietary methods used to evaluate COTS which, if broadcast, could benefit their market competition. Another is that high value spacecraft sponsors still cling to low-risk time consuming and expensive techniques that require the use of space hardware built with parts that have historical performance pedigrees.

Keeping this data hidden does not help the space industry, especially when there is a push to field space systems that are built with modern technologies at a faster rate. This is causing a change in basic assumptions as stakeholders begin to embrace using parts from other industries such as the automotive, aviation, medical, and the like on a more frequent basis. No longer are COTS relegated to use in CubeSats or research and development spacecraft that have singular and limited missions that are expected to function for a brief period. This is because COTS that are produced for terrestrial markets are equally as dependable because of the optimized manufacturing and quality control techniques that reduce product variability. This increases the use of COTS parts in space hardware designs where until recently space programs had dared not to tread. But using COTS does come with a unique set of uncertainties and risks that still need to be identified and mitigated.

Despite legacy risk management tools being mature and regularly practiced across a diverse industrial field, there is not a consensus on which risk management tools are best to use when evaluating COTS for space hardware applications. However, contained within technical literature amassed over the last twenty-plus years there exists significant systems engineering controls and enablers that can be used to develop robust COTS-use risk management frameworks. The controls and enablers become the basis to identify where aleatory and epistemic uncertainties exist within a COTS-based space system hardware design. With these statements in mind, unique activities can be defined to analyze, evaluate, and mitigate the uncertainties and the inherent risks to an acceptable level or to determine if a COTS-based design is not appropriate.

These concepts were explored and developed in this research. Specifically, a series of COTS centric risk management frameworks were developed that can be used as a roadmap when considering integrating COTS into space hardware designs. From these frameworks unique risk evaluation processes were developed that identified the unique activities needed to effectively evaluate the non-space grade parts being considered. The activities defined in these risk evaluation processes were tailored to uncover as much uncertainty as possible so that appropriate risk mitigation techniques could be applied, design decisions could be quickly made from an informed perspective, and spacecraft fielding could be accomplished at an accelerated rate. Instead of taking five to ten years to field a spacecraft, it can now take less than one to three years. Thus, if effectively used, COTS integration can be a force multiplier throughout the space industry. But first, the best practices learned over the last few decades must be collected, synthesized, documented, and applied.

To validate the risk frameworks discussed, a COTS-based space-grade secondary lithium-ion battery was chosen to demonstrate that the concepts could work. Unique risk evaluation activities were developed that took into consideration the spacecraft's mission, environment, application, and lifetime (MEAL) [2] attributes to characterize the battery's COTS cells, printed circuit board, electrical design, and electrical-electronic-electromechanical (EEE) performance, strengths, and weaknesses. The activities defined and executed included risk evaluation activities that included a variety of modeling, analyses, non-destructive examinations, destructive physical assessments, environmental testing, worst case scenario testing, and manufacturing assessments. These activities were developed based on the enablers and controls extracted from the data that was resident in the literature that was reviewed.

The techniques employed proved quite successful in uncovering and mitigating numerous aleatory and epistemic uncertainties. The mitigation of these uncertainties significantly improved the battery's design and improved the battery's performance. As a result, the COTS-based battery was successfully built, qualified, and flown on a fleet of launch vehicles and payloads.

The information that follows documents how the risk management frameworks were created, what influenced its architecture, and how these were successfully validated. Validating the COTS centric risk management framework was important because it demonstrated the risk management frameworks' utility to uncover uncertainty. It also proved that methods exist that can be readily employed that are not typically within the scope of traditional space hardware design and qualification techniques. This is important because it provides the industry a new set of systems engineering tools that can be employed to limit the impact of supply chain constraints, reduce reliance on expensive low-yield hardware procurement practices, and minimize the amount of obsolete hardware in designs which tend to constrain the space system hardware's performance. As a result, the techniques developed in this research start to fill a gap that exists in the space industry's systems engineering toolbox.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Dr. Thomas Bradley and Dr. Ronald Sega from Colorado State University's (CSU) Department of Systems Engineering (SE) for being superb mentors during this journey to obtain a Systems Engineering Doctor of Philosophy (PhD) degree. Serving as my PhD advisors, both professors guided my studies and research to obtain the best results and to improve my academic and professional acumen. My appreciation is also extended to my CSU Doctoral Committee comprised of Dr. Daniel Herber, Dr. Kamran Shahroudi, and Dr. Daniel Wise. Their tutelage was instrumental in developing research that benefits the aerospace industry, academia, and the space industry systems engineering community. Additionally, I want to thank Ms. Ingrid Bridge for her fantastic support in helping me navigate the CSU PhD administrative processes.

I am forever in debt for the professional guidance, research assistance, advice, support, and friendship provided to me by Dr. Jeanne M. McGraw from the Aerospace Corporation and the NASA Goddard Space Flight Center Chief Engineer for Safey and Mission Assurance, Dr. Jesse Leitner. Both dedicated long hours helping me to understand the intricacies of developing a space-grade battery, understanding how to evaluate hardware for use in space, developing cogent arguments, and evaluating the data collected.

This appreciation is also for Dr. Edmund Burke, President of the Space Information Laboratories, and his company's team. The support he and his staff provided was invaluable and exceptional. Without them, this research could not have been pursued.

I wish to extend my sincere appreciation to a team of brilliant scientists, engineers, technicians, analysts, professional colleagues, and friends who provided tremendous support in

developing and executing the modeling and simulation, analyses, and tests performed to collect the data needed to complete this research. Those who assisted include T. Albright, G. Arnold, T. Brand, C. Hammoud, N. Ives, W. Kaida, J. Matumoto, J. Nemanick, D. Patel, V. Petrosyan, M. Quinzio, L. Rios-Reyes, G. Stupian, T. Tsubota, J. Wood, A. Vanrell, and L. Walker. This same appreciation is sent to David and Gail Liniger who partially funded this research through their Liniger Honor, Service, and Commitment Scholarship. Their dedication to support United States veterans to reach higher bounds is exceptional.

I wish to express my heartfelt thanks to the librarians at the Aerospace Corporation's Charles C. Lauritsen, the Colorado State University's Morgan, the Pennsylvania State University's Pattee and Paterno, and the Naval Postgraduate School's Dudley Knox libraries. The librarians at each of these dedicated countless hours helping me to locate the resources used to complete this research. They truly are the gatekeepers of knowledge.

Lastly, but not least, I want to express my gratefulness to my entire family. The support and encouragement they provided me during this professional and academic journey was limitless.

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DISTRIBUTION

The material presented in this research was first approved for public distribution on 1 March 2017 by a United States Department of Defense (DoD) organization, the Space Information Laboratories, and the Aerospace Corporation. This was accomplished in support of the submission of a technical paper and presentation at the 30th Aerospace Test Seminar held at El Segundo in March 2017.

A subset of this material was used for an additional submission to the 33rd Aerospace Test Seminar held in May 2023. The material used for the 33rd Aerospace Test Seminar and an International Council on Systems Engineering (INCOSE) *Systems Engineering* Journal article were expansions of the initial research. These submissions underwent additional Aerospace Corporation technical reviews to ensure the research submissions for public release continued to adhere to the previously approved criteria and to verify the new papers and briefs did not violate United States export control statutes and non-disclosure agreements. Additionally, in support of this research, permission was provided by the Space Information Laboratories to use the aforementioned material for this Systems Engineering Doctorate's research and publishing requirements. The Aerospace Corporation Office of Technical Relations (OTR) coordinated the reviews and the subsequent approvals. Aerospace OTR approval file numbers 2017-00320, 2023-00559, and 2023-00981 refer.

The INCOSE *Systems Engineering* Journal submission and this dissertation were approved for public release review by the Pennsylvania State University Applied Research Laboratory (Penn State ARL) on December 14, 2023, and February 26, 2024, respectively. These two reviews were completed per the Penn State ARL Corporate Communications policies and the United States

Department of Defense Instruction 5230.24 (January 12, 2023). Per the DoD instruction, this dissertation meets the requirements for public release and unlimited distribution.

1. INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

Since 2005, the space industry realized a 256% increase in the launch and deployment of payloads into space [3]. This pace is expected to increase by 55% through 2026 [1] with efforts being concentrated on launching satellites into Low Earth Orbit (LEO) to provide additional civil, commercial, and military space-based services. This rapid growth across the space domain is fueled by an increasing demand for data services around the globe. This space operations tempo exemplifies how the space industry is responding to customers like the United States Air and Space Forces (USAF, USSF) who recently established a revised spacecraft acquisition policy to accelerate the production, launching, and insertion of spacecraft into orbit in less than three years [4] .

To achieve goals such as those laid out by the USAF and USSF, launch and space vehicle (LV / SV) manufacturers are seeking alternate supply channels from non-space industries to supply the parts needed to build space hardware. So, the space industry actively seeks commercial-off-the-shelf (COTS)[1] parts that can be used instead of relying on those that are unique, expensive, and take a long time to procure, test, and field. The industry is engaging the aviation, automotive, maritime, medical, mining, and other industrial supply chains as sources of COTS that can be used in their LV / SV hardware designs. Like the space industry, these industrial sectors must operate in stressful and harsh environments yet be just as dependable and resilient as those used in space applications.

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[1] "Commercial-Off-the-Shelf parts" is abbreviated using the acronym COTS throughout this document.

COTS are attractive because they can be rapidly produced with minimal variability, delivered at a fraction of the cost, and operate equally as well, if not better, than long-lead space-grade parts. Using COTS provides additional benefits such as making modern technologies available, improving performance, reducing LV / SV size and weight profiles, and accelerating production and fielding schedules. But slow legacy space-grade parts procurement methods impeded by extreme oversight requirements during the design, testing, and fielding of space-grade hardware are still the norm. Alternatively, if space-grade parts are not available, then the legacy approach pivots to using Military Specification (MIL-Spec) parts that could be adopted for space use. If this search proves unsuccessful, then spacecraft designers reluctantly turned to COTS vendors and their inventories. But this legacy paradigm is rapidly disappearing, as the low-rate production levels of expensive space-grade and MIL-Spec parts cannot keep pace with demand.

The commercial space industry is increasingly motivated to use COTS to decrease costs, relieve schedule pressures, and field equipment quickly using modern technology. Similarly, space-grade parts vendors are equally under cost and schedule pressures from their customers to provide reliable and resilient space hardware that is less expensive and more readily available. But because the space industry does not yield as much profit as it did in the past many vendors are turning their attention to more lucrative markets. Instead of supplying the low-volume, high-cost space industry market with qualified parts, parts vendors are shifting their focus to higher production, higher yield, and higher profit terrestrial commercial markets. This leaves a parts supply gap that can only be partially filled by using COTS hardware. But, because the quantity of non-space-grade parts on the market is vast, LV / SV designers must develop pro-active identification, screening, and risk management processes to determine if a COTS part is a suitable candidate for integration into a LV / SV design. For example, using COTS in severe radiation, thermal, shock, vibration, acoustic, and electromagnetic environments can lead to failure if risks are not uncovered and appropriately addressed. That means the COTS selection process needs to be effectively managed. For example, per NASA Goddard, [5], approximately 5% of electrical-electronic-electromechanical (EEE) components used in circuit designs are susceptible to damaging radiation exposure. Possessing knowledge like this during the hardware design phase widens the selection trade space.

In response to these challenges, this research's goal is to develop a risk management framework (RMF) that can be tailored and used by the space industry to determine if using COTS components in space-grade hardware is feasible, efficient, cost effective, reliable, and safe. This research developed systems engineering risk management methods designed to uncover performance uncertainties and to manage any identified risks. It presents this proposed method in the context of a successfully executed risk management campaign to uncover uncertainties and to address the risks associated with using COTS hardware to build a LV / SV space-grade secondary (rechargeable) lithium-ion battery. To develop this RMF, this research presents COTS background information, the risk management methods developed and used, and the processes developed to mitigate the risks and uncertainties. The resultant processes are examples of how a risk management strategy can be tailored and successfully executed when considering using COTS in LV / SV hardware designs. These proposed processes can be used by the space industry to develop their own unique strategies to identify, analyze, evaluate, and treat (mitigate) risks when considering a COTS-based design solution.

1.2 BACKGROUND

Using COTS components to build space-grade hardware is one method that has been proposed to meet the demand for hardware to build launch and space vehicles. The use of non-space-grade COTS components requires designers to identify and manage risks early in the development stages. Once the risks are identified, then sound and robust risk management efforts can be applied. The methods must verify that the COTS components are reliable, resilient, safe, and able to survive rigorous and damaging launch and space environments for the mission's required longevity. Additionally, a risk management plan must address parts obsolescence, manufacturing stability, logistical, handling, storage, and statutory requirements. To address these, the space industry validates COTS-built hardware using various techniques like performing in-depth component selections, rapid prototyping to identify design uncertainties, optimizing designs, instituting robust stress screening, incorporating redundancy, or subjecting the hardware to rigorous testing such as Highly Accelerated Life Tests (HALT) and Highly Accelerated Stress Screening (HASS).

Though there is a broad set of commercial, civil, and military space hardware acquisition policy documents [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] published that encourage using COTS in space hardware designs little guidance exists on how to evaluate COTS performance and manage inherent risks associated with their use. One reason is because companies do not wish to reveal their proprietary methods used to evaluate COTS because doing so could benefit their market competition. Keeping this data hidden does not help the space industry which has a finite number of hardware producers willing to produce low-production space-grade hardware. Another example is that high value spacecraft sponsors cling to low-risk time consuming and expensive techniques that require the use of hardware built with parts that have historical performance pedigrees.

However, there is a set of discrete data available in technical literature published over the last twenty-plus years that documents methods that have been successfully used. This data can be mined and distilled to develop useful risk management guidance. Moreover, despite risk management tools being mature and regularly practiced across a diverse industrial field, there is not a consensus on which risk management tools are best to use when evaluating COTS for space hardware applications.

1.3 COMMERCIAL-OFF-THE-SHELF DEFINED

The space industry obtains COTS hardware from industries that are equally as complex. The automotive, aviation, electronic, medical, military, and mining fields are good examples. These industries have proven to be useful sources to explore for components that could have relatively good form, fit, and function in space applications. These industrial grade parts have been successfully used to build COTS-based space hardware such as cameras, antennas, receivers, transmitters, instrumentation, batteries, computer processors, power supplies, electrical distribution units, and inertial measurement units.

To achieve a COTS-based design solution requires stakeholders to understand what a COTS component is. However, a definition that is collectively agreed upon by industry and government does not exist. Table 1 lists six COTS definitions used by different organizations. Each is slightly different from the others; however, the common theme behind each is that COTS components are produced for sale and distribution in the general market. It should be noted that there are other terms that are similar. Alternate Grade Parts (AGP) [18] is another phrase meant to represent

COTS or parts other than space-grade. Even though it is starting to be used in COTS discussions, it has not been formally defined in any standard or acquisition policy. AGP is being suggested for use because it focuses the technical community on industrial parts (i.e., automotive, aviation, medical, et. al.) because these have demonstrated high reliability in highly stressful conditions.

Table 1. Commercial-Off-the-Shelf (COTS) Definitions

Activity	Commercial-Off-the-Shelf Definition
Defense Acquisition University (DAU)	*"... commercial items that require no unique government modifications or maintenance over the life cycle of the product to meet the needs of the procuring agency." [6]*
European Cooperation for Space Standardization	*"...commercial electronic component readily available and not manufactured, inspected, or tested in accordance with military or space standards." [8]*
Federal Acquisition Regulations (FAR)	*"(1) Means any item of supply (including construction material) that is–* *(i) A commercial product (as defined in paragraph (1) of the definition of "commercial product" in this section).* *(ii) Sold in substantial quantities in the commercial marketplace; and* *(iii) Offered to the Government, under a contract or subcontract at any tier, without modification, in the same form in which it is sold in the commercial marketplace…" [9]*
Federal Aviation Administration (FAA)	*"Component, integrated circuit, or sub-system developed by a supplier for multiple customers, whose design and configuration is controlled by the supplier's or an industry specification." [7]*
National Aeronautics and Space Administration (NASA)	*"A part for which the manufacturer solely establishes and controls specifications for configuration, performance, quality, and reliability. This includes design, materials, processes, assembly, and testing with no Government-imposed requirements (i.e., no Government oversight). COTS typically are available on a manufacturer's catalog (e.g., website) or from various distributors."* [2]
National Security Agency (NSA)	*"A software and/or hardware product that is commercially ready-made and available for sale, lease, or license to the general public." [10]*

Two other important terms defined in the Department of Defense (DoD) Parts Management Guide [16] are Alternate and Substitute Parts. An alternate part is defined as

> *"…a part that possesses functional and physical characteristics so as to be equivalent in performance, reliability, and maintainability to an original design part without selection for fit or performance." [16]*

A substitute part is defined as

> *"…a part that possesses functional and physical characteristics so as to be capable of being exchanged with the design part only under specified conditions, or in particular applications, without alteration of the parts themselves or adjoining items." [16]*

These are important because COTS are not defined in the DoD Parts Standardization Guide. This is surprising because many DoD acquisition policies and engineering guides explicitly discuss COTS use and that their use should be considered. So, before COTS can be used, space hardware developers and risk managers need to agree upon what will be considered COTS and what will not. Establishing an agreed upon lexicon is an important step before entering into hardware design and risk management tailoring.

Since COTS parts, as a concept, are defined differently in the civil, commercial, military, and space industrial sectors (Table 1) and despite their differences, it should be recognized that each definition holds to a singular interpretation that COTS are parts or assemblies that are produced for sale on the open market. Therefore, for this research, the updated National Aeronautics and Space Administration (NASA) definition will be used as captured in a 2022 NASA enterprise COTS utilization study [2]. Specifically, this research defines a COTS part as stated in Table 1 as,

> *"A part for which the manufacturer solely establishes and controls specifications for configuration, performance, quality, and reliability. This includes design, materials, processes, assembly, and testing with no Government-imposed requirements (i.e., no Government oversight). COTS typically are available on a manufacturer's catalog (e.g., website) or from various distributors." [2]*

The NASA definition will be used because NASA is a globally recognized and trusted expert in the aerospace field. This revised NASA definition states that COTS manufacturing is not controlled or influenced by the government or end user. This is an important distinction because it highlights a difference from traditional space-grade or MIL-Spec parts acquisition processes which generally use rigid performance and mission assurance requirements.

1.4 RISK MANAGEMENT DEFINED

Successful space operations are dependent on adherence to sound mission assurance practices. The United States Air Force defines Mission Assurance (MA)

> *"…as the disciplined application of proven scientific, engineering, quality, and program management principles towards the goal of achieving mission success. MA follows a general systems engineering (SE) framework and uses risk management (RM) and independent assessment as cornerstones throughout the program life cycle." [19]*

As described above, risk management is a subset of MA. The international aerospace industry routinely practices RM to identify and address issues that could hinder the successful development, launch, and operations of spacecraft. However, it is not a perfect science and depends highly on seeking, finding, and addressing potential issues early, expeditiously, and with engineering rigor throughout a product's life cycle. Thus, to achieve the objectives set forth in this research, we must first understand what a risk is and what risk management is supposed to do.

As defined by the DoD Systems Engineering Guide [20],

> "*Risks are potential future events or conditions that may have a negative effect on achieving program objectives for cost, schedule, and performance. They are defined by:*
>
> - *The undesired event and / or condition,*
> - *The probability of an undesired event or condition occurring,*
> - *The consequences, or impact, of the undesired event, should it occur."*

Table 2 lists risk management objectives that the commercial, civil, and defense space sectors strive to achieve through their respective risk management programs.

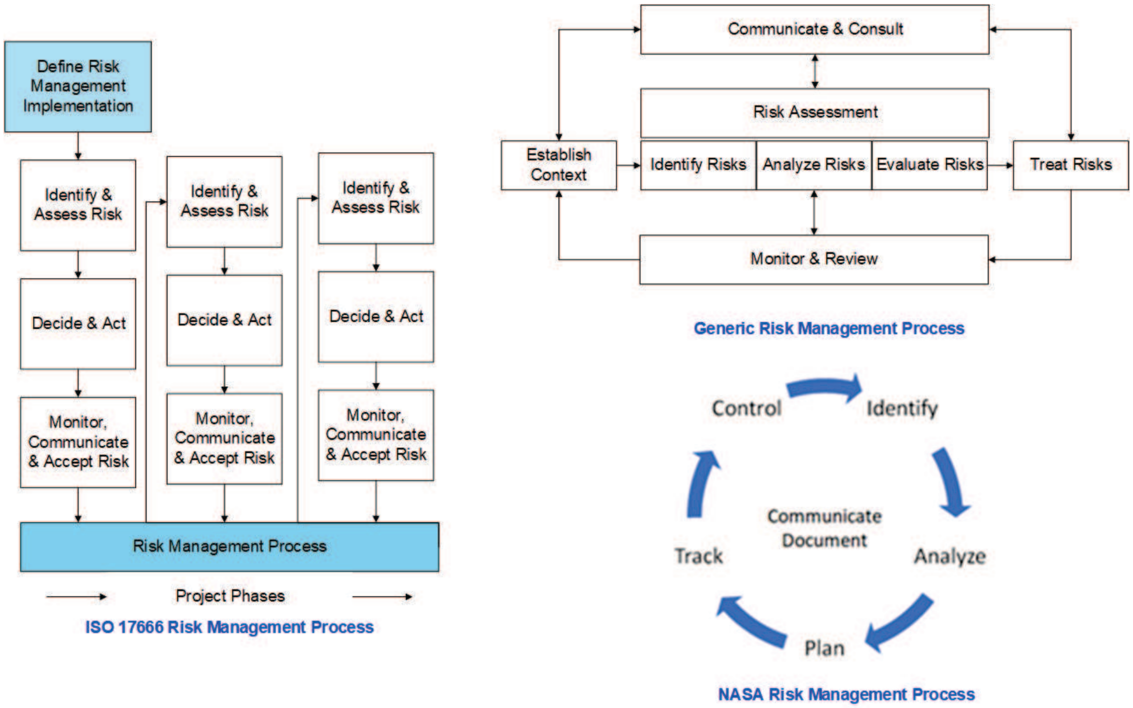
Managing risk starts by identifying a potential issue, characterizing its likelihood, the probability of it occurring, the consequence if the risk is realized, and the level of severity incurred [21]. These are difficult to predict and manage but possible to forecast. Proper selection and application of risk management tools can provide valuable insight into the item's performance capabilities and limitations. However, there are numerous methods and techniques to select from; but not all are appropriate for managing COTS risks. Selecting the appropriate tools to use depends on the goals of the program, the level of risk a program will accept, the degree of resources that can dedicated to achieving an acceptable level, the data available, and how the COTS will be used.

Table 2. Risk Management Objectives

Source	**Document No.**	**Objective**
International Organization for Standardization	ISO-17666	*"... to identify, assess, reduce, accept, and control space project risks in a systematic, proactive, comprehensive, and cost-effective manner, taking into account the project's technical and programmatic constraints."*
NASA Goddard Space Flight Center Safety and Mission Assurance	GPR 7120.4D	*"... is a deliberative, systematic process to analyze and communicate the risk of performance shortfalls. This process involves development of risk handling and mitigation options, and implementation of approved strategies to reduce or eliminate the likelihood of occurrence and/or severity of consequence."*
United States Air Force	AF Instruction 90-802	*"... is a decision-making process to systematically evaluate possible courses of action, identify risks and benefits, and determine the best course of action for any given situation."*

Common amongst all risk management efforts are processes designed to identify potential issues, to develop and execute methods to resolve the issues, and a continuous assessment process to determine if mitigations protocols are working or if risks are worsening. This information is used to make insightful and informed technical and programmatic decisions.

The NASA Goddard Procedural Document (GPR) titled *Risk Management* calls these attributes *Continuous Risk Management (CRM)* and *Risk Informed Decision Making (RIDM)* [22]. Figure 1 shows three examples of RM investigatory, action oriented, and iterative concepts common throughout the space industry despite minor differences in style. Each risk management process includes evaluation and planning, identification, analysis, mitigation, and monitoring in common; albeit, using different words to reflect these attributes. The US DoD Systems Engineering Guidebook [20] defines these traits as follows:



ISO 17666 Risk Management Process

Generic Risk Management Process

NASA Risk Management Process

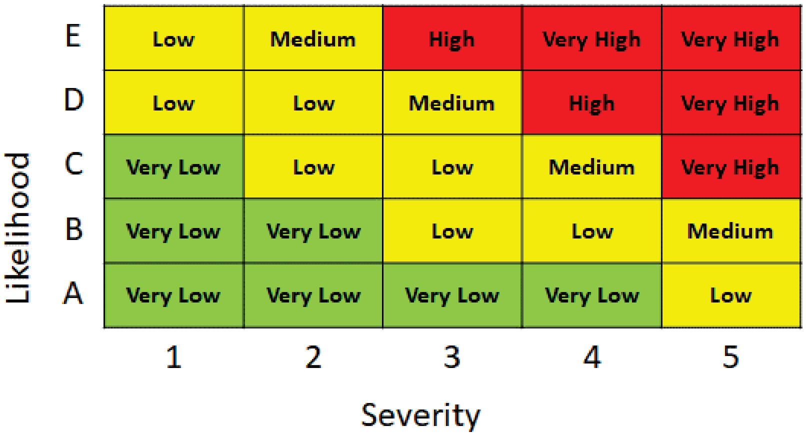
Figure 1. Risk management process examples used in industry [21] [23] [24].

- "*Risk Planning: "...process [to] document the activities to implement the risk management process."*
- *Risk Identification: "... involves examining the program to identify risks and associated cause(s) that may have negative consequences."*
- *Risk Analysis: "...estimates the likelihood of the risk event occurring, coupled with the possible cost, schedule, and performance consequences (if the risk is realized) in terms of impact to the program. Risk consequence is measured as a deviation against the program's performance, schedule, or cost baseline and should be tailored for the program."*
- *Risk Mitigation:*
    - *"...decide[s] whether the risk should be accepted (and monitored), avoided, transferred, or controlled."*
    - *"...seeks to reduce risk to an acceptable level in order to minimize potential program impacts."*
    - *"...reduce the likelihood of a risk event occurring, although consequences associated with a risk may be reduced if the program changes the design architecture or addresses binding constraints."*
- *Risk Monitoring: "...systematically track and evaluate the performance of risk mitigation plans against risk burn-down plans as well as assess performance achievement through associated TPMs [technical performance measures]."* [20]

Identifying risks starts by locating technical design weaknesses and potential issues associated with cost and / or schedule. These are discovered using different techniques which commence the risk analysis process. Some tools (not all inclusive) that could be used include brainstorming, checklists, hazards and mapping exercises, fault tree analyses, cause-consequence analyses, event tree analyses, reliability block diagrams and analyses, failure modes, effects, and criticality analyses (FMECA), preliminary hazards analyses, or statistical analyses based on probability assessments, or master logic diagrams [21].

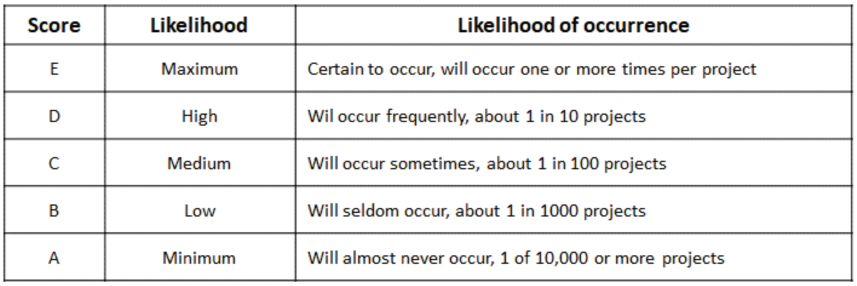
During this effort, technical, cost, and schedule risks are evaluated. For space enterprises, this includes evaluating design, testing, production, launch, and mission risks. Once the risks are identified the probability of likelihood and the consequences are estimated. These are mapped to an assessment table. A common mapping method is to use a risk matrix as exemplified in Table 3. The horizontal axis represents risk severity [23]. The vertical axis represents risk likelihood. These are typically unique to each company or government program. It is dependent on the risk management plan that is developed; however, they tend to be similar. Tables 4 and 5 illustrate an example on how the likelihood of risk realization and its severity is measured and assessed. Table 6 is ISO's risk magnitude and the proposed actions associated with each. These risk matrices are methods used to qualitatively prioritize risks and to communicate the level of concern associated with the issues identified. These can be tailored according to a program's risk management plan. It is a qualitative approach and is dependent on the type of data available used. This initial

Table 3. Sample Risk Matrix [23]



Likelihood	1	2	3	4	5
E	Low	Medium	High	Very High	Very High
D	Low	Low	Medium	High	Very High
C	Very Low	Low	Low	Medium	Very High
B	Very Low	Very Low	Low	Low	Medium
A	Very Low	Very Low	Very Low	Very Low	Low
	Severity				

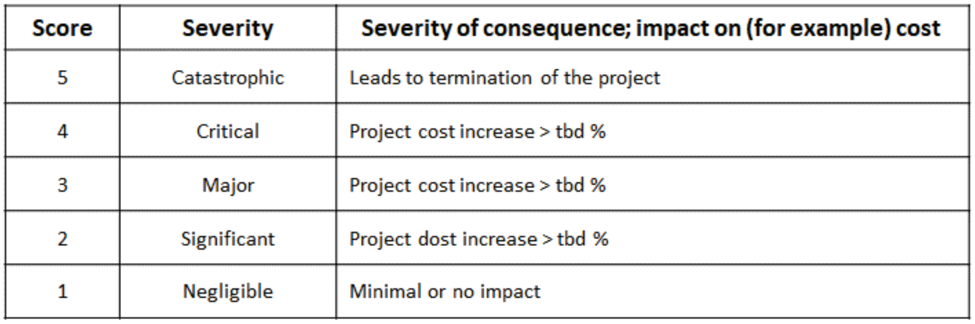
Table 4. Sample Likelihood Scoring Scheme [23]



Score	Likelihood	Likelihood of occurrence
E	Maximum	Certain to occur, will occur one or more times per project
D	High	Wil occur frequently, about 1 in 10 projects
C	Medium	Will occur sometimes, about 1 in 100 projects
B	Low	Will seldom occur, about 1 in 1000 projects
A	Minimum	Will almost never occur, 1 of 10,000 or more projects

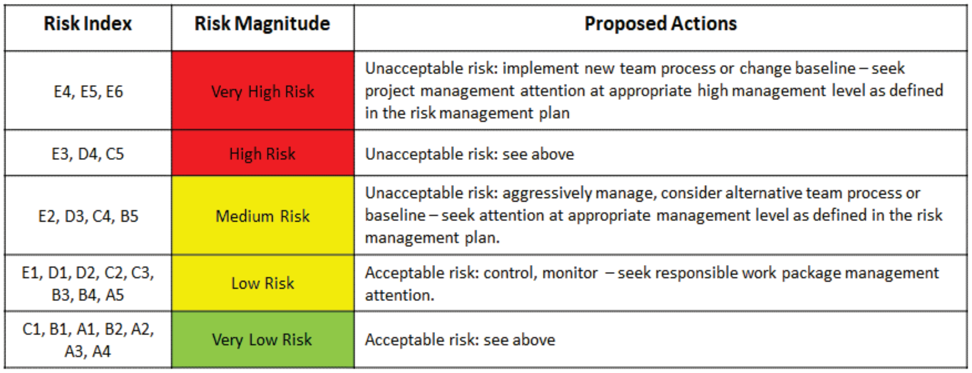
assessment is used to determine where a risk resides on the risk matrix which will dictate the level of risk analyses, mitigations and monitoring required.

Table 5. Sample Severity-of-Consequence Scoring Scheme [23]



Score	Severity	Severity of consequence; impact on (for example) cost
5	Catastrophic	Leads to termination of the project
4	Critical	Project cost increase > tbd %
3	Major	Project cost increase > tbd %
2	Significant	Project dost increase > tbd %
1	Negligible	Minimal or no impact

Table 6. Sample Risk Magnitude Designations and Actions [23]



Risk Index	Risk Magnitude	Proposed Actions
E4, E5, E6	🟥 Very High Risk	Unacceptable risk: implement new team process or change baseline – seek project management attention at appropriate high management level as defined in the risk management plan
E3, D4, C5	🟥 High Risk	Unacceptable risk: see above
E2, D3, C4, B5	🟨 Medium Risk	Unacceptable risk: aggressively manage, consider alternative team process or baseline – seek attention at appropriate management level as defined in the risk management plan.
E1, D1, D2, C2, C3, B3, B4, A5	🟨 Low Risk	Acceptable risk: control, monitor – seek responsible work package management attention.
C1, B1, A1, B2, A2, A3, A4	🟩 Very Low Risk	Acceptable risk: see above

Keeping the COTS definition in mind and the risk management information presented, attention moves to how to evaluate COTS risks. COTS risk assessments are defined and performed within an RMF. Philosophically, the use of COTS itself does not increase risk relative to a non-COTS approach. COTS equipment can have better or worse performance than what is required. However, since COTS represents a large trade space, the use of COTS has many subsets that do involve elevated risk. This risk applies to non-COTS products like new space-grade or MIL-Spec parts too, especially if those parts that have never been proven in the space environment. In many cases, the term COTS is used to represent a non-radiation-hardness assured (non-RHA) product, which has nothing to do with whether a product is COTS or not, or a product that is being used outside of its limits or proper context. For example, non-RHA MIL-Spec parts (representing most MIL-SPEC parts) are often denoted COTS [5]. Therefore, to ensure the research's foundations were set, this effort adopted NASA's risk management definition which states (as noted in Table 2) that it is,

> *"…a deliberative, systematic process to analyze and communicate the risk of performance shortfalls. This process involves development of risk handling and mitigation options, and implementation of approved strategies to reduce or eliminate the likelihood of occurrence and/or severity of consequence." [24]*

This concept is illustrated in Figure 2. It depicts a generic RMF model as developed by Meyer

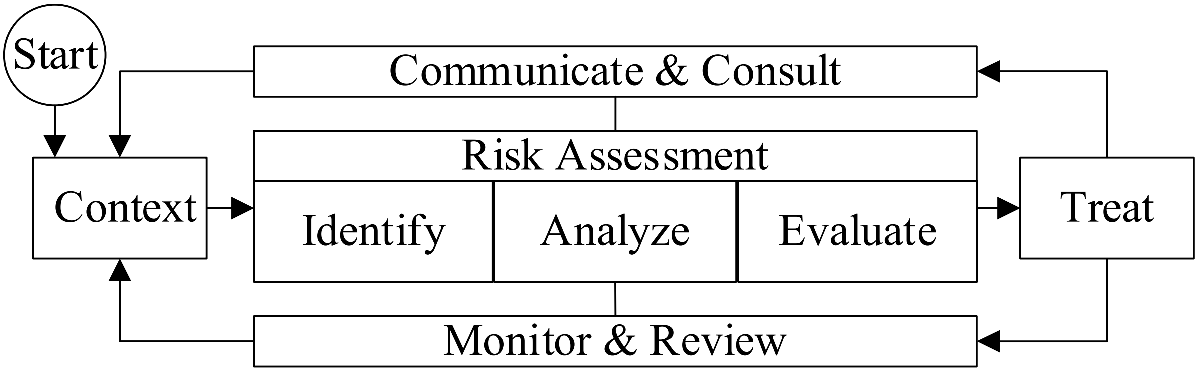


Figure 2. Generic risk management iterative framework used as the foundation to create a COTS risk management process [21].

and Reniers [21]. [The 'START' node was added for clarity.] This model presents RMF as a closed loop process used to identify, analyze, evaluate, and treat (mitigate) risks. Stakeholders use this information to decide whether to accept, avoid, control, mitigate, or transfer risks [20]. This cyclical process continuously feeds information to stakeholders for situational awareness and action. It is this model (Figure 2) combined with the COTS and RM definitions that was used in this research as the starting point to develop a robust COTS RMF. Discussion on how this was accomplished is detailed in the follow-on sections.

1.5 COTS IN SPACE

Space vehicles are a broad and diverse set that includes launch vehicles, ballistic objects, satellites, cislunar vehicles, interplanetary travelers, space instruments, and deep space exploration vehicles. According to a recent analysis completed by the Space Report Online for 2021,

> *"The global space economy reached a new record of $469 billion in 2021. Commercial and government space activities continued to grow alongside revenue and budget increases, and this year set a record for launch and payload activity." [1]*

When compared to the amount of funding invested in the space industry in 2005 ($176 billion) to current investments, there has been a 265% increase by global industries and government programs. This is a significant increase that is forecast to increase by an additional 55% by 2026 [1]. Figure 3 is an excerpt from the Space Report Online analysis showing how quickly the space industry is growing. The data shows the commercial sector as the fastest growing sector as compared to government sponsored programs who used to be the aerospace industry's prime sponsor. Future space activity will focus on hardware that will orbit the Earth, especially at Low Earth Orbit (LEO) orbital profiles, though a small percentage is allocated to cislunar and deep space exploration missions. These LEO missions will primarily service commercial applications instead of the scientific or military communities that previously dominated the domain. Developing space systems is expensive and time consuming. Space system development is measured in years, not months or weeks. As such, the space industry continually seeks opportunities to reduce costs and to shorten production times. As previously discussed, one method taking further root is using more COTS components in hardware designs. This is an attractive alternative compared to developing unique custom-built products that are

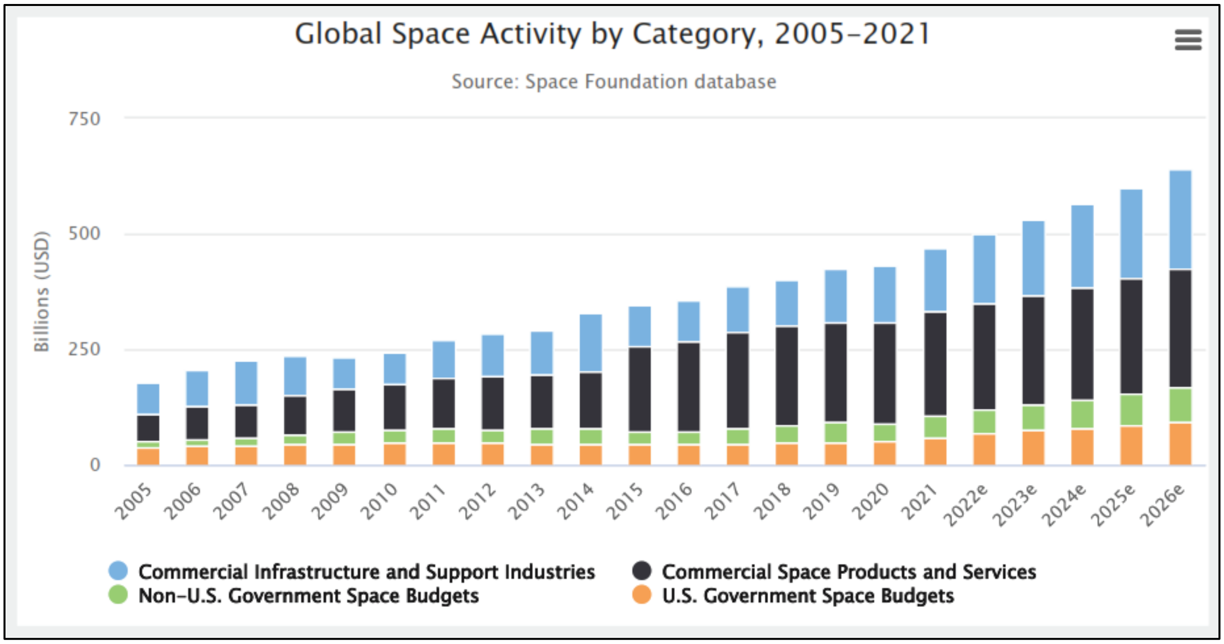


Figure 3. Space industry state between 2005 to 2021 and its predicted growth [1].

Expensive and produced in low quantities. However, the effort required to implement space hardware built with COTS can be significant yet rewarding if successful. Using COTS could yield considerable savings if effectively managed and used judiciously.

Another reason COTS are being heavily considered is that product suppliers that provide space-grade and MIL-Spec parts are dwindling. These are expensive to produce, are encumbered by rigid compliance requirements, and are a small sub-set of a supplier’s business. Thus, suppliers are rightly incentivized to focus on producing non-space-grade hardware that can be supplied efficiently, quickly, and in larger quantities. This business practice ensures they supply their high value commercial customers who provide more revenue than the aerospace industry. Moreover, as production processes mature, the hardware that they produce is proving to be more reliable and less prone to failure as experienced during the early days of space exploration. This increase in hardware resiliency makes COTS good candidates for space hardware applications.

The aerospace commercial and government sectors have used COTS components at the system, sub-system, and unit-level in the past, but not typically in high value spacecraft that had to survive in the rigors of space for extended periods. Use of COTS components are found in applications such as communications (i.e., RF systems, antennas, etc.), computing and data acquisition systems, electrical energy (i.e., batteries, power supplies, solar, etc.), instrumentation and sensors (i.e., cameras, radiation, etc.), and component level electronics (field programable gate arrays, resistors, capacitors, etc.). For example, Table 7 lists a sampling of hardware built with COTS that were successfully evaluated, deployed, and operated in space. This list references an effort completed by the National Space Development Agency of Japan. The Japanese integrated COTS into avionics systems used on three research satellites flown from 1998 to 2010 for 12-to-24-month mission durations [25] [26].

A more recent example is NASA Goddard Space Flight Center's (GSFC) SPACECUBE program that started in 2006 and continues today. The program's purpose was to build small space cube satellites that flew, "*...NASA developed space processors that established a hybrid-processing approach combining radiation-hardened and commercial components while emphasizing a novel architecture harmonizing the best capabilities of CPUs, DSPs, and FPGAs.*" [27] As shown in Table 8, the GSFC has launched and operated thirteen space cube satellites with 12 of the 13 built with COTS FPGAs. Seven of the CubeSats flown were comprised of greater than 95% COTS. NASA reported that they have not observed any of the COTS EEE parts fail while in orbit [27].

Despite successes such as these, COTS implementations and recommendations are typically kept within the company or government agency. One reason for this is companies do not wish to reveal proprietary methods which, if done, could benefit their market competition: so, valuable data remains hidden. However, there is data widely available in published technical literature that documents methods used to assess and enable COTS integration into space hardware. This research asserts that this data can be mined and distilled to develop useful COTS-based hardware risk management methods that can be compiled into guidance for the space industry to use.

Table 7. COTS-based Space Hardware Examples [25] [26]

Country	**Mission**	**Year**	**Type**	**Hardware**	**Duration**
Japan	COMETS	1998	SAT / GEO	Color CCD Camera	18 mo
Japan	COMETS	1998	SAT / GEO	330 k Pixels RGB CCD	18 mo
Japan	COMETS	1998	SAT / GEO	Camera Lens	18 mo
Japan	COMETS	1998	SAT / GEO	MPU (30 bits RISC Chip)	18 mo
Japan	COMETS	1998	SAT / GEO	Camera Head FPGA	18 mo
Japan	COMETS	1998	SAT / GEO	Camera Controller FPGA	18 mo
Japan	COMETS	1998	SAT / GEO	8/512 SRAM	18 mo
Japan	COMETS	1998	SAT / GEO	16x128 kbits Flash ROM	18 mo
Japan	COMETS	1998	SAT / GEO	Power Supply Unit	18 mo
Japan	SERVIS 1	2003	SAT / LEO	1 Mbit SRAM	24 mo
Japan	SERVIS 1	2003	SAT / LEO	4 Mbit SRAM	24 mo
Japan	SERVIS 1	2003	SAT / LEO	128 kbit SOI SRAM	24 mo
Japan	SERVIS 1	2003	SAT / LEO	32 Mbit Flash Memory	24 mo
Japan	SERVIS 1	2003	SAT / LEO	EEPROM FPGA	24 mo
Japan	SERVIS 1	2003	SAT / LEO	SRAM FPGA	24 mo
Japan	SERVIS 2	2010	SAT / LEO	4 Mbit SRAM	12 mo
Japan	SERVIS 2	2010	SAT / LEO	8 Mbit SRAM	12 mo
Japan	SERVIS 2	2010	SAT / LEO	256 kbit DRAM	12 mo
Japan	SERVIS 2	2010	SAT / LEO	512 Mbit DRAM	12 mo
Japan	SERVIS 2	2010	SAT / LEO	128 kbit SOI SRAM	12 mo
Japan	SERVIS 2	2010	SAT / LEO	128 Mbit Flash Memory	12 mo
Japan	SERVIS 2	2010	SAT / LEO	SRAM FPGA	12 mo
Japan	SERVIS 2	2010	SAT / LEO	EEPROM FPGA	12 mo

However, to incorporate COTS effectively, the spacecraft's mission, environment, application, and lifetime (MEAL) [28] must be considered. Accordingly, the risk management processes used should be tailored to determine if COTS can be used. For example, Table 9 describes five spacecraft by their mission profiles, the time the SVs are required to survive in space, and the stimuli that could impact their operations. As can be seen, there are several hazardous stimuli that can impact the hardware's performance. These environmental influences are quite dynamic and are difficult to model and predict. During the launch, deployment, and operation of a LV and SV, there are several use cases (i.e., launch, separation, thermal exposure, etc.) that are considered when developing the systems architecture, engineering design, and testing plans.

Table 8. NASA GSFC SPACECUBE COTS-based Field Programmable Array Successful Use From 2006 to 2020 [27]

NASA Goddard Space Flight Center SPACECUBE (2009 - 2020)				
Project	**Version**	**BOM Sum**	**COTS%**	**COTS Months Flown**
RNS	v1.0	3700	1%	12
MISSE-7	v1.0	3100	2%	22320
SMART	v1.5	1000	95%	32
STP-H4 CIB	v1.0	1500	1%	900
STP-H4 ISE2.0	v2.0-EM	1250	99%	111375
STP-H5 CIB	v1.0	1500	1%	1101
STP-H5 ISEM	v2.0 Mini	1000	98%	35966
STP-H5 Raven	v2.0-EM	1500	99%	136249
RRM3	v2.0	1429	99%	41498
STP-H6 CIB	v1.0	1500	1%	295
STP-H6 GPS	v2.0	1157	99%	22527
Restore-L Lidar	v2.0	2000	0%	[Data Not Listed in Ref]
STPSat6	v2.0 Mini	1500	98%	[Data Not Listed in Ref]

Figure 4 is an artist illustration to show how risks increase as a function of exposure to the space environment. It also shows how the risks are lowered when robust risk management techniques are enforced. In many cases, the likelihood that an issue will occur can be reduced using various techniques such as carefully selecting the component used, developing a robust design using those cherry-picked parts, enhancing production quality assurance protocols, adding redundancy, incorporating shielding, hermetically sealing the product, controlling its thermal exposure, implementing robust testing, or using software to control its operational cycles. These are examples of the five methods used to resolve risk as expressed in the DoD Risk Management Guide which are [30] “*acceptance, avoidance, control, burn-down, and transfer*”.

Table 9. Space Vehicle Characterization and Stimuli [29]

Space Vehicle	**Mission**	**Longevity**	**Hazard**
Launch Vehicle	Transport SV to space	< 100 hours	Acceleration Acoustic Atmospheric Drag Charged Particles Electromagnetics Gravity Pressure Micrometeorites Radiation Shock Space Debris Space Weather Thermal Vibration
Research & Technology Development	Space vehicle or hardware development	< 2 years	
Cislunar	Designed to support scientific research to support travel and operations related to the moon	< 5 years	
Satellite	Consumable products (i.e., cartography communications, defense, meteorology, surveillance, etc.)	<15 years	
Exploration	Scientific research	1 to ‘n’ years	

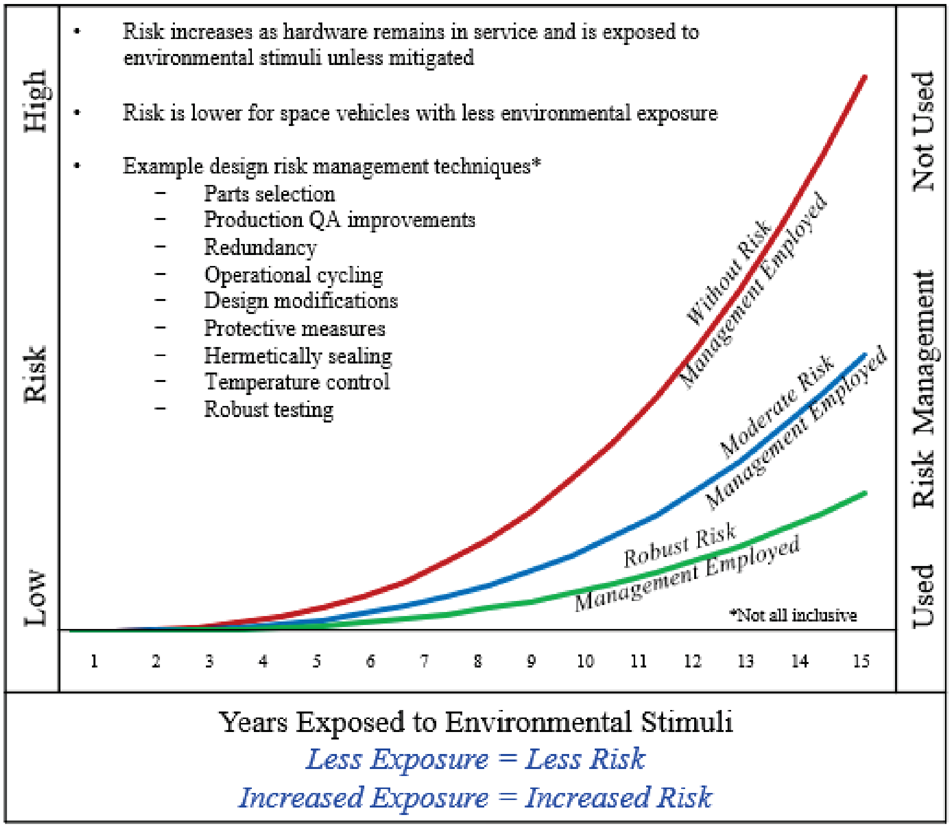


Figure 4. Increased risk as a function of environmental exposure.

1.6 COTS USE RISKS AND BENEFITS

Designs developed with COTS are often asserted in technical literature as being less expensive, easier to produce, and can perform as well as space-grade hardware. The FAA report discussed earlier (Table 1) captured this sentiment eloquently by quoting the DoD 5000.2R [11] acquisition policy that states , *"…Commercial and nondeployment items shall be considered as the primary source of supply*". Furthermore, the report cites the 2001 DoD procurement guidance [11] as stating,

> *"The use of COTS products to build military systems accomplishes the following objectives:*
> - *Reduces system acquisition costs by reducing development costs.*
> - *Reduces the time required to field new military systems by reducing development time.*
> - *Capitalizes on commercial research and development to field state-of-the-art systems more quickly.*

- *Offers opportunities to reduce life-cycle costs."*

To comply with this guidance, designers need to seek and embrace alternative methods to validate COTS parts for space applications. For example, Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Screening (HASS) are techniques that can be used to discover design weaknesses which would not have been discovered using traditional qualification test methods. Such tests and screening methods could yield significant cost and schedule savings. However, there exists hesitancy within industry and their customers to embrace an evolved and more aggressive risk management paradigm. Some reasons for this include:

- Lack of supplier oversight is believed to induce risk which is not desirable [7].

- Compared to MIL-Spec parts, part-level verification for COTS used in spaceflight systems remains a major challenge, since there is no government insight or direct / formal communication channel existing with the COTS parts manufacturers [31].

- Companies, especially payload owners, desire to stick with tried-and-true development and qualification methods to adhere to contractual levies to use only hardware that meets design and testing requirements [32].

- *"…traditional MIL-SPEC [U.S. defense standard / military specification] methodology is based on risk avoidance by testing finished parts."* [33]

- In the past, reliability of EEE parts that were not trusted caused the genesis of establishing strict standards, testing, material traceability, and adherence to key and *"tightly controlled"* parameters [34].

- Defense Acquisition Reform in the 1990s modified mission assurance practices from having the government involved in the oversight to allowing industrial contractors to use their best practices. Without having to show compliance to a specific benchmark, suppliers and customers developed their own processes for demonstrating parts survival in harsh environments [35].

- *"…technical specifications / scopes of work (SOW) specify an absolute reliability limit to be met, penalizing use of COTS."* [33]

- DoD high value payload stakeholders desire to reduce and mitigate risk to the maximum extent possible as demonstrated by their program categorization. There is not an appetite to accept more risk because the payload is needed to complete missions that support national defense strategies [19].

For example, Table 10 is from the USAF Space and Missile Systems Center "Mission Assurance Tailoring Guide", SMC-G-007 [36]. It classifies space vehicle risk into four acquisition categories. Class A and B are shown to be the most restrictive. For these spacecrafts, the USAF / USSF have profound oversight authority to pursue *"...all practical measures taken to minimize risk to mission success.*" [36] as reflected in Table 10. Thus, stepping away from methodical and effective yet costly and time-consuming hardware development processes are, in essence, assuming more risk because there may be numerous variables associated with COTS use. But as parts manufacturers steer further and further away from producing space-grade and MIL-Spec hardware, the space industry will have to adapt, evolve, and find other supply sources for the required components or modify their designs accordingly. Moreover, using COTS could

Table 10. USAF [USSF] Space Vehicle Risk Class Attributes [36]

	Class A (Typically ACAT I/II Programs)	**Class B (Typically ACAT II Programs)**	**Class C (Typically ACAT III Programs)**	**Class D (Typically Experimental Programs)**
Risk Acceptance	Lowest	Low	Moderate	High
National Significance	Extremely Critical	Critical	Not Critical	Not Critical
Payloads	Operational	Operations demonstrates operational utility; May become operational	Typically Experimental	Typically Experimental
Acquisition Cost	Highest	High	Medium	Lowest
Development Time	May take 4 or more years	May take 3 or more years	May take 2 of more years	May take 1 or more years
Mission Life	Long, greater than 5 yrs, typically 8-10 years	Medium, up to 5 years	Short, less than 2 years	Short, less than 1 year
Launch Constraints	Critical	Medium	Few	Few to none
Specifications and Standards Compliance	Specs/Stds fully incorporated as compliance documents with no to limited tailoring of requirements. All practical measures taken to minimize risk to mission success.	Specs/Stds required as compliance documents with minor tailoring in application to maintain a low risk to mission success.	Medium risk of achieving mission success may be acceptable. Reduced mission assurance requirements with tailoring acceptable.	Higher risk acceptance of achieving mission success. Reduces set of mission assurance requirements acceptable.

yield further complications because eventually there is a point of diminishing returns. If the efforts to include COTS are overly complex and cost prohibitive, then it does not make fiscal sense to expend the resources to develop the COTS-based hardware. Therefore, defining risk management processes early assists hardware architects and their stakeholders to make risk-enabled choices whether to keep, modify, or to reject the COTS-based design.

Figure 5 is a conceptual comparison of the development process of a COTS-based design solution against a traditional custom hardware development process. The figure depicts both paths starting with the project's ramp-up and initial design processes. The two paths diverge but run in parallel after an Analyses of Alternatives is completed to identify feasible design solutions that may meet the hardware's performance requirements. Both concepts run in parallel to develop prototypes. But, in this illustration the custom prototyping effort tends to take longer to complete because procurement lead times for space-grade components can be lengthy due to rigid design and component level testing required. After a prototype has been built, it is subjected to developmental testing followed tests to qualify the design. It is after this the designer will need to decide on whether to proceed or not.

There exist inherent risks when using COTS to develop space-grade hardware. If COTS incorporation requires multiple iterations to obtain an acceptable product, it could equal or exceed the time and cost it would have taken to complete a custom-built product. The designer eventually reaches a point where a decision must be made to abort the COTS-based solution, move on to the next concept, or follow the custom build route. So, understanding the benefits and risks early in the COTS-based hardware development process will assist in making difficult development decisions early in the design process.

A sample of the risks and benefits affiliated with using COTS are shown in Table 11. These were some of the points inferred in Katz's paper titled, "*Evaluation of COTS Hardware Assemblies for use in Risk Averse, Cost Constrained Space-based Systems*." [37] Besides what Katz describes, Table 11 lists several attributes associated with potential risks that were extracted from the technical literature review. To address using COTS risks, Katz developed a simple roadmap, Figure 6, that could be used as a starting point to evaluate COTS-based hardware. Her roadmap broadly examines a method to evaluate COTS being incorporated into hardware designs. Her proposed process is articulate; however, there are many details that require amplification. This is especially true when a developer is attempting to understand what should and what should not be considered a risk.

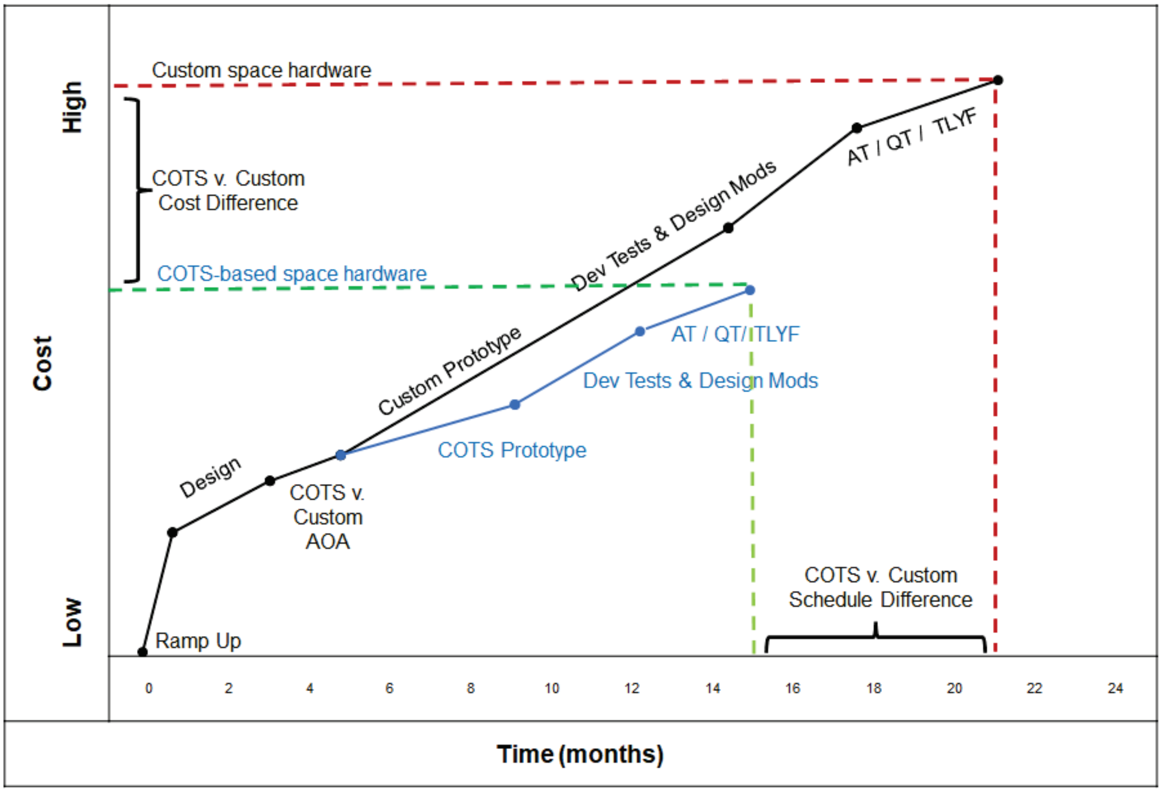


Figure 5. Hypothetical COTS versus custom space hardware development comparison.

The research documented in this study significantly expands Katz's model by developing a refined RMF and risk evaluation processes that can be used to answer many of the questions she poses. Substantial focus is put on her model's "*Analyze to Determine Gaps*" and "*Perform Risk Assessment and Document Results*" blocks. One such area explored further is the block that Katz dedicated to collecting technical data about the product being considered. This is accomplished by obtaining the COTS candidate's technical literature that details its design, testing profiles, and

Table 11. COTS-based Hardware Benefits and Risks [37]

Benefit	Risk
Modern technology used	− Technology Readiness (TRL) is not mature. − Rapid obsolescence requires mitigation. − Counterfeit parts require mitigation. − Information assurance requirements require assessment.
Rapid design development & fielding	− Potential need to assess design to component level. − Potential off-nominal function can indicate hidden weaknesses. − Characteristics and performance may not be adequate.
Significant cost savings	− Significant testing negates savings. − Development demonstrates product will not work as expected equating to lost time and investments.
COTS evaluated by manufacturer	− Test data not shared creates uncertainties. − Design weaknesses are unknown. − Might not work in space environments. − Overabundance of testing may negate benefits.
High production = high reliability	− Reliability assessment may not agree. − Lack of production insight equals uncertainty. − Supplier production processes changed without insight. − Supplier quality control processes may lack rigor.
Mature production processes	− Manufacturing Levels (MRL) are not mature. − Production weaknesses are unknown. − Lack of manufacturing quality control requires mitigation. − Potential inability to affect the production process.
Rapid delivery	− Supply changes will create unforeseeable issues. − Delivery delays will create unforeseeable issues. − Handling, transportation, and storage requirements are unknown.

historical performance. If this information is not available, then steps are taken to measure the COTS capabilities and limitations.

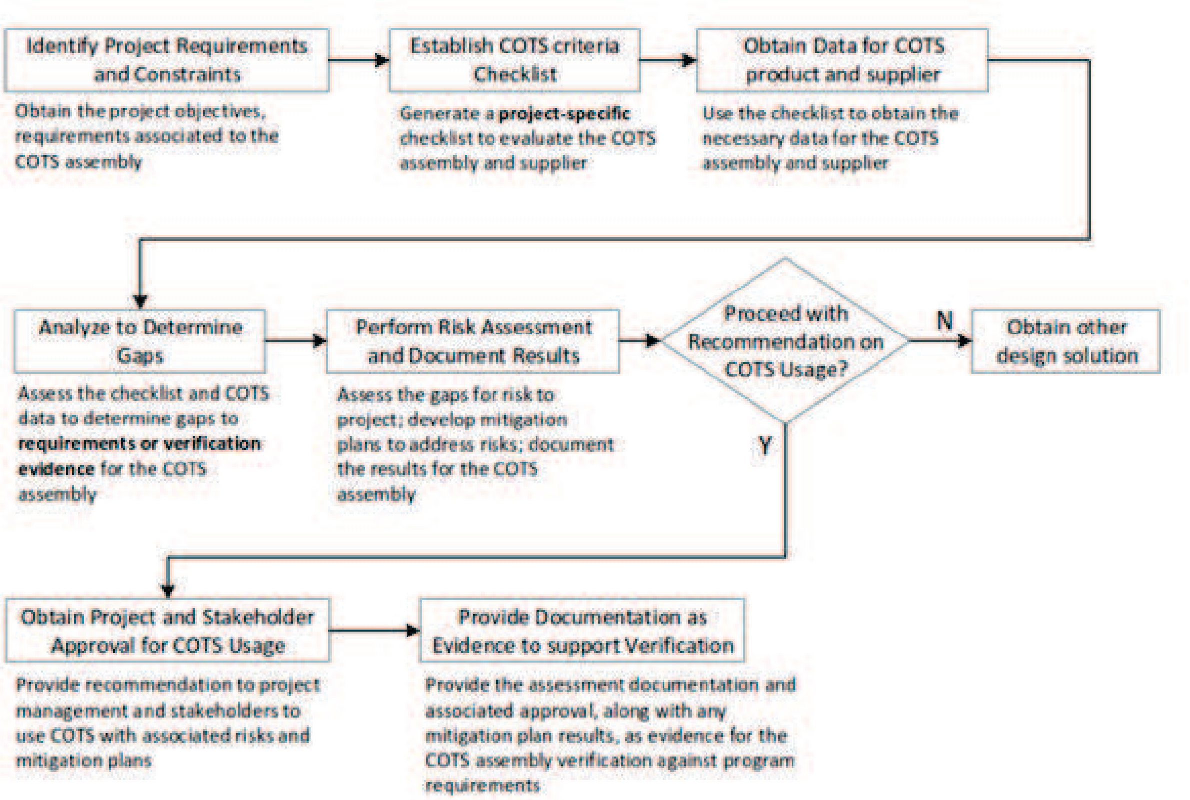


Figure 6. COTS-based hardware risk management focus areas. [37]

The second part of Katz's gap analysis process is more complicated. Figure 7 explores some of the considerations taken when performing the requirements gap assessment as she recommends. First, a designer must learn what the COTS' hardware was originally designed to do. Then, this knowledge is compared against the parts' available technical information, space and industrial standards, stakeholder policies, and legal statutes to determine if requirements gaps exist. Based on the gaps identified, plans can be developed to mitigate the risks when the parts are exposed to the harsh space environments. In this example, the red and blue blocks represent space and MIL-Spec standards and acquisition policies. The yellow and green blocks depict industrial and legal requirements.

The diagram is meant to show how all of these could or could not intersect. The hope is that all do. Realistically, they probably do not. As depicted in the diagram, there are at most four intersections between the various requirements. The ideal situation is for all four sets to converge and intersect. This means that there would be minimal work required to assess and manage any risk. However, were the number of intersections to lessen, it would mean that the hardware will have to undergo an increased amount of scrutiny.

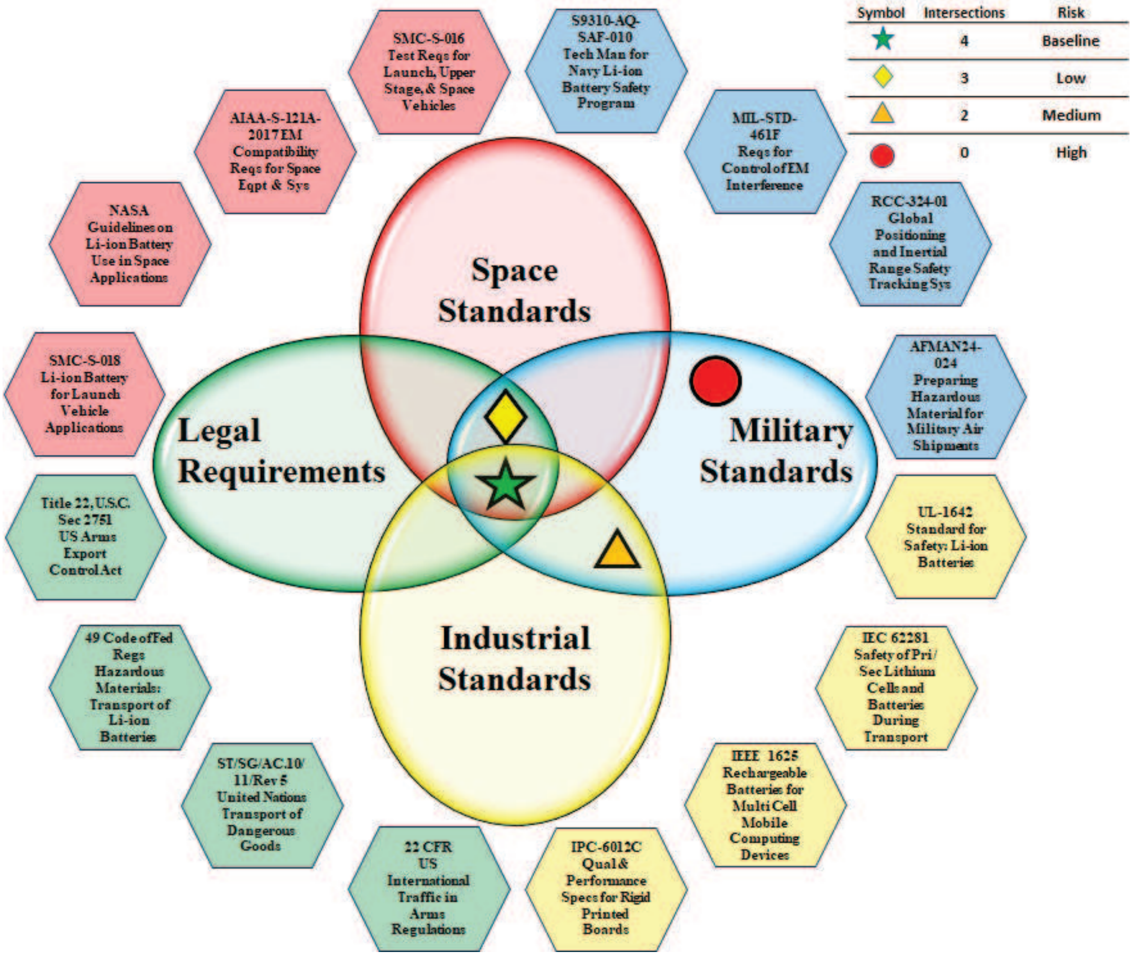


Figure 7. Example space hardware gap analysis that is used to reveal initial risks when considering the use of COTS in the design.

This means more risk would be incurred and the risk management efforts would increase. This is what is depicted using colored symbols.

The area where the green star resides shows the four areas intersecting which is interpreted as baseline risk and the parts can be integrated immediately into the hardware's design. The yellow diamond is placed where three ovals intersect. The orange triangle shows two intersections and a red circle showing zero intersections. These are meant to represent where low, medium, and high risk reside. Meyer and Reniers [21] describe these as risk uncertainty types which are listed below.

- *"Type I ...historical data is available,*
- *Type II little or extremely little historical data is available,*
- *Type III No historical data is available."* [21]

Undoubtedly, if there is a preferred type of uncertainty it would be Type I because it is slightly above the baseline level and most likely easily mitigated. However, the Type II and III uncertainties may require substantial resources to ascertain COTS suitability. Accepting these as a base assumption, space hardware designers need to select the tools and techniques needed to identify, analyze, evaluate, and treat the risks associated with using COTS to build space hardware. Just as Katz proposed, performing requirements gap analysis is a good datum to start the risk management effort and a good example of how to initially identify risks as discussed in the previous section. From this, management processes can be developed that are used to guide the use of COTS to build space hardware. But what is not covered by Katz's model is what the risk management processes are and what they are supposed to do. This is what this research investigated with the results presented in the sections to follow.

1.7 COTS AND RISK MANAGEMENT SUMMARY

The material presented provides the context for this research. The work accomplished in this study is meant to partially fill a gap that exists in current space design standards and policies when it comes to considering using COTS in space hardware applications. Because COTS and the concept of risk management varies, a defined lexicon was established. This lexicon was used to lay the foundation in the development of a COTS-based space system RMF. The material presented discussed three levels of uncertainty and two simple risk management frameworks developed by Katz [37], Meyer, and Reniers [21]. From these three elements a refined and detailed COTS centric RMF and evaluation processes were developed. To accomplish this research's goals, the objectives listed below were defined. How these objectives were met is what will be presented in the rest of this document.

- Establish a clear and concise research agenda that outlines the methods used to develop and validate a COTS-based space system risk management framework.

- Perform a comprehensive technical literature review to decide how COTS have been successfully used to design, build, test, and field space hardware,

- Extract best practices from the technical literature to develop feasible and effective risk evaluation and mitigation strategies,

- Categorize the use of COTS based on a space vehicle's purpose, performance, longevity, and the environmental stimuli it will be subjected to,

- Identify the hazards and stimuli that will induce risk to the hardware's nominal performance,

- Develop risk management strategies and evaluation processes that the space industry can mimic, tailor, and employ when considering a COTS-based design solution,
- Demonstrate how a COTS centric risk management framework can be validated by employing tailored risk management processes during the design, testing, and fielding of a COTS-based space-grade exemplar hardware unit.

2. RESEARCH AGENDA

The focus of this research is the development of a risk management framework that can be used by the space industry to decide if using Commercial-Off-the-Shelf (COTS) components in space-grade hardware is possible, efficient, cost effective, dependable, and safe. Once developed, the risk management strategies could be tailored and used by the space industry to make informed risk management decisions when considering using COTS to build space hardware. To achieve the research goal, five Research Questions (RQ) were posed which were:

- Research Question No. 1: What are the controls, enablers, and activities of a risk management strategy for COTS-based space system hardware?

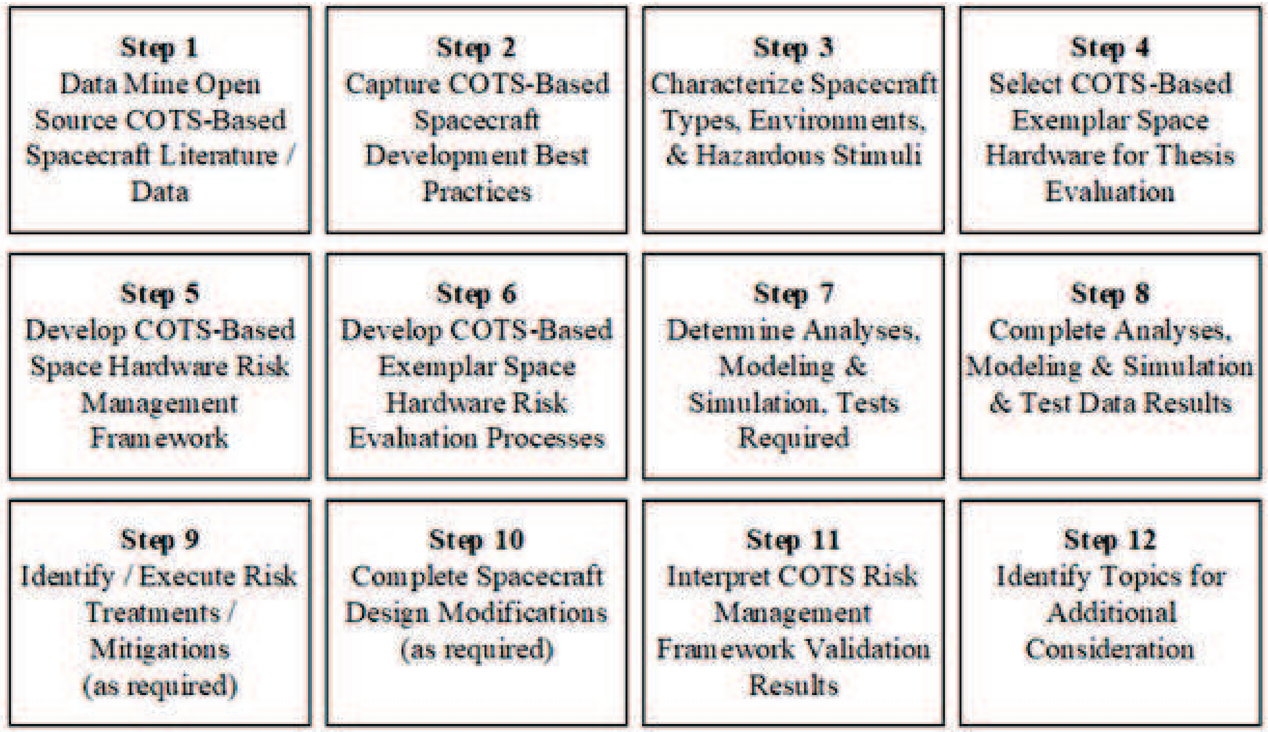
- Research Question No.2: What are the missions, space vehicle types, and environments that need to be considered when evaluating COTS components for integration into LV / SV architectures and designs?

- Research Question No. 3: What type of industry risk management methods can be tailored to assess COTS-based hardware designs?

- Research Question No. 4: What COTS analyses, modeling, and tests can be used to validate COTS-based space system hardware risk management strategies?

- Research Question No. 5: What lessons can be learned from this effort that can benefit the space industry and what recommendations can be made to further the research?

To answer the research questions, a twelve-step process was employed which is shown in Figure 8. The first step in the twelve-step research process was to review open-source technical literature that described COTS being successfully integrated into space hardware. The study of RM textbooks, organizational RM policies, technical journal articles, and conference proceedings yielded valuable information about methods that were successfully used to evaluate and integrate COTS into spacecraft designs.



Step 1 Data Mine Open Source COTS-Based Spacecraft Literature / Data

Step 2 Capture COTS-Based Spacecraft Development Best Practices

Step 3 Characterize Spacecraft Types, Environments, & Hazardous Stimuli

Step 4 Select COTS-Based Exemplar Space Hardware for Thesis Evaluation

Step 5 Develop COTS-Based Space Hardware Risk Management Framework

Step 6 Develop COTS-Based Exemplar Space Hardware Risk Evaluation Processes

Step 7 Determine Analyses, Modeling & Simulation, Tests Required

Step 8 Complete Analyses, Modeling & Simulation & Test Data Results

Step 9 Identify / Execute Risk Treatments / Mitigations (as required)

Step 10 Complete Spacecraft Design Modifications (as required)

Step 11 Interpret COTS Risk Management Framework Validation Results

Step 12 Identify Topics for Additional Consideration

Figure 8. Twelve-step research process used to develop a COTS-based risk assessment framework.

Step 2 provides for a synthesis of the data collected in Step 1. Specifically, this step’s goal was to find industry best practices, controls, enablers, and activities that could be used to develop an RMF used to uncover technical uncertainties and how best to deal with them.

Step 3’s purpose was to characterize launch and space vehicle types. This was important because the success of using COTS is dependent on the LV’s / SV’s mission, environment, application, and lifetime or MEAL [31]. Also, it proved to be the starting point of the first risk management process developed. This parent RM process was used as the foundation to build other methods which were tailored to address uncertainties and risks discovered during the development of a space-grade secondary lithium-ion battery built with.

Steps 1 through 3 set up the knowledge baseline for the research. Steps 4 through 6 used this knowledge to create COTS-centric risk management and evaluation processes. These are the refinements of Katz's generic RMF as presented in Figure 6.

Step 4 identified the space hardware unit designed with COTS for use as subject to confirm that the COTS RMF was a useful system engineering tool. For this research, a secondary (rechargeable) lithium-ion battery made with COTS cells, a printed circuit board, and EEE components was chosen as the unit under test.

Once the exemplar was selected, Steps 5 and 6 were completed. Specifically, a tailored RMF and evaluation processes were developed to determine how best to characterize the COTS-based battery's performance.

Steps 7 through 9 executed the COTS-based exemplar's design evaluation. This included identifying the types of analyses, modeling and simulation, and testing needed and coordinating the scientific skills sets and tools needed to complete the assessments. After these preparations were completed, the exemplar technical evaluation was done. The results from each evaluation event were assessed to decide if more uncertainties were uncovered and how the COTS performed. It was during this phase that the battery exemplar components, subsystem, and system were exposed to varying degrees of hazardous stimuli to evaluate the product's response.

Step 10 was a task that was executed in parallel with Steps 8 and 9. As the analyses, modeling and simulation, and testing were completed, a cyclical and iterative assessment was completed to determine if any design modifications were required or if any other forms of preventative or protective measures needed to be incorporated. These risk treatment options were continuously checked for impact (if any) on the overall LV / SV production schedule and budget.

The final steps as shown by Steps 11 and 12, were to retrace the research's steps to determine whether the research's hypotheses were validated or not. Once completed, a holistic review was completed to document other topics that should be considered by the space industry when considering using COTS in spacecraft designs.

The results based on this research agenda are presented in the chapters that follow.

3. COTS-BASED SPACE HARDWARE SYSTEMS RISK MANAGEMENT CONTROLS, ENABLERS, AND ACTIVITIES

Deciding which risk management controls, enablers, and activities are used to develop COTS-enabled space system hardware required a deep dive into aerospace industry, military, and commercial standards, acquisition policies, and technical literature related to the development, fielding, and operation of space vehicles. The goal of the literature review was to extract industry best practices to answer Research Question No. 1 which was, "*What are the controls, enablers, and activities of a risk management strategy for COTS-enabled space system hardware?*"

3.1 SYSTEMS ENGINEERING RISK CONSIDERATIONS

Like space-grade parts, considering integrating COTS into space vehicles should be done as early in the project development process as possible. As Figure 9 illustrates, technical risk is not a mutually exclusive event. If the COTS implementation into the space vehicle does not adhere to the ideal development path as depicted in Chapter 1's Figure 5, there can be significant impacts to the program's budget, schedule, and potentially, the mission's success.

Another risk consideration is that design modifications are not always introduced into a space vehicle's architecture solely during the intended design phase. Depending on the program's development state there is precedent when architecture modifications were introduced during the middle and even at the end of a project's development and production phases [38]. Obviously, these types of events induce even more risk. Therefore, any risk management framework devised must be examined minutely and closely watched throughout the entire risk management process. This concept is depicted in Figure 2's "*Monitor & Review*" and "*Communicate & Consult*" generic risk management iterative framework that is used as the foundation to create a COTS risk management framework.

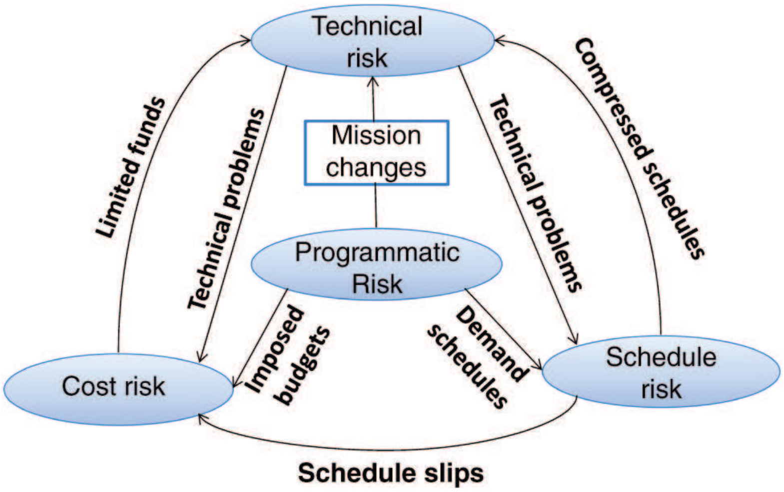


Figure 9. Technical, cost, and schedule risk interdependencies that must be addressed when considering using COTS in space hardware system designs [39].

Figure 10 [40] illustrates the effect that projects incur when technical issues occur late in the project's development schedule. As shown, it will cost more to address the issues in the latter phases of the project's design and production phases. The figure also shows how project manager's options and trade spaces are substantially reduced as well. So, when considering using COTS in a space vehicle's design, like any new hardware being explored, the best point to introduce it is during the conceptual and preliminary design phase. For example, using NASA's product development process as depicted in Figure 11 [39], the most opportune time to introduce COTS into a space vehicle design would be during the "*Concept Studies*", "*Concept & Technology Development*", and "*Preliminary Design and Technology Completion*" phases. This is highlighted using the green, yellow, red, and maroon overlays on the figure. In this case, green represents the area where COTS-based risks are deemed manageable from a technical, cost, and schedule perspective. As the program marches towards its end state (yellow to maroon), the risks become more pronounced, and their effect is acutely and quickly felt across the program's spectrum.

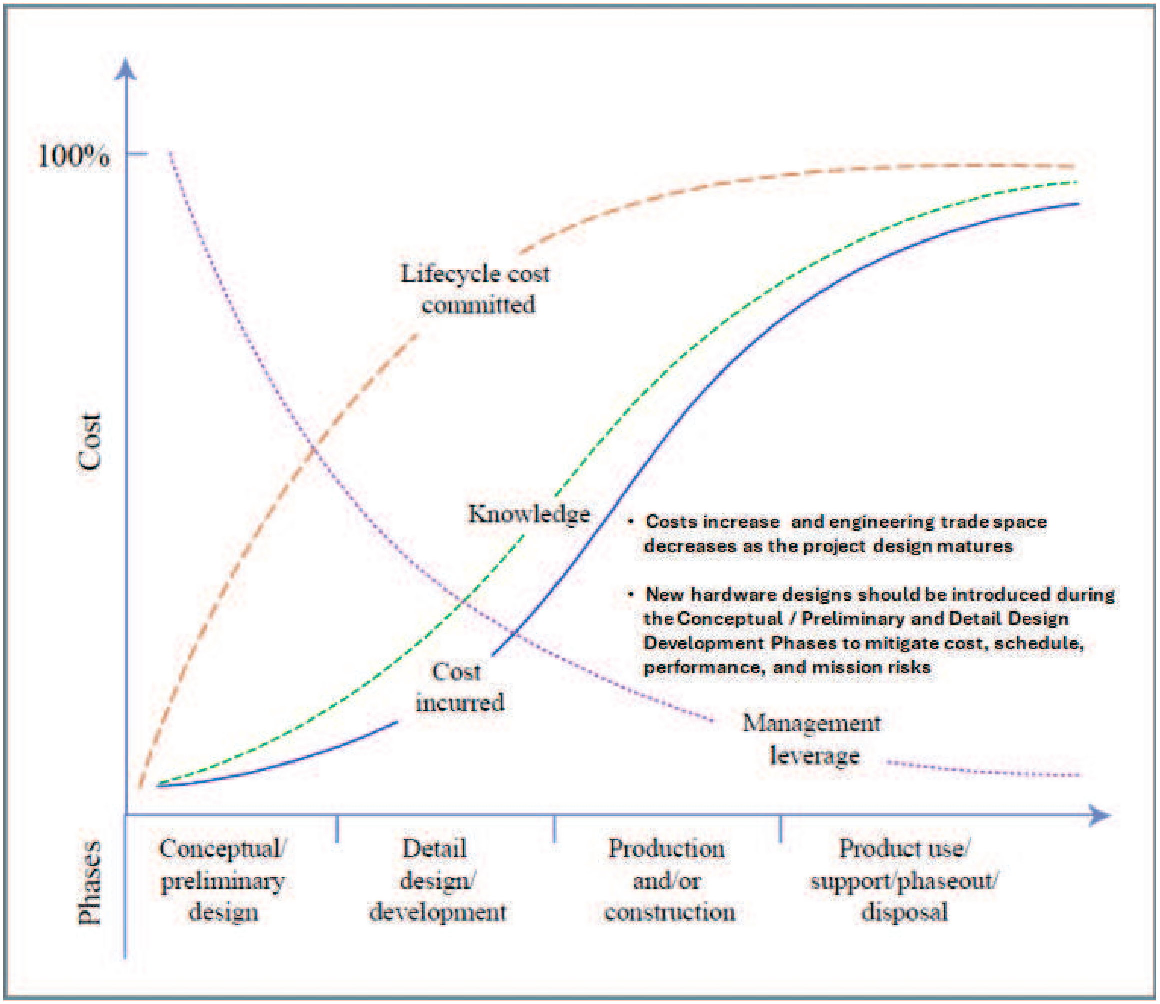


Figure 10. Conceptual illustration that depicts the increased costs and decreased development trade space incurred if issues arise during a project's development and production lifetime [40].

Because developing space system hardware is complex the risk management framework used needs to be agile to respond to off-nominal design developments. Contingency plans should be developed if a COTS-based solution does not appear to be possible. Waiting until the project reaches the point where the production baseline is approved is too late.

During the early stages of the project development, a cost and schedule analysis should be completed to pinpoint when a COTS-based design increases risk instead of reducing it. Along with this analysis, contingency plans should be in place which allow the program to pivot to an alternative, i.e., space-grade hardware development, which will keep the program on track to meet its goals. To complement this analysis, other traditional risk management tools such as risk mitigation burn-down graphs, technical and manufacturing readiness level assessments, reliability, maintainability, availability, and requirements compliance analyses can be used to inform decision authorities and stakeholders on the COTS-based hardware design's progress. This should be done often to ensure that preparations to execute contingency plans are completed. For example, Figure 12 is a tool illustrated in the INCOSE SEH [39] that can be used to watch how technical performance measures (TPM) or technical parameter values (TPV) are maturing during the concept and preliminary design phases. It can also be used as a tool to display the demarcation point which is fixed to a decision gate. This can be used to show when a decision needs to be made to continue with the COTS-based design or not. An example that illustrates the use of risk burn-down matrices is presented in Section 6.9.

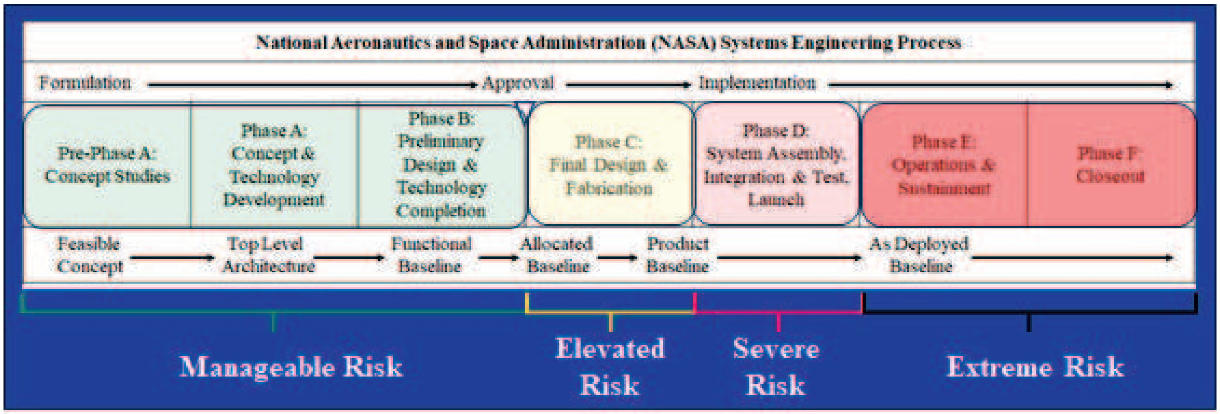


Figure 11. NASA systems engineering process used to develop space vehicles annotated to reflect the most opportune times to introduce new hardware designs [39].

Another consideration is evaluating the effect at the system level when a COTS-based unit does not perform its function nominally. For example, design architects would rightly ask what they could do, from a satellite bus design aspect, if a COTS-based battery used to power the satellite's subsystems (i.e., environmental control system, command and data handling, etc.) does not perform as expected. One such solution is to incorporate more batteries into the satellite design. This method is illustrated in Figure 13 which shows how hardware redundancy of identical units can be an effective risk mitigation measure at the system level. In this example, using the parallel network reliability equation, $R= 1- (1-R)^n$, [41], the addition of an additional battery raises the reliability from 0.95 to 0.9975. The addition of a third unit raises the reliability to 0.9998. In this case, if one battery fails, there are two other batteries that will

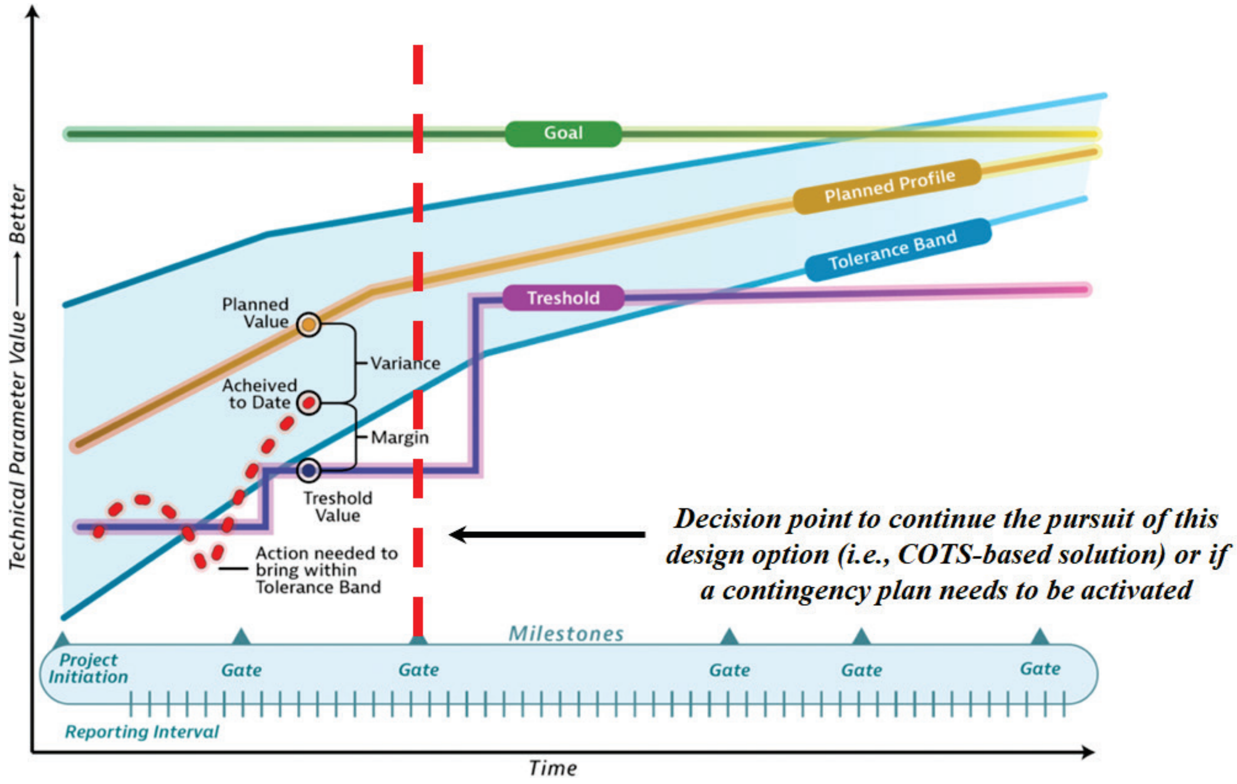


Figure 12. Technical Parameter Value tracking profile used as a risk management tool to inform space hardware architects, stake holders, and decision authorities on the progress of COTS-based hardware design progress [39].

assume the electrical load. Other mitigation options like these will be discussed in a later chapter when the COTS-based space system hardware risk management framework is presented.

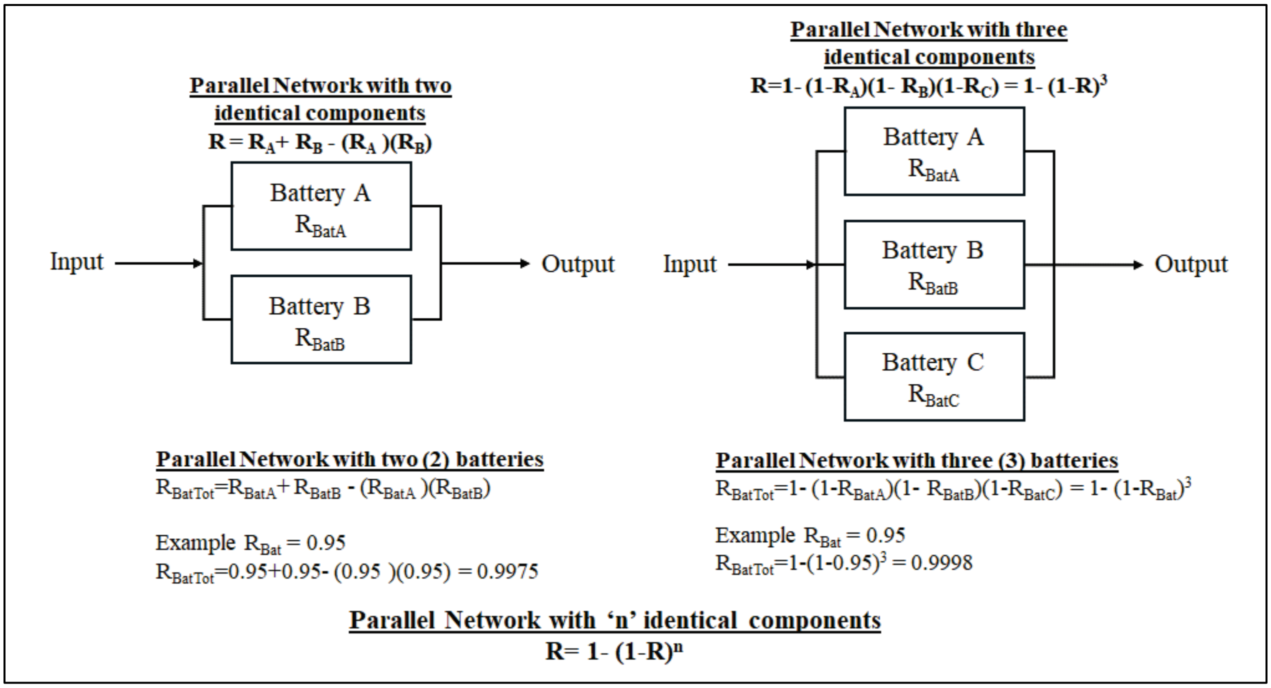


Figure 13. COTS-based hardware redundancy example used to address system level risks [41].

The systems engineering considerations discussed above are the reasons why spending the time to classify the controls, enablers, and activities that will influence the development of a COTS-based risk management framework is important. This is what will be discussed in the next section.

3.2 SYSTEMS ENGINEERING CONTROLS, ENABLERS, AND ACTIVITIES

The International Council on Systems Engineering (INCOSE) uses the terms controls, enablers, and activities to show how various influences contribute to a system's life cycle process [39]. INCOSE refers to controls as attributes that,

> *"...represent those typical inputs and outputs that control, or limit, the execution of the system life cycle processes. They either come in as an external (EXT) typical input or from one or more life cycle processes." [39]*

Enablers are the traits that,

> *"...represent those typical inputs and outputs that enable, or assist in, the execution of the system life cycle processes. They either come in as an external (EXT) typical input or from one or more life cycle processes." [39]*

Activities are considered "*a set of cohesive tasks of a process*." [39]

Figure 14 is an adaptation of the 2015 and 2023 INCOSE System Engineering Handbooks' input-process-output (IPO) process that illustrates how controls, enablers, and activities contribute to the development of a system and its life cycle process(es) [39] [42]. When this figure is related to a COTS in space systems context, many controls and enablers, as shown in Figure 14, surely will need to be addressed. For example, Table 12 identified laws and regulations (i.e., federal regulations), standards (i.e., SMC-S-018), agreements (i.e., UN Transportation Tests and Criteria) that fall under the controls category. Regarding enablers, the processes used to evaluate COTS, how risks are accounted for, and the methods used to practice sound quality assurance measures are used in concert with controls to develop activities that can be employed to evaluate COTS [39]. Once the appropriate controls and enablers are established, space vehicle architects can use those to identify the most appropriate activities that would be needed to characterize COTS performance. In this case, the activities being discussed would be those outside of the normal standards-based qualification regime. These activities would be used to gather the data to address the three uncertainty types previously discussed in Section 1.6. Additionally, these activities would be tailored to extract the minimum information needed to mitigate the risks associated with the uncertainties. An example would be to use various forms of non-destructive testing such as computed tomography or microscopic techniques to evaluate a COTS component without compromising its integrity. Activities like these were used to validate this research's risk management framework and will be discussed in length in follow-on chapters.

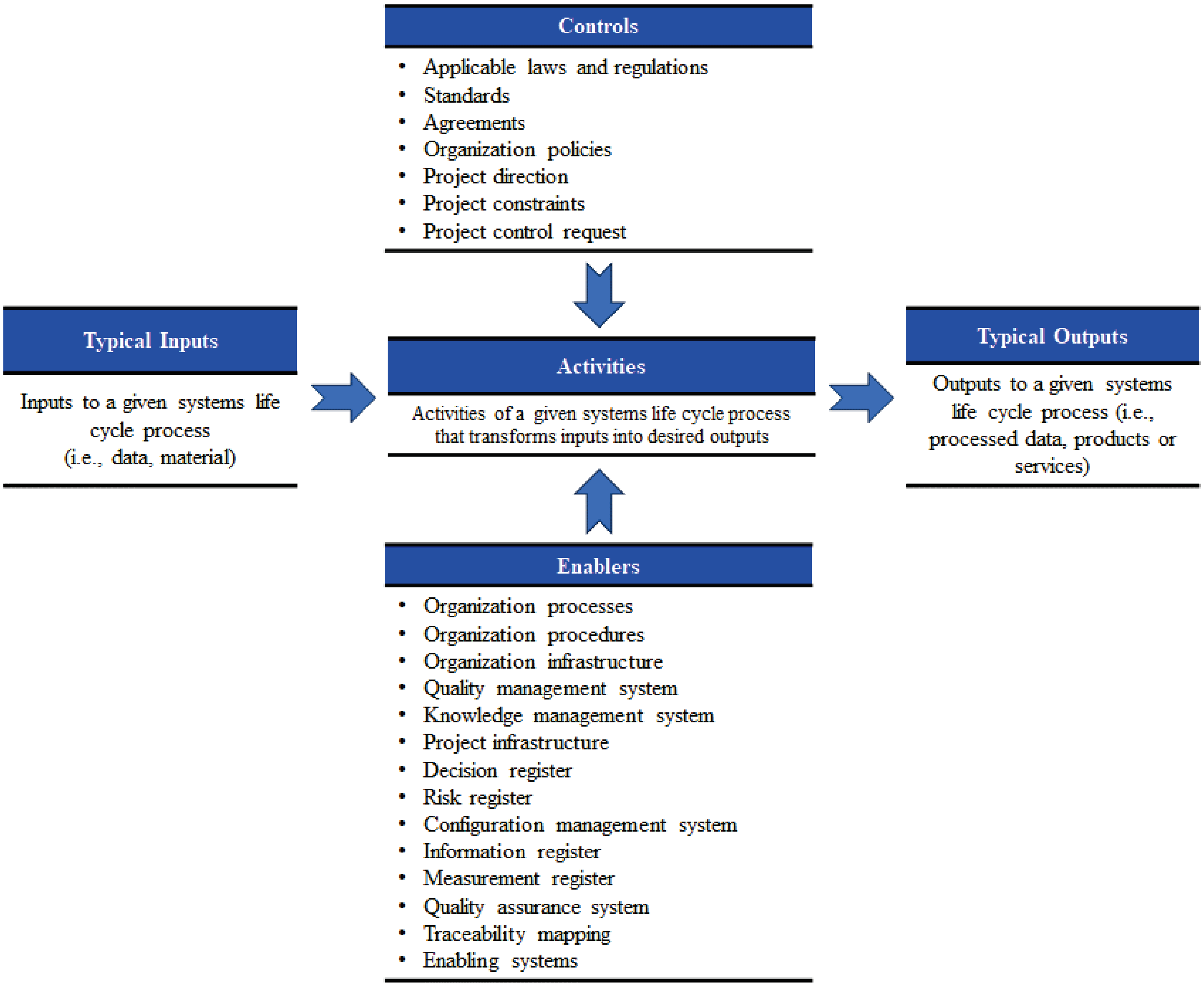


Figure 14. Representation of INCOSE's SEH (2015 & 2023) IPO diagrams that exhibit the contributions that controls, enablers, and activities have when considering a systems overall lifecycle development process [39] [42].

The INCOSE SEH infers that requirements are "project reports" that can be considered as an input to the IPO diagram [39]. In this case, it can be argued that the inputs are the requirements that a spacecraft must meet. Outputs can be considered results of activities that are executed. An output example would be a "risk management strategy / approach" which is defined by INCOSE as “*Approaches, schedules, resources, and specific considerations required to perform risk management”* [39].

Leveraging the systems engineering IPO concept and, as previously said, best practices and formal guidance on how to evaluate COTS are not established or agreed upon within the aerospace community. It can be proposed that when considering using COTS for space systems applications, all the major IPO components (inputs, controls, enablers, activities, and outputs) as illustrated in Figure 14, should be examined to find the best course of action. This was the goal behind the technical literature review. Specifically, systems engineering controls, enablers, and activities were found from this technical literature review. These were used to develop risk management frameworks and evaluation processes that are considered IPO outputs. These RMFs and risk evaluation processes will be presented in detail in Chapters 5 and 6.

3.3 LITERATURE REVIEW SCOPE

The scope of the technical literature review was wide. The material reviewed included aerospace and other relevant industry standards, policies, guides, textbooks, and peer reviewed technical articles. The research reviewed subject matter developed by the United States and their international space peers. This work focused on how COTS were successfully integrated into space hardware applications. Special emphasis was given to information related to the development and testing of lithium-ion batteries because a space-grade COTS-based secondary battery was chosen to confirm this research’s RMF. Listed below is a sample of the literature that was examined for this review.

- AIAA, ASTM, DoD, IATA, IEEE, IPC, ISO, NASA, and USAF/USSF standards relating to the design, development, testing, and qualification of hardware that will be used in space, military, or commercial applications.

- INCOSE, ISO, DoD, NASA, USAF/USSF, USN acquisition policy documents which provide guidance regarding the use of COTS hardware in programs that operate in extreme environments such as space, aviation, weapon systems, etc.

- DoD, ISO, NASA, USAF/USSF, and academic textbooks that described risk management, its use, and techniques applied to identify, manage, assess, and mitigate risk.

- Numerous domestic and international peer reviewed technical papers detailing the work accomplished to assess COTS components for use in space hardware designs.

- Academic and space industry specific documents related to launch vehicle and spacecraft architecture, design, and the space environments they would be required to operate in.

- Standards and testing guidance documents related to the screening of electronic components for use in space hardware applications.

- Standards and test protocols associated with electromagnetic interference (EMI) and electromagnetic compatibility (EMC).

- Standards, technical articles, textbooks, and testing guidance related to the evaluation of printed circuit boards, circuit designs, and electronic components.

- Technical articles that addressed how to evaluate lithium-ion cells, their circuit design, and safety features.

- Standards, regulations, statutes, range and transportation safety documents, and peer reviewed articles relating to the development, testing, and qualification of primary and secondary space-grade batteries. Specific emphasis was focused on work related to secondary space-grade lithium-ion batteries.

An example of the type of material reviewed is shown in Table 12. The documents listed are a subset of those that contain the driving performance, safety, and space qualification requirements for building a space-grade secondary lithium-ion battery. The literature in Table 12 is highlighted because it shows that the LV / SV architecture has to take into consideration requirements owned by a variety of stakeholders who are charged with overseeing various aspects of hardware design. For example, the COTS-based secondary Li-ion battery chosen as the research's test unit had to prove compliance with an extensive list of performance, qualification, safety, and transportation requirements that could not be waived. Requesting waivers to safety related requirements were considered undesirable because lithium-ion batteries could quickly transition to an unsafe state if not meticulously designed and controlled.

It was documents such as these that were used to conduct the requirements gap analysis on the COTS hardware being considered for integration into the exemplar battery's architecture as described in Figure 7. This review found there were numerous uncertainties associated with the compliance of the foreign produced lithium-ion COTS cells with the set of standards, how the circuit design would perform when subjected to hazardous stimuli (i.e., shock, thermal, acoustics,

Table 12. Applicable Lithium-ion Battery Compliance Standards and Statutes

Document Name	Doc. No.	Sponsor	Applicability
49 Code of Federal Regulations / Hazardous Materials: Transportation of Lithium Batteries	CFR-2010-Title49 Sec 173-185	DoT	Commercial and Military Transportation
NASA Guidelines on Lithium-ion Battery Use in Space Applications	TM-2009-215751	NASA	NASA Affiliated Programs
Preparing Hazardous Materials for Military Air Shipments	AFMAN24-204	USAF	DoD Military Aircraft Transportation
Qualification and Performance Specification for Rigid Printed Boards	IPC-6012C-2010	IPC	Dependent Upon Contract Compliance
Recommendations on the Transport of Dangerous Goods: Manual of Tests and Criteria	ST/SG/AC.10/11/Rev.5	UN	Commercial and Military Transportation
Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment	MIL-STD-461F	DoD	Dependent Upon Contract Compliance
Space and Missile Systems Center Standard: Lithium-ion Battery for Launch Vehicle Applications	SMS-S-018	DoD	Dependent Upon Contract Compliance
Space and Missile Systems Center Standard: Test Requirements for Launch, Upper-Stage, and Space Vehicles	SMC-S-016	USAF	Dependent Upon Contract Compliance
Space Systems - Lithium Ion Battery for Space Vehicles - Design Verification Requirements	ICO/TC 020/SC 014 CD 17546	International Organization for Standards	Dependent Upon Contract Compliance
Standard for Safety: Lithium Batteries	UL 1642	UL	Commercial LIB Cells & Batteries
Technical Manual for Navy Lithium Battery Safety Program Responsibilities and Procedures	NAVSEA S9310-AQ-SAF-010	NOSSA	DoD Applications

etc.), and if the battery management system (BMS) would perform the functions required to safely operate and manage the lithium-ion battery. The uncertainties were considered as Type III as described earlier. This uncertainty was selected because there was minimal technical data provided by the cell manufacturer and little was known about the BMS design. This lack of pedigree data made it difficult to assess the battery design's requirements compliance as defined in the Table 12 documents. Therefore, the comparison between the requirements documents and the battery's performance data demonstrated that there were wide gaps and few intersections as depicted in Figure 7. This effort goes directly to Katz's recommendation to *"…determine gaps to requirements or verification evidence for the COTS assembly*" [37] as depicted in Figure 6.

The technical literature review yielded several best practices that will be classified as systems engineering controls and system enablers that could be transformed into process activities to evaluate the COTS performance. Examples of the controls and enablers extracted were:

- Assessments that compared the space hardware's requirements to COTS hardware capabilities can identify COTS design strengths and weaknesses, and where risks potentially resided. Methods such as a gap assessment can identify the types of risks that would have to be treated.

- COTS candidate components must be assessed discretely to determine the attributes needed to develop a tailored risk management plan. The initial assessments provide valuable information to determine facets about the COTS components' strengths and weakness. At a minimum, attributes that should be evaluated are:
    a. Candidate's form, fit, and function to determine if any adaptations would be required.

b. Technical data and pedigree information that is available to determine if its performance, availability, maintainability, reliability, and resiliency are sufficient or if additional actions would be required.

c. Performance and resiliency margins when exposed to hazardous environments are acceptable or the analyses and testing required to characterize the hardware's performance does not levy any unacceptable burdens.

d. Level of product protection or preventative measures that would be required to be incorporated into the space hardware's or space vehicle's design.

e. Amount of analysis and testing that would be required to characterize its capabilities and limitations.

f. Cost and time required to characterize the COTS components' capabilities and limitations.

g. Mature and stable manufacturing processes with appropriate production quality assurance methods are established to determine if the product's meets design compliance.

h. Material quantity required to provide enough hardware for mission use, testing, sparing, and negation of obsolescence concerns.

i. Packaging, handling, storage, transportation, or safety considerations are feasible and do not levy any unacceptable burdens.

j. Special considerations as required by law, such as hazardous material safety measures, are accounted for and do not levy any unacceptable burdens.

k. Internal and external stakeholders who support program and technical decisions to prevent delaying hardware development, testing, and fielding.

l. Decision authorities' communication paths are clearly established and functioning to receive timely program, technical, and risk management decisions.

All the attributes described above are unspoken elements of the risk management cycle as depicted in Figure 2 and contribute to the expansion of Katz's process depicted in Figure 6. These are examples of how COTS-based space hardware development risks could be identified, which is the first step in risk management processes. For example, Table 13 considers items j, k, and l in the list above. The table identifies the internal and external stakeholders that had to be coordinated to approve the COTS-based lithium-ion battery (LIB) for use in a DoD space application. Due to the hazards associated with the LIB, in this case, seven stakeholders had to verify that the battery design complied with their respective and separate performance, qualification, and safety requirements. Each stakeholder was accountable for approving the battery's use to meet their respective responsibilities as identified in domestic and international law, DoD command and acquisition policies, range safety requirements, or technical standards. Their respective responsibilities were:

- *Department of Defense (DoD) Battery Safety Engineering Agent*
  - DoD's Battery Center of Excellence responsible for the assessment and design approval of any battery used in US military equipment.

- *Launch Service Provider (LSP)*
  - Contracted to design, build, sustain, and launch a fleet of launch and space vehicles.

Table 13. Lithium-ion Battery Stakeholder Areas of Responsibility

Stakeholder	Civil Transport Safety	DoD LIB Approval	HAZ MAT Safety	Military Transport Safety	Range Safety	Space Qual	Testing
DoD Battery Safety Engineering Agent	X	X	X	X	X		X
Launch Service Provider	X	X	X	X	X	X	X
LIB Battery Vendor	X	X	X	X	X	X	X
Military Aircraft Engineering Agent	X	X	X	X			X
DoD Range Safety			X		X	X	X
Space Vehicle Program Mgt	X	X	X	X	X	X	X
DoT	X		X	X			X

- *Lithium-ion Battery Vendor*
  - Contracted by the LSP to develop and deliver fully operational and qualified batteries that would provide power to launch and space vehicle hardware.

- *Military Aircraft Program Engineering Agent (EA)*

  - United States Air Force engineering agent responsible to ensure the safety of its logistics aircraft and personnel when transporting hazardous material.

- *Department of Defense Range Safety*
  - Responsible to ensure that launch vehicle flight termination system power supplies are reliable, resilient, and safe.
  - Responsible to ensure that launch and space vehicle power systems are reliable and safe while conducting operations at the range.

- *United States Department of Transportation*
  - Responsible to ensure that domestic and international hazardous material transportation safety requirements are met, and data proves compliance.

To satisfy each of the stakeholders' accountabilities, space, DoD, safety, and commercial standards, and statutes required extensive review. The technical documents covered a vast spectrum that required comparison to determine what was similar and what required risk management. The primary lesson learned was to engage the stakeholders early in the development process, to learn their respective verification and approval processes, how to communicate analysis and test results, and how to gain their approvals. The close collaboration provided the information to develop timely analyses and tests that would satisfy their respective stakeholders' data requirements. This coordination saved a great deal of time and money because discrete analyses and tests did not have to be accomplished. It is a good example of how to identify the way technical data could be developed as recommended by Katz in Figure 6.

Another lesson learned was from a NASA technical paper titled "*Modernizing NASA's* [*R*]*isk* [*C*]*lassification* [*S*]*ystem,*" [43] which suggested that space vehicles are generally over-designed.

Specifically, NASA tabulated space vehicles that were flown with COTS-based space hardware [44], the mission's risk class, the vehicles planned lifetime, its actual lifetime, and reason the missions ended which is contained in Appendix A (NASA COTS-BASED SPACE VEHICLE FLIGHT LONGEVITY DATA). The most curious observation extracted from this data is that many of the space vehicles exceeded their projected mission lifetime. Only two of the space vehicles listed did not complete their missions and projected lifetimes. These were the GLORY (2011) which experienced a launch failure and the ASTRO-H (2016) which experienced an attitude control failure. Neither failure was attributed to a COTS part. Since there remains thirteen space vehicles still in an 'active' state which have not achieved their predicted lifecycle yet, it would be a good topic for future research to follow these space craft to determine their state.

A second observation extracted from the Appendix A data is that all the Class A and B spacecraft that reached their predicted life span continued to operate until the point that operations were discontinued, or the spacecraft surpassed its longevity requirement. Two subjective takeaways that can be surmised from this data are that the NASA space vehicles were over-designed and that the COTS used met the performance requirements. This could be an indication that design requirements could be relaxed. This observation illustrates that risk management can be a means to open this trade space and to quantify the opportunity.

3.4 COTS-BASED SPACE HARDWARE DESIGN PROTOCOLS

Besides the controls and enablers already identified, there are specific protocols that were followed during many of the successful COTS-based hardware design examples. Identifying protocols such as those observed in the technical literature followed what Leitner, Patrick, and Green [31] eloquently stated in their paper titled, "*Approaches for Phasing Commercial-Off-the-Shelf Electronic Parts into NASA Missions*". Specifically, they stated that,

> *"...practices and best practices should [could] provide the correlation between parts selection, evaluation, screening, and qualification process with respect to project category/classification, and address Mission, Environment, Applications and Lifetime (MEAL) for COTS...."*

With this concept in mind, additional controls and enablers were extracted from the technical literature that describes how projects successfully incorporated COTS into SV designs. From a RM standpoint, these can be categorized into three groups which are labeled Technical, Process, and People [21] [45].

Technical topics are those that are related to the hardware's design and how to evaluate its performance when considering using non-space-grade parts in a spacecraft design. Process topics are those that require analysis on how operations and assessments are performed. People topics relate to the culture that exists around viewing, managing, and acting on risks.

Tables 14 through 16 summarize these and are considered additional controls and enablers that can be used to establish the foundation of a risk framework. These can be employed to uncover performance uncertainties associated with the use of COT to build space hardware.

This data proved useful in developing the risk management protocols used to mitigate the risks associated with the uncertainties. These attributes can be applied to MIL-Spec and COTS hardware which are both considered non-space-grade parts. The lists contain the lessons extracted from the literature review and that pertain to the architecture's design and schema associated with the evaluation of the hardware's capabilities and limitations. For example, as described in Table 14, an attribute in the list recommends the spacecraft design team to evaluate the COTS manufacturing process. This can be considered a control and enabler from the technical and process perspectives. NASA's Engineering and Safety Center (NESC) highlights that if there are not any space-grade parts available to incorporate into the design that the designer should establish criteria in selecting MIL-Spec or COTS parts. One criterion that NASA recommends is selecting a parts vendor that is an *Industry Leading Parts Manufacturer (ILPM)* [2]. This is a new term recently suggested for use by NASA to recognize that some vendors who manufacture parts demonstrate superb reliability, acceptable performance history, and are recognized for their product's quality. NESC describes an ILPM as a manufacturer that [2]:

Table 14. Successful Risk Management Technical Controls and Enablers

Technical
• Perform initial assessments, screenings, analyses, and tests that provide valuable information to determine the COTS hardware's strengths and weakness [46].
• Examine how the SV's space positioning (orbit) and MEAL impact COTS candidate's performance and reliability [31] [47].
• Determine if any design adaptations are required to conform to form, fit, and function requirements [12].
• Examine performance and resiliency margins after the COTS are exposed to harsh space environments [48] [45].
• Evaluate if the SV designs need to be modified to add COTS protection from space or SV induced issues [26].
• Evaluate manufacturing processes to determine if appropriate production quality assurance methods are established to determine if the product's meets design compliance [32].
• Consider using rapid prototyping to quickly assess the COTS hardware design [49].
• Follow Test-Like-You-Fly testing strategies and attempt to integrate COTS into technology development hardware that will operate in space to collect data that can be used to assess its performance in the environment [50].

- *"...implements a "Zero Defects" program,*

- *...designs parts for manufacturability, testability, operating life, and field reliability,*

- *...manufactures parts on automated, high-volume production lines with minimal human touch labor,*

- *...understands and documents their entire manufacturing and testing processes and impacts and sensitivities of each process step on product characteristics and quality,*

- *...implements production testing that includes 100% verification of datasheet electrical parameters, multi-lot qualification, shift-based, lot-based, daily, weekly, and quarterly sampling for process monitors and ongoing reliability testing, generating relevant Early Life Failure Rates, outgoing [Defective Parts Per Million] DPPM , and useful life Failure In Time statistics,*

- *...implements rules for removing outlier parts and removes abnormal lots,*

- *...implements a robust change system that assures all major changes are properly qualified and that customers are notified of major changes,*

- *...implements a robust quality management system (QMS) acceptable for spaceflight."*

Table 15 is a summary of the process related to successful risk management controls and enablers that should be included in a non-space-grade parts assessment RMF. For example, it may be more prudent to evaluate the COTS performance after it is integrated at the assembly level. This may be the appropriate level to characterize its performance because the manner the COTS are integrated into the hardware could have a protective effect. An example of this would be when EEE COTS are used in a circuit board design. This circuit board could be buried deep in the unit; thus, the surrounding sub-assemblies and case could shield it from otherwise damaging radiation. If this is the case, then the use of the EEE COTS could be considered a baseline risk or, at best, a low risk which is a very favorable outcome. A method to determine this is to expose the COTS-based unit to radiation to evaluate the effects.

Table 16 highlights controls and enablers associated with how people perceive and manage COTS use expectations. These attributes were discussed in the previous sections and as depicted

Table 15. Successful Risk Management Process Controls and Enablers

Process
• Determine if COTS pedigree data is available to determine if its performance, reliability, and resiliency are compatible with SV design requirements [46]. • Perform gap assessments comparing SV performance requirements versus COTS hardware data to identify COTS design strengths and weaknesses [37]. • Identify all COTS uncertainties to prioritize technical characterizations [51]. • Determine the types of worst-case analyses that would be required [51]. • Determine if COTS assessments should be accomplished at the assembly level or if a bottoms-up approach is required [33]. • Determine methods required to characterize the COTS capabilities and limitations [48]. • Determine the cost and time required to characterize the COTS [46]. • Assess if the cost and time invested in characterizing COTS candidates is effective, feasible, and will meet schedule milestones [39]. • Assess the amount of production escapes and non-conformances that occur during the manufacturing process to determine if the processes are stable and reliable [44]. • Determine the material quantity required to provide enough hardware for mission use, testing, sparing, and negation of obsolescence concerns [52]. • Account for handling, transportation, storage, or safety considerations and do not levy any unacceptable burdens [20]. • Address special considerations as required by law, such as hazardous material safety measures, and determine if those levy any unacceptable burdens [46].

in Figure 2 RM iterative framework. The importance of engaging stakeholders early and often about how COTS will be used will hopefully assuage concerns. The people factor especially comes into play because, in many cases, readily accepting COTS into space hardware appears to be a significant cultural shift. To positively affect a paradigm shift such as this requires a great deal of explanation supported by technical evidence. Additionally, the people factor is not discrete.

As shown in Table 12, the coordination amongst stakeholders is not just limited to those directly involved from the space vehicle’s internal programmatic cadre. It typically involves asking for advice and concurrence from numerous external and internal decision makers and subject matter experts. For example, as exhibited in Appendix A data, the satellites’ lifetime performance suggests that there is trade space available to lessen the rigid risk controls and enablers. This will be difficult because these highly conservative processes are institutionalized. Convincing people to deviate from this paradigm will be a challenge.

Table 16. Successful Risk Management People Controls and Enablers

People
• Identify, coordinate, and routinely communicate with internal and external stakeholders to receive timely program and technical decisions without delaying hardware development, testing, and fielding [46].
• Establish clear communication paths with authorities to receive timely program, technical, and risk management decisions [37].
• Educate stakeholders about the benefits of using COTS in SV development programs, proposed risk management methods, willingness to explore alternate risk assessment and evaluation techniques, and the willingness to accept risk that departs from traditional risk adverse cultures [53].
• Engage and collaboratively work with hardware manufacturers to assess and improve their design, production, testing, and quality control processes to gain confidence in COTS hardware [31].
• Educate stakeholders on modern production processes and quality assurance methods used to gain confidence in manufacturers reliability and resiliency data [46].
• Select manufacturers that have verifiable manufacturing history for a ‘t’ period and produce ‘n’ number of parts with ‘r’ levels of reliability [17].

3.5 CONTROLS, ENABLERS, AND ACTIVITIES SUMMARY

The purpose of performing a technical literature review was to gather the information to answer Research Question No.1 which was, "*What are the controls, enablers, and activities of a risk management strategy for COTS-enabled space system hardware?*"

Numerous controls and enablers were extracted and were identified as related to the Technical, Process, or People portions of an RMF. For example, a Process related control and enabler attribute was associated with the determination of whether to evaluate COTS-based space hardware at the component level or the system level. Identifying which level related to the COTS characterization is important because it will affect the types of modeling and simulation, analyses, and tests (activities) that need to be accomplished to evaluate the hardware.

Undoubtedly the level of complexity in doing these will drive up cost and schedule. But, doing it at the unit level may not uncover any COTS related issues that could have been discovered if it were assessed separately. Thus, controls and enablers as expressed in this chapter were examined closely to determine which fits best with the COTS being considered for use in this research.

Now that an understanding of controls, enablers, activities, and best practices is established, the next chapter focuses on how Research Question No. 2 was answered. The next chapter will discuss the types of space systems that COTS could be good candidates for use in and the environments that may affect their performance. Once this knowledge was obtained and coupled with the controls and enablers, a COTS-based space hardware RMF was developed. With this framework established, unique risk evaluation processes were developed to identify and mitigate uncertainties associated with the COTS-based lithium-ion battery development effort.

4. MISSION, ENVIRONMENT, APPLICATION, AND LIFETIME (MEAL)[2]

Effectively managing space hardware risk requires knowledge about what is being designed, what it is designed for, in what role it will be used, and for how long. As previously said, this is known as the LV's / SV's MEAL which stands for "*Mission, Environment, Application, and Lifetime*" [2]. NASA defines the elements of MEAL [54] as:

- Mission – *"The ultimate science goal or objective of the overall effort.,"*
- Environment – "*The relevant ambient conditions the system would experience during the life cycle to accomplish the mission (i.e. thermal effects, electromagnetics effects, electrostatic effects, radiation effects, etc.).,"*
- Application – "*Specific function(s) to be executed to meet the goals of the mission.,"*
- Lifetime – *"The total time during which the system must perform its intended functions, including subcomponent manufacturing, systems development, system implementation, system execution / operations, and retiring of the system to accomplish the mission.*"

This chapter uses the NASA MEAL concept to establish the context to answer Research Question No. 2 which was: *What are the missions, space vehicle types, and environments that need to be considered when evaluating COTS components for integration into SV / LV architectures and designs?*

Answering this question will be accomplished by describing a spacecraft's application, and missions spacecraft typically execute, the environments the space system hardware must operate in and their dynamic nature, and a nominal lifetime associated with each.

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[2] National Aeronautics and Space Administration. *Recommendations on the Use of Commercial-Off-The-Shelf (COTS) Electrical, Electronic, and Electromechanical (EEE) Parts for NASA Missions (Phase II),* Greenbelt: NASA Engineering and Safety Center, 2022.

4.1 MISSION & APPLICATION

Space hardware applications are dependent on their mission objectives and the purpose the hardware was created for. It also depends on which portion of the space system the hardware resides on. To put this concept into context space mission programs require three separate but equally important segments. These are the launch, space, and ground segments which are illustrated in Figure 15.

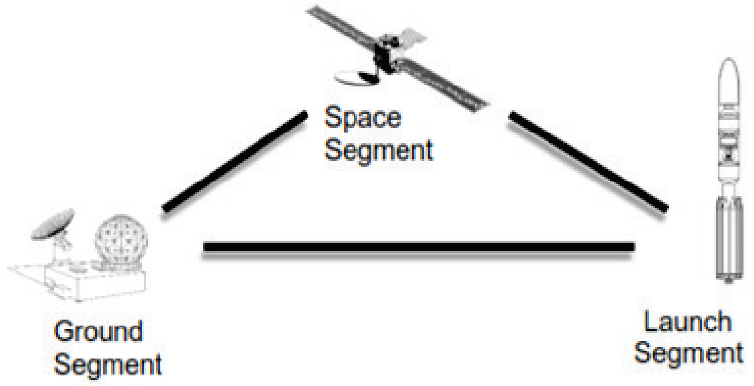

Figure 15. The three systems needed to carry out a space mission are the ground, launch, and space segments [29].

The ground segment is comprised of two subsegments. These are the launch pad and the command-and-control center. The launch pad subsegment provides the interfaces to command the LV and the services necessary to prepare it (i.e., propellant, ground power, etc.) for launch from Earth to deliver its payload into space. The second subsegment is the terrestrial based command-and-control center. These are used to monitor the LV / SV during its ascent into space. Once there it interfaces with the SV via radio communications to monitor and command its functions. It is the conduit between it and Earth to control space segment’s mission related operations.

The third is the space segment, which is typically two subsegments, the spacecraft bus and the payload. A payload could have a singular or multifaceted purpose depending on its configuration and mission.

This research focuses on the LV and SV because it is these that travel into space and are subjected to the harsh rigors of space. Whereas the ground segment, though a critical legs of the space segment triad, risks can normally be readily mitigated using established engineering methods.

The importance of understanding the mission and applications is because the segment's architecture will be developed based on it. If a satellite is designed to operate in space for a long time (i.e., > ten years) or if it is exposed to severe radiation and thermal gradients then the hardware's architecture must be built to mitigate those, regardless if space or non-space-grade parts are being used or not. For example, a space system's build of material is typically comprised of hundreds to thousands of EEE parts. These parts are affected by radiation differently. These effects are also dependent on the type, level, and accumulated radiation that parts are exposed to. Some parts are extremely sensitive to single event upsets while others are not but tend to degrade based on the total ionization dose experienced over an established period. To combat these effects the architecture will be purposely built using several types of mitigation techniques such as incorporating redundant components, incorporating shielding, or altering the hardware's operational cycles. Moreover, NASA recognizes how important a spacecraft's application is because "*Designers must consider how parts interface with the rest of the electrical circuit and other subsystems over the entire mission.*" [54]

The discussions that follow provide the details about the three segments and why understanding the missions and applications is imperative when considering using COTS in space system hardware.

4.1.1 LAUNCH SEGMENT

The launch vehicle is used to supply the motive force to propel the payload into space. The USAF [USSF] Space Command defines a launch vehicle as,

> *"…one or more of the lower stages of a flight vehicle capable of launching upper stage vehicles and space vehicles, usually into an orbital trajectory. A fairing to protect the space vehicle during the boost phase is typically considered part of the launch vehicle." [55]*

An example of a launch segment is the newest NASA Space Launch System (SLS). The SLS with the Orion spacecraft integrated to it is shown in Figure 16. Figure 17 is a refined view of the SLS which shows the rocket's avionics separated into four subcategories: flight control, telemetry, flight safety, and electrical power sub-systems. These are subsystems that can readily use COTS in their designs. For example, an IMU is a critical component of an SV's attitude control subsystem. It "*...is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body using a combination of accelerometers, gyroscopes, and sometimes magnetometers*" [56]. Since many IMU designs are made with a variety of EEE parts it would be a prime candidate to use COTS components to populate printed circuit boards that contain electrical circuits that are used to funnel electricity and logic data. This is also true for the telemetry subsystem's receivers, transmitters, and computer processing units.

Another example is the use of COTS battery cells that are used in secondary (rechargeable) batteries which are part of a spacecraft's electrical power and distribution system. The same is

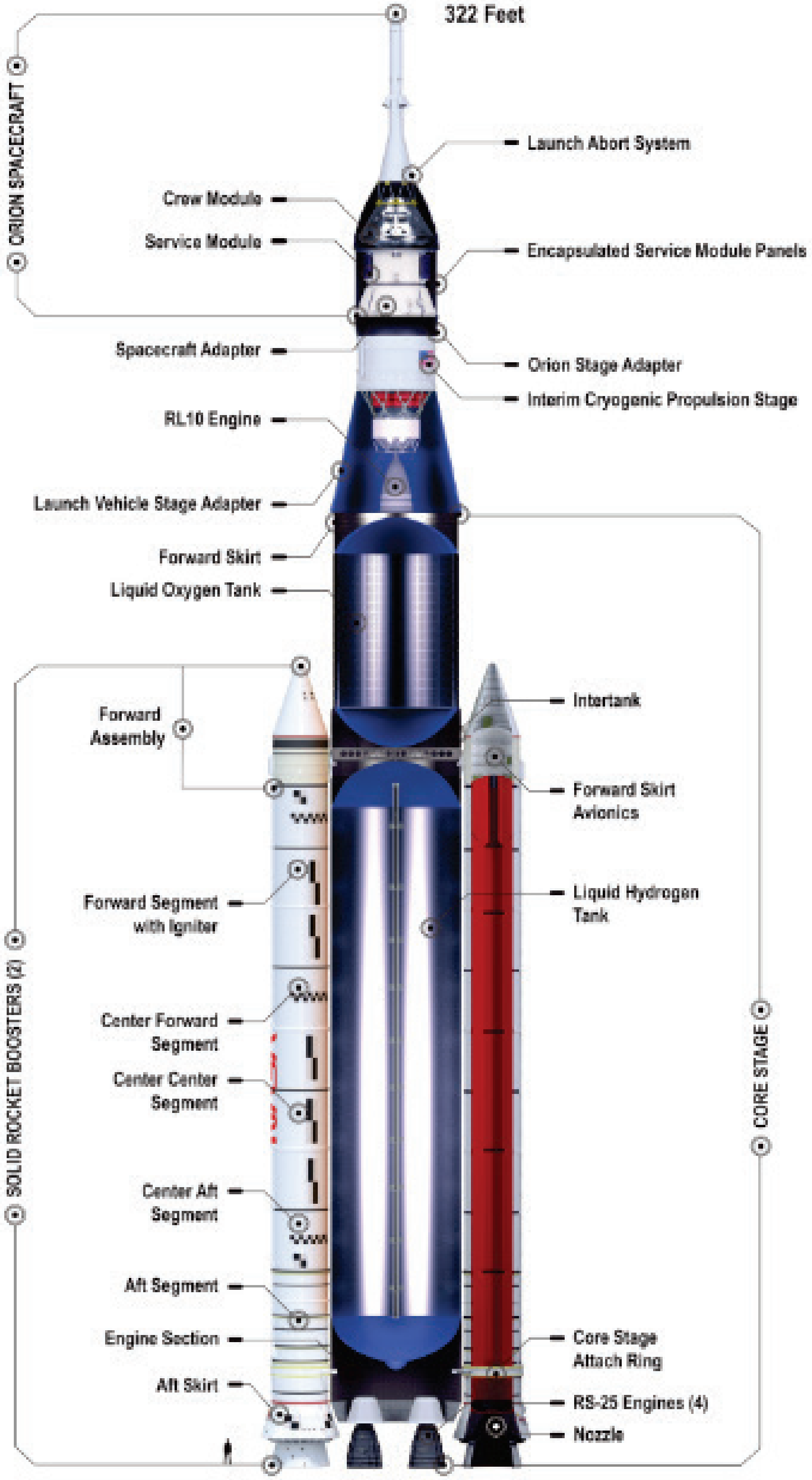

Figure 16. NASA’s Space Launch System (SLS) designed to propel space hardware into space to support a return to the Moon [57].

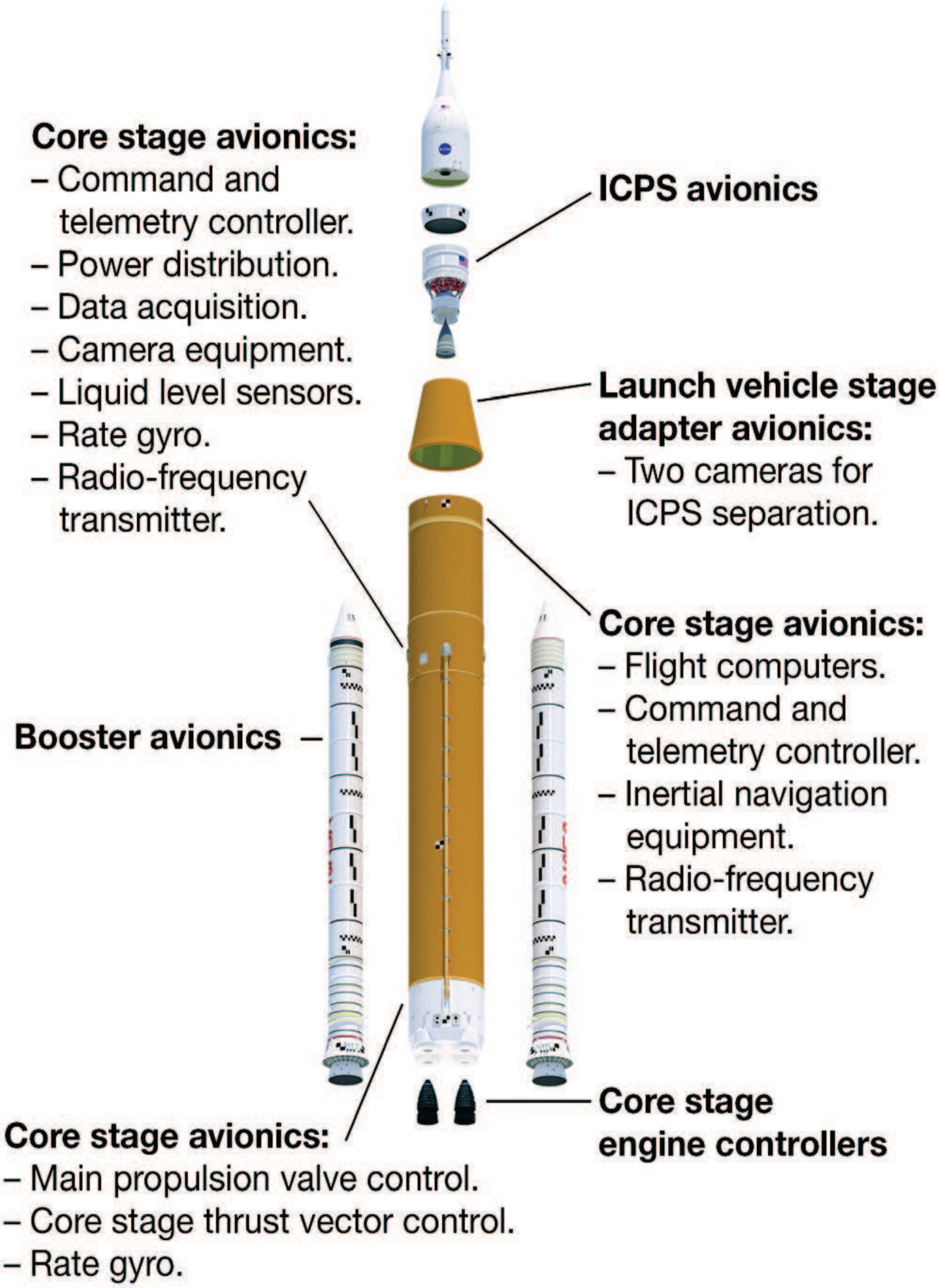

Figure 17. Launch vehicle elements that are good hosts for COTS [57].

true for other avionics carried onboard an LV. Cameras are routinely used on LVs to capture video of launch and ascent significant events such as liftoff and stage separation. An example of cameras built with COTS being successfully used was discussed in section 1.5 as exhibited in Table 7.

4.1.2 GROUND SEGMENT

The ground segment's purpose is twofold. The first is to supply the necessary ground control, testing, and commodities needed to launch the rocket carrying the payload. The second is to command and control the spacecraft once it is deployed from the LV. The launch subsegment is known as the launch system and is defined as,

> *"…the composite of elements consisting of equipment, skills, and techniques capable of launching and boosting one or more space vehicles into orbit. The launch system includes the flight vehicle and related facilities, ground equipment, material, software, procedures, services, and personnel required for their operation." [55]*

Figure 18 depicts the SpaceX Falcon 9 LV loaded with the Iridium-1 satellite at the Vandenberg Space Force Base Space Launch Complex's launch pad [58]. The photo that shows the Falcon 9 vertically mated to a hydraulically lifted support structure (strongback) and surrounded by various tanks and equipment that supply fuel, oxidizer, environmental control commodities, and other products needed to service, control, and launch the Falcon 9. As previously stated, this research did not concentrate on the ground segment because these are quite mature and methods to mitigate risks are established.

Figure 18. SpaceX Falcon 9 launch vehicle in a vertical position at the Vandenberg Space Force Base being readied to launch the Iridium-1 satellite into orbit [58].

4.1.3 SPACE SEGMENT

The space segment is an SV that is designed for a unique purpose in space. SVs are defined as,

> *"…an integrated set of subsystems and units, including their software, capable of supporting a specified mission. It can also be called a satellite or spacecraft and includes the integrated bus and payloads." [59]*

SV purposes can have singular or multi-faceted applications designed to achieve various purposes. Table 17 lists six classes of spacecraft that are categorized by their size, mass, and mission attributes. As depicted in the table, spacecraft range from extremely small to large. Predominantly in the industry, the Pico, Nano, and Micro CubeSat spacecraft carry hardware for research and development purposes in the space environment. It is these spacecrafts that are routinely built with COTS. Many of these are made with COTS components because their life in space is relatively short as compared to the small, medium, and large spacecraft.

The methods used to insert it into orbit or to send it on its space journey are dependent on the spacecraft's mission and applications.

Figure 19 shows the architecture of a spacecraft which includes two sub-sections. The first is the spacecraft bus which is the portion that provides its attitude determination and control (ADC), communications, command and data handling (C&DH), electrical power and distribution system (EDPS), propulsion, structure, mechanical, and thermal control. Table 18 lists the functions of the subsystems and alternate names used by the aerospace industry.

Table 17. Spacecraft Classes by Size, Mass, and Complexity [29]

Spacecraft Type	Mass (kg)	Attributes	Example
Large	> 2500	Multi-mission, complex design, redundancy, primary payload	International Space Station
Medium	< 2500	Multi-mission, complex design, redundancy, primary payload	Global Positioning System
Small	< 500	Single mission, reduced redundancy, primary payload	Iridium
Micro	<180	Simple design, minimal redundancy, secondary payload	Space Test Program Satellite (STPSat)
Nano	< 10	Modular mass design, little-no redundancy, secondary payload	3 U* + CubeSats
Pico	< 1	Integrated circuit, MEMS, multi-chip, secondary payload	1 U* CubeSats

** Unit (U) is a CubeSat standard measurement = 10cm x 10cm x 10cm @ < 1.33 kg* [49]

The other portion of the spacecraft is the payload. The payload could be one of many types and is dependent on its purpose. Examples of payloads includes those built for communications (i.e., civil, commercial, military), those designed to observe specific Earth related phenomenon (i.e., weather, oceanography), scientific research (i.e., planetary space probes, navigation), space operations (i.e., manufacturing, repair), and military related (i.e., intelligence gathering, reconnaissance) [29].

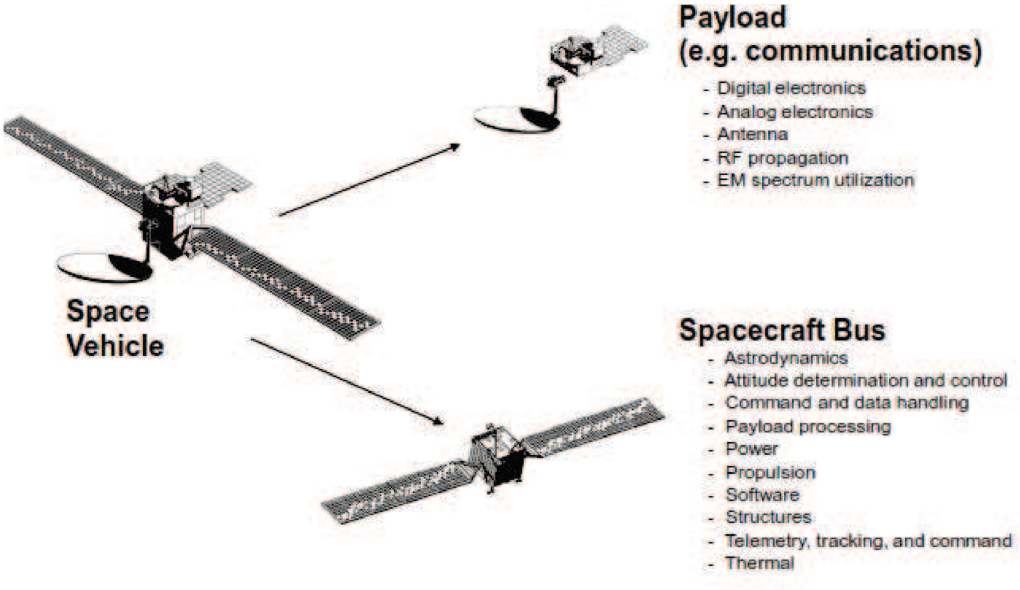

Figure 19. Space vehicle bus carries and services the payload which is made up of the SV's mission hardware and software [29].

Based on the Chapter 1's Table 9, space vehicles are categorized as either launch vehicles (i.e. Saturn V) [60], research and technology development spacecraft (i.e. CubeSats) [61], satellites (i.e. GPS) [62], cislunar (i.e. NASA Gateway) [63], or deep space exploration craft (i.e. NASA Voyager) [64]. The categories were selected based on their mission longevities and mission purposes. The author compiled definitions of the five space vehicles are listed below.

- Launch vehicles operate for a short duration. The duration is the sum of time needed to complete LV production, integration testing, launch pad testing, and the launch operations. This period would be less than one hundred hours because the LVs are built to propel a payload into space. But the LV and its payload and are subjected to severe environmental stimuli. The stimuli experienced during launch and ascent includes extreme acoustic, drag, electromagnetic interference (EMI), gravity, lightning, pressure, shock, thermal, and vibration. An example of a launch vehicle is the SpaceX Falcon 9 [58].

Table 18. Spacecraft Bus Subsystems [29]

Subsystem	**Principle Function**	**Alternate Nomenclature**
Attitude Determination and Control System (ADCS)	Provides determination and control of attitude and orbit positioning and spacecraft and appendages pointing	Attitude Control System (ACS) Guidance, Navigation & Control (GNC) Control System (CS)
Command and Data Handling (C&DH)	Processes and distributes commands, processes, stores, and formats data	Spacecraft Computer System Spacecraft Processor
Communications (Comm)	Communicates with ground and other spacecraft, spacecraft tracking	Tracking, Telemetry, and Command (TT&C)
Power	Generates, stores, regulates, and distributes electrical power	Electrical Power System (EPS) Electrical Power and Distribution System (EDPS)
Propulsion	Provides thrust to adjust orbit and attitude and to manage angular momentum	Reaction Control System (RCS)
Structures and Mechanisms	Provides support structure, booster, adapter, and moving parts	Structure Subsystem
Thermal	Maintains equipment within allowed temperature ranges	Environmental Control System (ECS)

- Research and Technology Development space vehicles are spacecraft designed for short duration operations in space. The SV has hardware integrated for experimental or future space exploration purposes. The data collected will be used to design future space vehicles that have longer mission durations or to further other scientific research. An example would be the National Space Development Agency of Japan’s SERVIS 2 Low

Earth Orbit satellite. It was purposely built with COTS components to evaluate the hardware's performance [26]. Mission lengths for these are typically less than 2 years.

- Cislunar space vehicles are those launched to conduct research and to gather data to support future lunar operations. An example is NASA's development of the Artemis I launch vehicle and the Orion space vehicle designed to enable a return to the moon [65]. Typical mission durations are less than 5 years.

- Satellite space vehicles are those designed to be placed in low, medium, high, or geosynchronous Earth orbits. These are satellites that have short to long mission durations which are dependent on the goals they were designed for. An example would be Global Positioning System satellites (GPS) which have long on-station mission times to provide accurate locational data to a variety of civil, commercial, and military consumers on Earth [62]. Typical mission durations are less than 15 years.

- Exploration space vehicles are those that are used for cislunar, deep space exploration, or carry unique instruments and are parked in a specific point in space. These are highly unique spacecrafts. An example would be the James Webb Space Telescope which is in an orbit about the Sun at the second LaGrange point [47]. Mission durations are dependent on the vehicle's purpose, position, and journey. Thus, the duration classification would be 'n' years which is defined by the controlling program authority and the performance requirements levied. Another example is the NASA Voyager I scientific spacecraft which was launched in 1977 and continues to operate even though it is greater than 46 years old and more than fifteen billion miles away from the Earth 9 (as of December 23, 2023) [64].

Besides being exposed to the environmental stimuli like those experienced by launch vehicles, spacecraft designs need to consider severe thermal gradients, exposure to distinct types of radiation, solar disturbances, partial gravity influences, electromagnetic influences, charged particles, space debris, high velocities, and micrometeorites.

As depicted in Table 18, Figures 17 and 19, much of the launch vehicle and spacecraft's architecture are good candidates to be built using some COTS. For example, all the units listed in the LV Figure 17 and the spacecraft bus and payload Figure 19 except for the propulsion, structural, and mechanical hardware, could be considered good COTS hosts. Even the exceptions noted are open for replacement by other than the legacy architecture designs. For example, additive manufacturing is rapidly maturing which could provide static portions of the propulsion system design. Another potential example would be using commercially manufactured composite overwrapped pressure vessels (COPV). COPVs manufactured by industries that service the Earth-bound markets could be easily evaluated to decide if those could be used in space. This could be a follow-on RMF validation opportunity such as the one documented in this research.

4.2 SPACE ENVIRONMENTS

Space vehicles are exposed to severe and harsh hazardous stimuli associated with the launch and space environments. The hardware subjected to these hazards has to survive while being launched and while performing its mission(s) in space. As Pisacone notes,

> *"An understanding of the space environment is critical to be able to develop systems that can robustly, reliably, and safely satisfy the requirements of a mission" [66].*

This statement is acutely important when deciding to deviate from using unique space-grade components and start to consider using COTS. Accordingly, the purpose of this section is to provide an overview of the most stressful environments that need to be understood when considering using COTS in space hardware applications.

The topic of space environments and their effects is extremely complex. So much so, many space industry engineers and scientists dedicate their entire careers to studying this subject. Therefore, when considering using COTS in space hardware applications, it is highly suggested that design engineers study the trove of technical literature that is associated with this topic and to seek out the guidance from space environment and other space systems subject matter experts for guidance. With that being said and referring to Table 9, space hardware designers can accurately account for the environments that could affect COTS hardware performance. Some of the environments that should be considered are acceleration, acoustic pressure, atmospheric drag and pressure, charged particles, electromagnetics, gravity, humidity, micrometeorites, radiation, shock, thermal, and vibration. These hazards are not static and are experienced differently depending on if the hardware is being designed for the launch or space segments. Also, once in space, where the space vehicle is located and how long it is exposed to the hazards are major factors. For example, a launch vehicle is designed to overcome the Earth's gravity, drag, and its atmosphere. The shock, vibration, and acoustic pressures experienced during the launch are quite severe. This requires robust launch vehicle designs that can withstand these forces to deliver the payload into space within a reasonable cost. Of course, the launch vehicle can be designed to withstand a great deal of force but there exists a balance that has to be achieved during this design practice to make it affordable and profitable to place objects into space. In this case, the LV must be developed to ensure the hazards will not damage its structure or the complex subsections' components needed to propel it into space, control its trajectory, induce an appropriate attitude, power its systems, and all the other details behind the launch vehicle's design. Besides these, designers have to take into consideration safety, reliability, exposure to weather, etc.

Similarly, the payload must be equally protected from these launch hazards and those it will be exposed to while performing its mission over its intended operational life. These are dependent on the spacecraft's journey and location. For example, Figure 20 illustrates five orbits satellites are typically placed around the Earth. The orbits included in this research are the

	LEO	SSO	MEO	GTO	GEO
Altitude, km:	160 - 1,500	600 - 800	5,000 - 20,000	up to 35,786	35,786
Period*, minutes:	up to 128	96 - 100	720	~630	436

*one sidereal rotation period

Figure 20. Five main Earth orbits where satellites reside [67].

Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Orbit (GEO), and Sun-synchronous Orbit (SSO), and Geostationary Transfer Orbit (GTO) [66]. The first four orbits are located at varying distances from the Earth and are used for different purposes. Objects placed into LEO and MEO travel around the Earth in relatively short periods and are inclined at different angles from the equatorial plane. For example, SpaceX's Starlink communications constellation is comprised of > 4500 LEO satellites in orbit at 550 kilometers (≈ 342 miles) above the Earth [68]. The European Galileo navigation constellation is a good example of space vehicles at MEO [13].

Like LEO and MEO positioning, the SSO is for space vehicles that transverse across the Earth's poles and do so on a regular basis with a period of approximately one hundred minutes and is synchronized with the Sun. An example is the Canadian RADAR-SAT2 that is used to provide imaging products for several purposes.

A GEO is a High Earth Orbit (HEO) where satellites operate at "*...42,164 km from the center of the Earth (about 36,000 kilometers from the Earth's surface*" [69]. GEO satellites are useful because they are fixed at a position in space which allows it to service the same Earth area all the time.

One of the newest GEO satellites is the US National Oceanic and Atmospheric Administration (NOAA) GOES-18 as shown in Figure 21. It was launched in March 2022 from Cape Canaveral Florida on a United Launch Alliance Atlas V launch vehicle. Because the distance to its final orbit is so great, the GOES-18 had to use a GTO to achieve its final positioning which took approximately two weeks to achieve [70]. Figure 21 illustrates the GTO path taken to station the GOES-18 satellite which, after it arrives at its final orbit, will be used to monitor weather on the US West Coast, Alaska, and Hawaii.

These five orbits were presented to demonstrate that space vehicles are built to perform different missions. Each experience differing effects from the space environment otherwise known as space weather. Additionally, there are numerous specialty orbits that are not mentioned here that space vehicles architectures need to consider. For example, a Molniya orbit, developed by Russia, is a unique type of MEO orbit that

> *"...combines high inclination (63.4°) with high eccentricity (0.722) to maximize viewing time over high latitudes. Each orbit lasts 12 hours, so the slow, high-altitude portion of the orbit repeats over the same location every day and night." [69]*

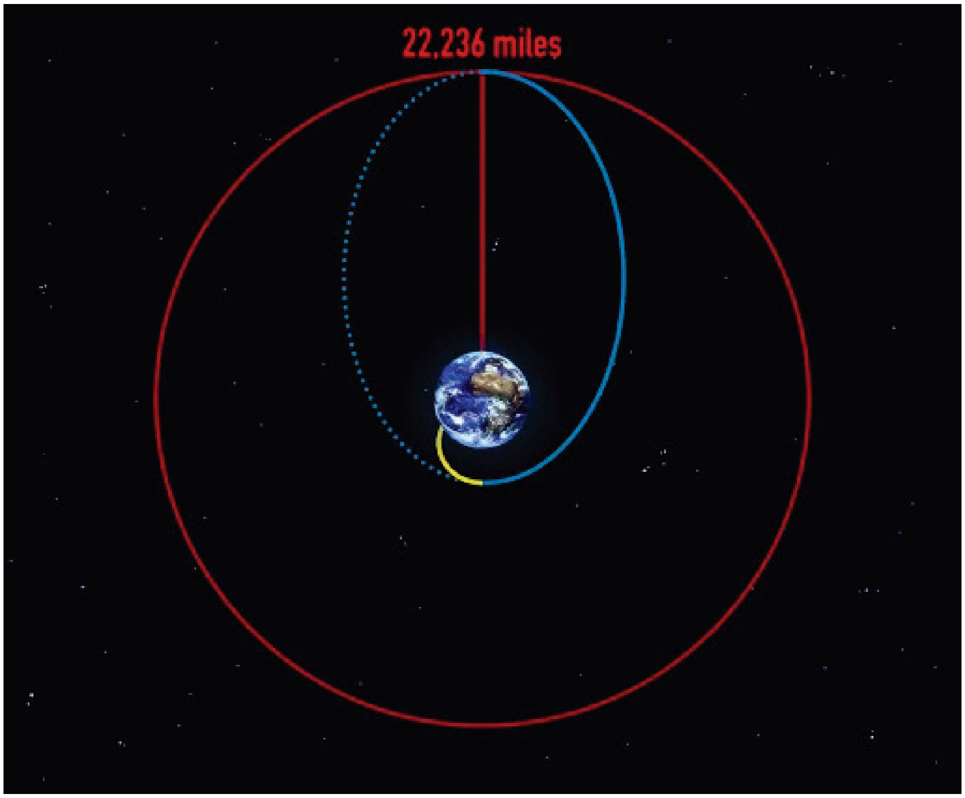

Figure 21. NOAA GOES-18 satellite Geostationary Transfer Orbit (GTO) taken to achieve its position to monitor weather phenomena on the US Western Coast, Alaska, and Hawaii [70].

Therefore, when considering using COTS, the SV designer will need to know exactly what type of orbit will be used. This is true for other positions in space that are used such as the Lagrange Points which are illustrated in Figure 22. These are positions in space where "*...the gravitational forces of a two-body system like the Sun and the Earth produce enhanced regions of attraction and repulsion"* [71]. For example, the James Webb Space Telescope is stationed at the L2 Lagrange Point which is approximately 1.5 million kms from the Earth. It is at this point that the telescope's light shields can provide protection from the infrared light from the Sun, Earth, and Moon [47].

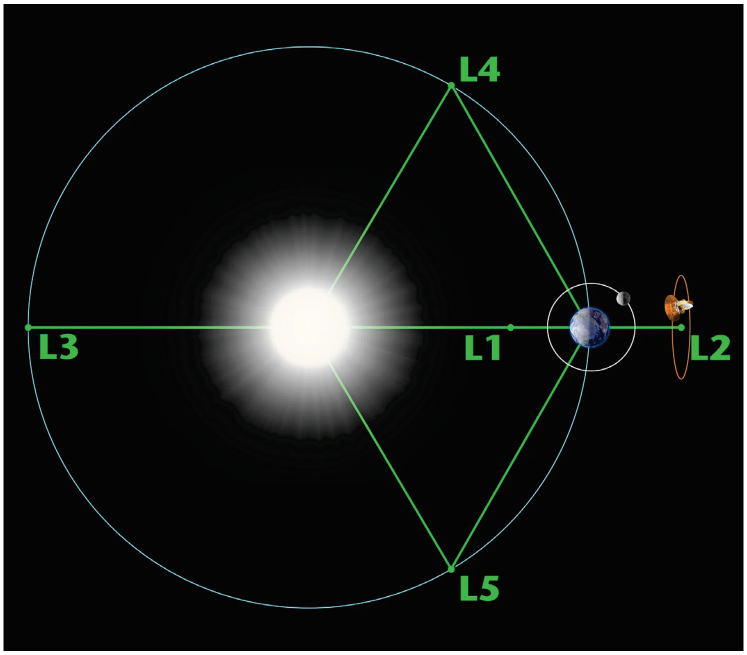

Figure 22. Lagrange points that are stable points in space [71].

4.3 SPACE VEHICLE ENVIRONMENTS

The space vehicle orbit examples were provided to establish the context that there are numerous areas in space that are utilized. These different positioning points are used to service a variety of academic, civil, commercial, military, and scientific communities' mission and application objectives. These points are subjected to varying degrees of gravity, radiation, magnetism, thermal exposure, space debris, meteorites, and space weather created by the Sun. Depending on where the space vehicle is, how it is orientated, how long it is exposed to the stimuli, and the protective and / or preventative mechanisms used in its architecture will determine how it withstands the space hazards. In his book titled, *The Space Environment and Its Effects on Space Systems* [66], Pisacone presents eleven attributes to measure the effects of various space hazardous stimuli to hardware stationed at specific orbit points. Tables 19 and 20 are re-representations of his observations. The Table 19 criteria is an example of how aleatory uncertainties can be categorized. This categorization furcates the effects which can be used to identify the measures needed to mitigate the risk or to help define how to further characterize the hazardous stimuli's effect. Table 20 is a re-representation of Piscone's survey that he uses to reflect what stimuli is most impactful at various orbits. As can be seen, the environments vary in degrees of effect. This data can be useful for a spacecraft designer to know what to take into consideration during hardware design activities. It can also be used to qualitatively measure the Uncertainty Risk Level (explained in detail in the next section) as illustrated in Figure 29. For example, Pisacone determines qualitatively that direct sunlight has an impact between 4 through 7 in all five of the orbits. This could be interpreted as a URL II (medium risk); thus, there are issues that need to be accounted for in the design's COTS usage. In this case, direct sunlight is interpreted as affecting the spacecraft's operation because of being exposed to thermal transients.

Table 19. Criteria to Measure Space Environment's Impact on an SV's Mission [66]

Impact	Significance
0	Effects produced can be ignored.
1	Effects produced may cause upsets.
2	Effects produced will cause upsets.
3	Effects produced may require design considerations.
4	Effects produced will require design considerations.
5	Effects produced may reduce mission effectiveness.
6	Effects produced will reduce mission effectiveness.
7	Effects produced may shorten the mission.
8	Effects produced will shorten the mission.
9	Effects produced may negate the mission.
10	Effects produced will negate the mission.

As Pisacone highlights, the hazardous stimuli are caused by different contributing sources such as solar activity, gravitational, magnetic, and electric fields. For example, the Van Allen Radiation Belts (discovered in 1958) [72] are depicted in a NASA artist conceptualization in Figure 23. This representation is meant to convey that the figure

Table 20. Space Environment's Relative Impact on Spacecraft in Selected Orbits [66]

Spacecraft Environment	**LEO Low Inclination**	**LEO High Inclination**	**Mid Earth Orbit**	**Geosynchronous Equatorial Orbit**	**Interplanetary Trajectories**
Direct Sunlight	4,5,7	4,5,7	4,5,7	4,5,7	4,5,7
Gravity Field	3	3	3	3	0
Magnetic Field	3	3	3	0	0
Trapped Radiation	1,3,5	2,4,5	2,4,5	0	0
Solar Particle Events	1,3,5	2,4,5,7	2,4,5,7,9	2,4,6,7,9	2,4,6,7,9
Cosmic Rays	1,3,5	2,4,5,7	2,4,5,7,9	2,4,6,7,9	2,4,6,7,9
Debris	3,5,7	3,5,7	3,5,7	3,5,7	0
Meteoroids	3	3	3,5	3,5,7	3,5,7
Ionosphere	1,3	1,3	0,1,3	0	0
Spacecraft Charging	1,3	1,4,5	2,4,5	2,4,6	2,4,6
Neutral Atmosphere	3,5,7,9	3,5,7,9	0,3	0	0

> *"...shows the radiation belts (green), which are two doughnut-shaped (torus) regions full of high-energy particles that fill the near-space around Earth. The blue and red lines between and around the belts depict the north and south polarity of the planet's magnetic field. The inner belt, a blend of protons and electrons, can reach down as low as 1,000 kilometers (600 miles) in altitude. The outer belt, comprised mainly of energetic electrons, can swell to as much as 60,000 kilometers (37,000 miles) above [the] Earth's surface. Both rings extend to roughly 65 degrees north and south latitude." [72]*

This is an important environment to consider when placing a spacecraft into LEO. This is especially true because, as discussed in the Introduction and Background section, most new satellites will be placed into LEO in the immediate future. "*Exposures to charged particle events radiation include the solar wind, radiation trapped in magnetic fields, cosmic rays, and solar particle events*" [66]. Unless mitigated in the spacecraft design, these can rapidly cause damage to the vehicle's operations and components. However, much of the mitigation can be implemented in the hardware's design, build-of-material (BOM) selection process, and operational use cases. For example, the NASA Goddard Space Flight Center (GFSC) [73] identified three factors that should be considered when exploring the use of COTS (and any other parts being considered for use). These factors and the contributing attributes are:

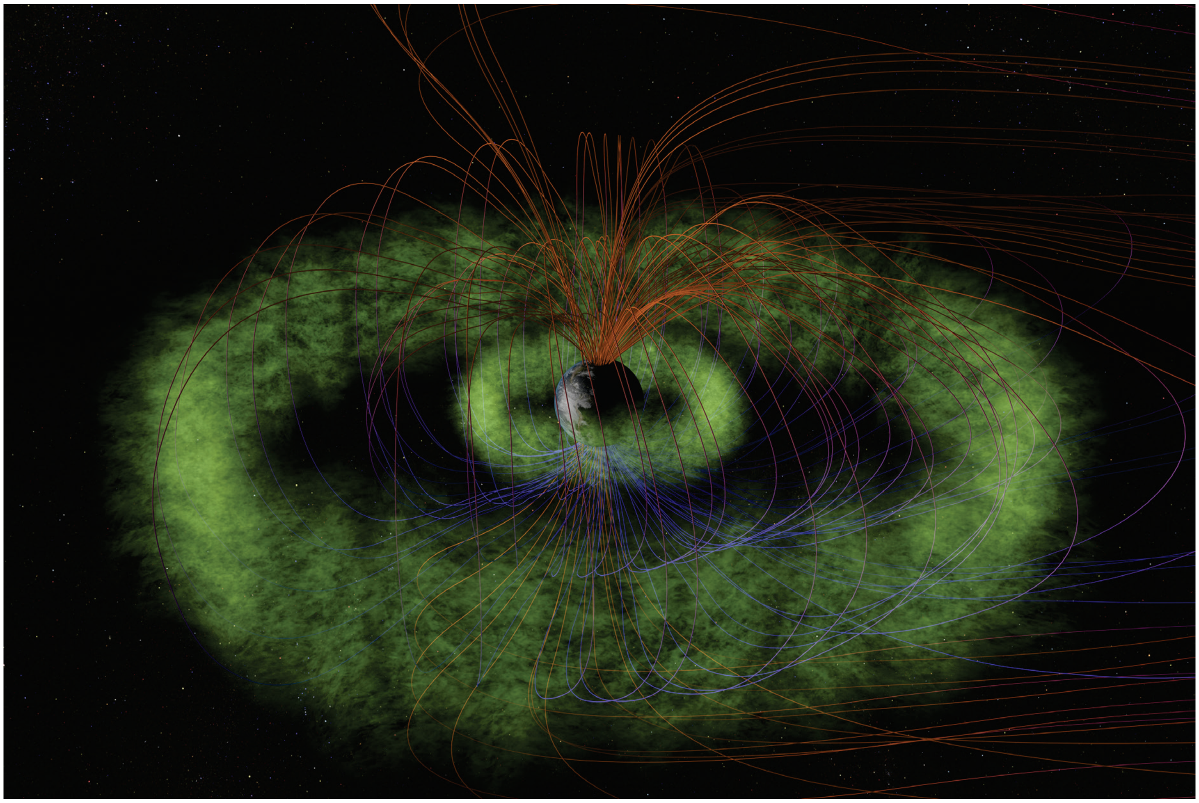

Figure 23. NASA artist illustration of the Van Allen Radiation Belts surrounding the Earth and the magnetic fields emanating from its poles [72].

- *“Conditional Factors: Orbit, Event Distribution, Time (accumulated), Time (in cycle),*
- *Controllable Factors: Part Susceptibility, Derating, Circuit Design, Shielding, Direction*
- *Operational Factors: Duty Cycle, Configuration Control” [73]*

GSFC provided data for this research as an example of how these factors were used to assess the Solar Dynamics Observatory (SDO) [74] GEO NASA Class B satellite’s build of materials (BOM) for a unit that was integrated into the SV’s design [75]. The SDO satellite was built to *“...study how solar activity is created and how Space Weather comes from that activity* [74]”. The SDO satellite required a mission longevity of five years.

Appendix B is an extract from the data provided by GSFC to the author [75]. Appendix B data is a list of space-grade, MIL-Spec, and COTS components assessed for susceptibility to radiation. As shown in Appendix B’s Table 27, 1042 parts were used in the unit’s build. The parts were classified as being passive (resistors, capacitors, etc.) or active (microcircuits and discrete semiconductors). Per NASA GSFC, the typical percentage of active parts used to build a unit is < 10% [75]. In this example, there are 1042 parts used with 5.1% considered to be active and susceptible to radiation damage if not rigorously evaluated, protected, or utilized in accordance with the three factors listed above. The rest of the 94.9% are passive parts and not considered susceptible to damage. Of these 1042 parts, 1.05% were active COTS EEE parts that underwent a radiation hardening assessment prior to being used. This left a mere 0.19% of the parts that required further evaluation. But, from an active parts perspective, it is significant that ≈ 21% of the BOM active parts on the list were COTS. This is an example of how COTS uncertainty and risks could be effectively evaluated. In this case, the SDO satellite was required to remain active for five years to collect data during one half of a solar weather cycle which is typically known to be 11 years [74]. As of this writing, the SDO, built with COTS, is still active and supplying a trove of scientific data. For example, Figure 24 is an image of the Sun taken on December 17, 2023, by the SDO satellite's instruments. So, a satellite with units built with COTS that is subjected to extreme radiation, thermal, and magnetic influences has remained operational for thirteen years. It has surpassed its operational life goal by eight years and is still on station collecting and transmitting data back to Earth. This is an entire solar weather cycle and then some. This satellite could be another example of overdesign and that the perception is less than what it truly is.

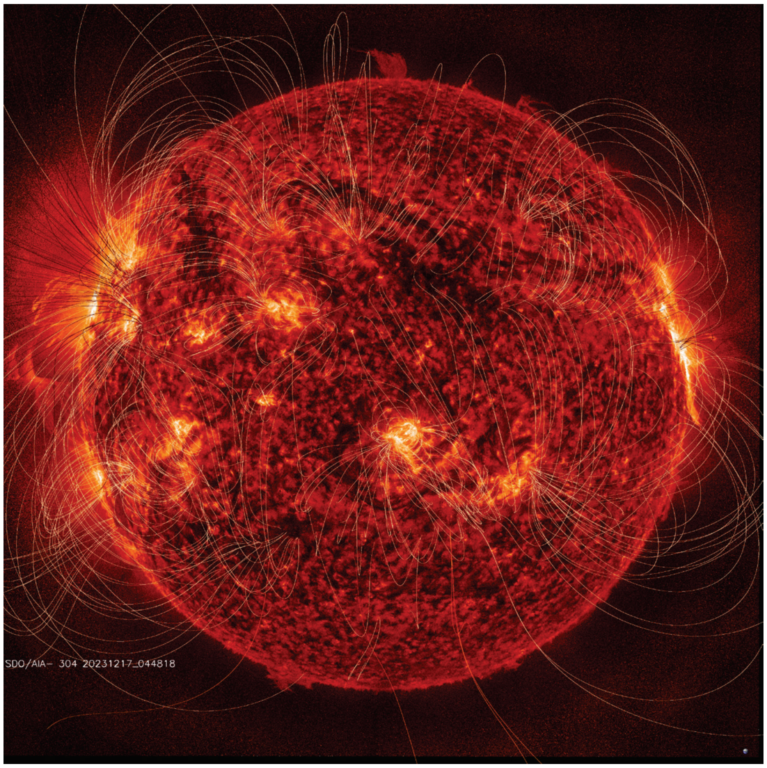

Figure 24. Photo capture of the Sun from the NASA Solar Dynamics Laboratory showing solar phenomenon that affects space weather [74].

Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

The aforementioned information was presented to provide a snapshot of the space environment. Appendix C has a more concise summary of the space environments designers must contend with. This information is intended to express the importance of understanding the hazards that can affect an SV's performance. Specifically, per Bedingfield, Leach, and Alexander,

> *"...the natural space environment includes nine environments: the neutral thermosphere, thermal environment, plasma, meteoroids and orbital debris, solar environment, ionizing radiation, geomagnetic field, gravitational field, and the mesosphere." [76]*

Appendix C contains Tables 26 - 27 that are extracts from their text. These tables associate the nine natural space environments listed above with the effects these have on an SV's subsystems and its operations. An example for using this table reflects the Introduction and Background section's Table 7. This table has data related to COMETS, SERVIS I, and SERVIS II satellites that carried hardware to perform high level photography with much of it built with COTS. For the National Space Development Agency of Japan to develop these, they must have considered how plasma would affect the performance of its camera lenses and how the solar environment would affect the hardware's susceptibility to damage from an increase or decrease in temperature.

4.4 LAUNCH VEHICLE FLIGHT DYNAMICS AND ENVIRONMENTS

As described by Edberg and Costa,

> *"A space launch vehicle has a simple objective: to accelerate and position a mass (the payload, usually a satellite or spacecraft) up to the velocity and location required for the payload's trajectory" [77]*

So, to accomplish this feat, the LV's propulsion system must be powerful enough to overcome gravitational and drag forces. Additionally, it must withstand acceleration, acoustic pressure, dynamic loads, shock, vibration, and weather phenomenon to achieve a specific payload deployment point in space.

Figure 25 illustrates the NASA's Space Launch System launch and ascent profile used during its November 2022 launch [78]. A launch profile must consider weather phenomenon, avoiding space debris, and accounting for space weather. Additionally, as SpaceX has proven, launch vehicles designs now must consider returning the LV safely to Earth for reuse. The latter is a recent capability that SpaceX has proven hundreds of times with its Falcon 9 LV [58].

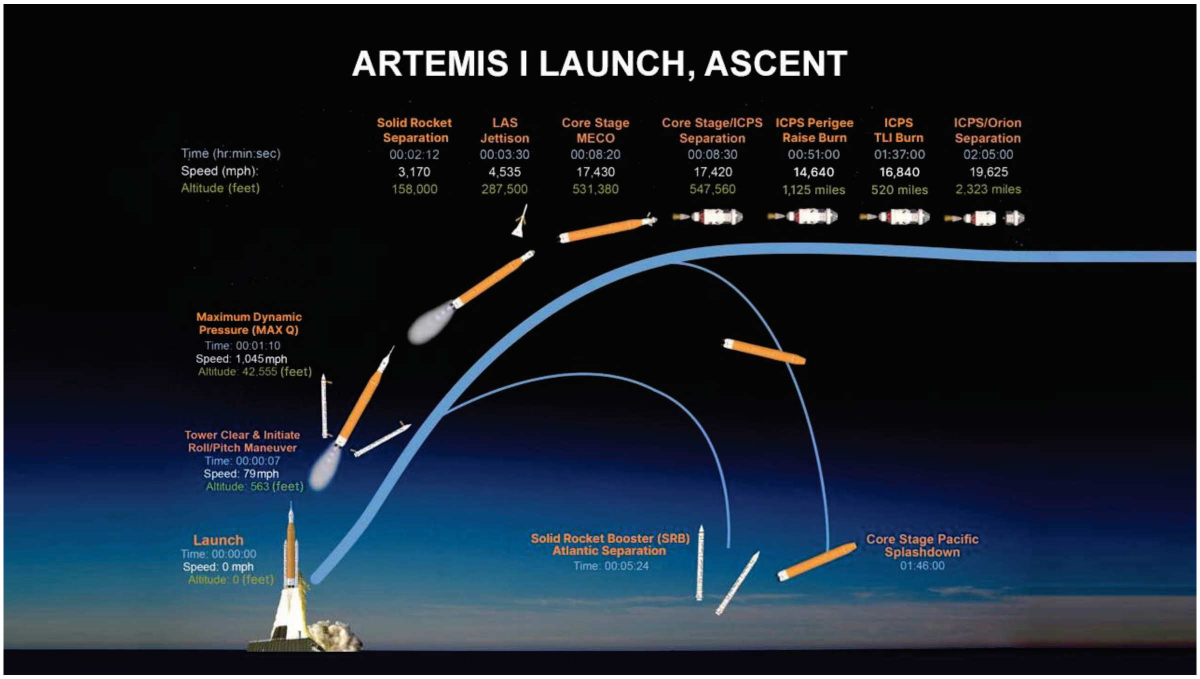

Figure 25. NASA Space Launch System Artemis I launch and ascent profile executed in November 2022 [78].

Per Edberg and Costa,

> *"Most LV ascents are divided into two phases, one occurring in the atmosphere and second at the higher altitudes where the atmosphere is negligible. The atmospheric ascent phase encompasses items 1-5 in the list, where the vehicle climbs while slowly reducing flight path angle." [77]*

Figure 19 exhibits the seven significant events [77] [paraphrased] which are:

1. Vertical climb for the LV to gain altitude to clear the launch structure,

2. Yaw maneuver which is used to supply more clearance from the launch structure,
3. Roll maneuver which is used to adjust the LV's pitch heading to obtain the desired orbital plane,
4. Pitch maneuver which is done to counteract gravity and minimize the angle of attack to reduce air loads,
5. Max-q which is the point the LV experiences the maximum dynamic pressure and air loads,
6. Ascent guidance where the LV is placed on the best trajectory needed to insert the payload into the required position in space,
7. Burnout which is the point the LV's engines no longer contribute any propulsion.

Items 6 and 7 in the list are those events that are accomplished after leaving the Earth's atmosphere.

Remembering that the primary LV objective is to deliver its payload to space, a LV must launch at the "*...proper speed, direction, and altitude to inject the spacecraft into its desired trajectory"* [77]. As previously discussed, this is function of the SV's intended orbit, the ability to overcome gravity to achieve the required velocity while overcoming drag on the LV, the propulsion system's efficiency, and all the losses associated with the LV's trajectory maneuvering profile. All of these impart induced environments onto the LV and payload. Figure 26 depicts a re-representation of Edberg's and Costa's launch vehicle design process. [Note: adjustments were made to the figure from the original to make it clearer to read and understand.]

Though this discussion will not go into detail of the process as Edberg and Costa do in their text, it is important to notice that they focus on identifying a LV's mass, flight characteristics, aerodynamics, axial / normal, Mach loads, loads distributions, impacts on the structural design from shear, axial, and moment perspectives, vehicle control, and attributes associated with the launch site and its location. Steps 1 through 8 portray the design process used to characterize the

LV to determine how the LV's architecture will respond to the imparted environments. To amplify this, Figure 27 is presented to provide an illustration of the forces

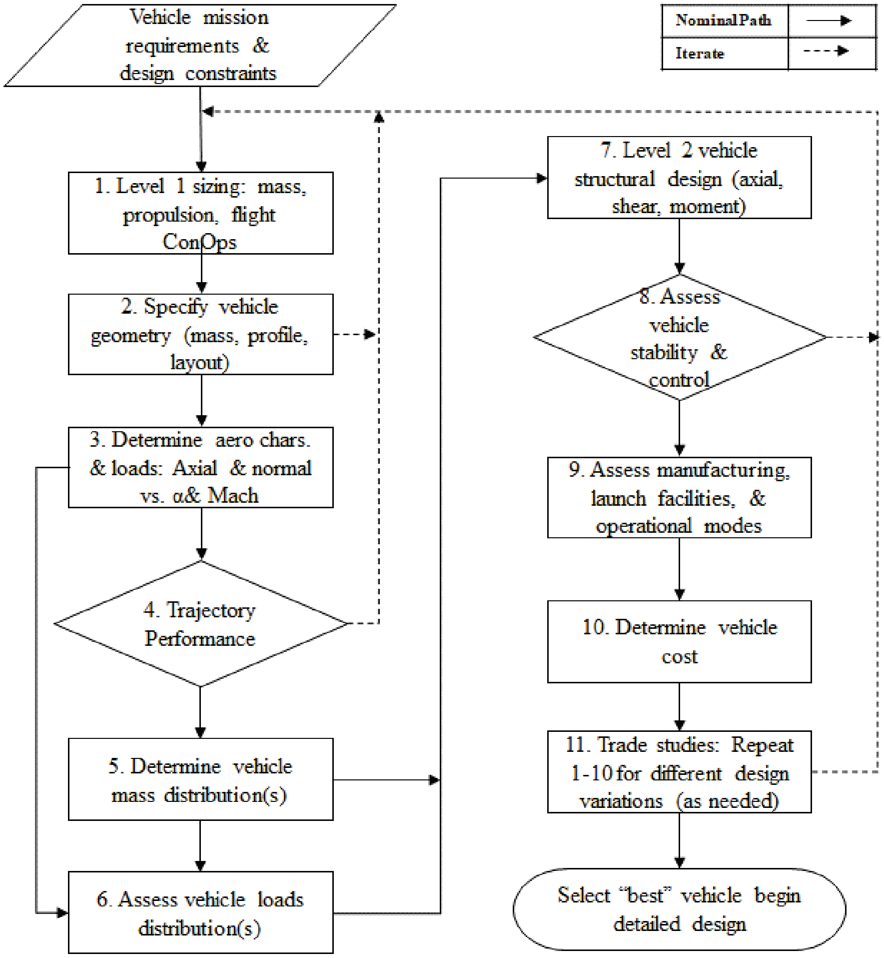

Figure 26. Re-representation of the Edberg's & Costa's LV design process displayed to communicate its complexity [77].

acting on a LV during the launch and flight profile. [This illustration is a re-representation as developed by Edberg and Costa [77]. As shown, the LV is illustrated with the Angle of Attack (AOA, α), flight path angle relative to the local horizon (γ), center of gravity (G), center of pressure (P), center of buoyancy (B), and the engine gimbal angle (δ). From these contributions, the LV's force vectors can be determined. The vectors include those associated with the LV's velocity (**v**), drag (**D**), lift (**L**), thrust (**T**), weight (**W**), aerodynamic force (**L**), buoyancy (**B**), and aerodynamic force ($\mathbf{F_A} = \mathbf{L}+\mathbf{D}$). From these forces, especially $\mathbf{F_A}$**,** "*...internal shear, bending moments, and disturbing moments...* [77]*"*, the LV architecture's response can be estimated.

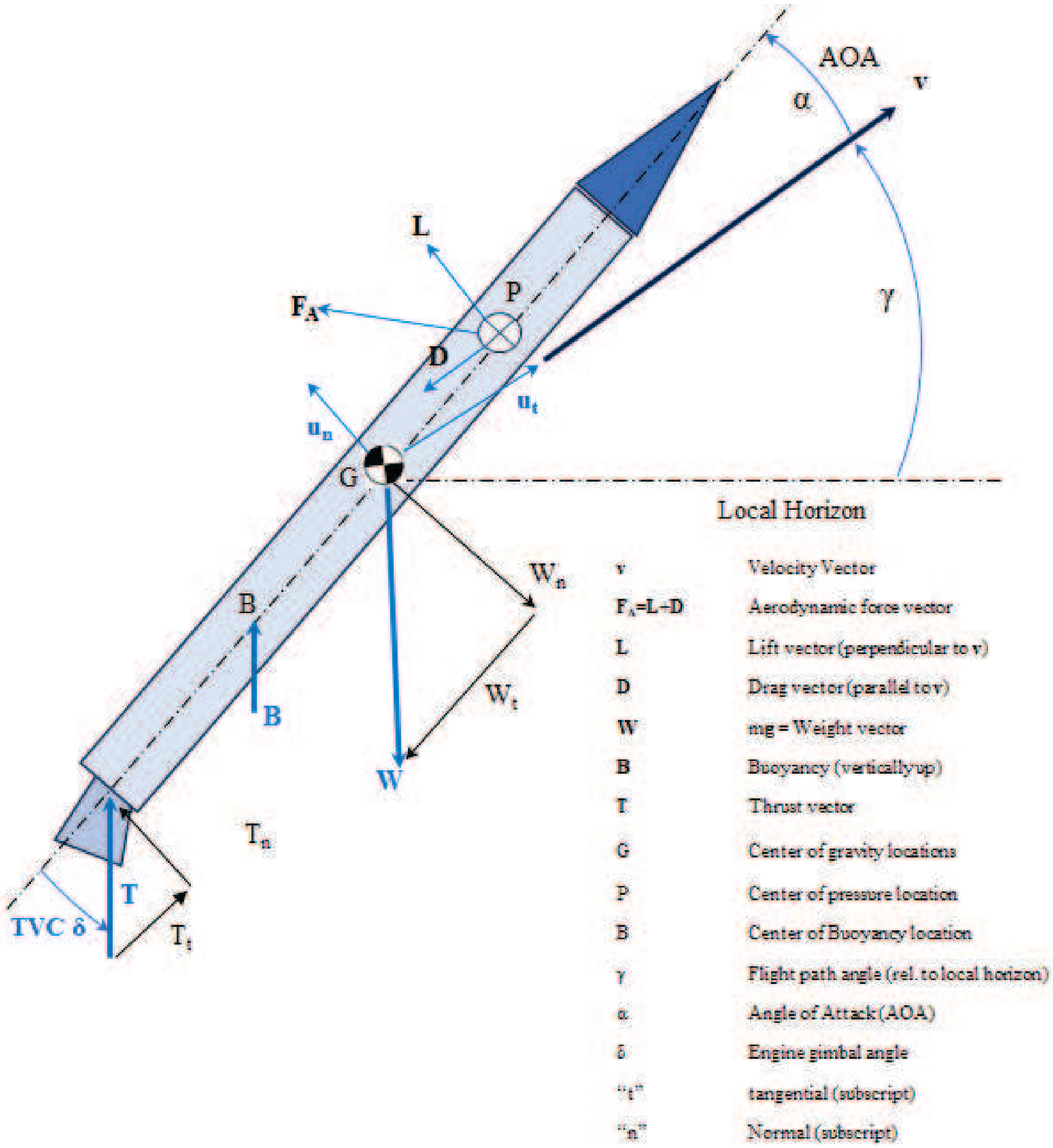

Figure 27. Characterization of forces that are imparted on the LV during its launch [77].

Now with a rudimentary understanding of the LV's launch, the ascent dynamics, and the forces that must be accounted for, we can now discuss the environments that are induced. During the LV's terrestrial movement by land, sea, and rail, its launch ascent, and the prescribed flight profile various forces will be imparted upon its structure and all elements contained within it.

Table 21 is a re-representation of a table created by Edberg and Costa that summarizes the various loads and environments associated with a LV. Besides affecting the LV's performance, these environments will be communicated to the LV's architecture to include those that have COTS integrated in its systems. Because of the transportation, launch, and flight disturbances, the LV / SV architects must decide how the various units and sub-systems will protect the hardware from over excitation. This may come in the form of identifying locations within the LV / SV that vibration, shock, thermal, dynamic loads, and acoustic effects are minimized. Other examples could include installing isolators, use of acoustic dampening material, selecting production materials that limit excitation, using water to reduce acoustic pressure, or designing the LV / SV ECS to control the internal thermal environment.

Table 21. Loads and Environments for a Launch Vehicle [77]

Load Description	Vehicle Condition
Truck, train, air, and sea handling and stacking	Transportation, assembly
Ignition (mechanical and acoustic); Release jerk (vehicle acceleration axial loads)	Prelaunch
Max-q and max-qα (loads arising from dynamic pressure and angle of attack produce both lateral and axial loads)	Flight loads: max-q, wind shear
Pogo and / or slosh or "tail wags dog" (liquid); resonant burn (solid) [refers to engine propellant]	Instabilities
Shutdown / MECO [main engine cutoff] (deceleration axial loads, lateral loads if multiengine); upper stage startups and shutdowns	Mechanical events
Separation / staging loads; payload fairing separation; payload separation	Pyro shocks
Acoustic; thermal effects	All conditions

Regardless of what mitigations are used, the hardware being considered for use in an LV or SV has to pass rigorous testing in accordance with space industry standards such as the United States Air Force Space Command Test Requirements for Launch, Upper-Stage and Space Vehicles (SMC-S-016) standard [59]. This standard is one of many references to consult when setting up a space hardware developmental, acceptance, and qualification regime.

Because there are differing types of hardware that COTS can be integrated into, there are other standards that may need to be consulted as well. For example, this research confirmed the proposed RMF using a secondary lithium-ion battery built with COTS battery cells, a printed circuit board, and EEE parts. The initial qualification regime was based on SMC-S-016. However, to ensure the battery was tested appropriately, other standards such as the IPC Qualification and Performance Specification for Rigid Printed Boards (IPC-6012C-2010), Air Force Space Command Lithium-Ion Battery for Space (SMC-S-017) and Launch (SMC-S-18) Vehicle Applications, and the DoD Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment (MIL-STD-461F) were used to develop robust workmanship and design qualification regime.

This same approach should be investigated for each specific COTS-based space hardware unit being considered for use. If able, the hardware should be designed to meet these requirements. However, that does not mean that there is not any trade space that can be evaluated. For example, as previously discussed, Appendix A presents data for NASA Class A through D satellites. Many of those exceeded their required lifetime requirement by several factors. As stated before, this could indicate that the hardware is being overdesigned; therefore, an argument could be made that the standards are overly conservative. This over conservativeness could be related to the fact that many of the standards that are used throughout the aerospace industry were based on a limited data set that was collected and used to draft the requirements almost two to four decades ago (depending on the standard). So, it warrants attention to reevaluate these requirements especially since material, manufacturing, reliability, and resiliency improvements have been achieved since the standards were written. This topic is highly recommended for future work.

4.5 MISSION, ENVIRONMENT, APPLICATION, AND LIFETIME SUMMARY

This chapter's purpose was to answer Research Question No. 2 which was, "*What are the missions, space vehicle types, and environments that need to be considered when evaluating COTS components for integration into LV / SV architectures and designs?*"

To answer this question, information was gathered that detailed various LV / SV missions, the environments operating in, how the LV or SV is used, and for how long the LV / SV has to operate to execute its mission(s). This is what is represented by the MEAL acronym (mission, environment, application, and lifetime) [2].

This chapter provided an overview of the space system segments needed to place an object into space, the environments that spacecraft will be exposed to during launch, ascent, and while operating in space, and some methods to estimate the environments' impact upon a LV / SV. In many cases, the effects that the space environments have on the LV's / SV's hardware is dependent on where it is in space. This was the reason the orbits and launch ascent profiles were presented. Another purpose for doing this was to communicate that LVs and SVs differ and the hardware that exists on each may need to be evaluated at the component, unit, subsystem, and system levels to uncover risk uncertainties. This is especially true when considering using non-space-grade COTS for use in the space hardware's design.

Now, based on this knowledge, the follow-on sections will describe the risk management frameworks developed to aid in the identification, analysis, evaluation, and mitigation of uncertainties and risks associated with using COTS. Moreover, the material presented in this section laid the foundation the way the RMF was validated using a COTS-based secondary lithium-ion battery as an exemplar. For example, the NASA GSFC SpaceCube satellite program utilized a series of analyses and tests to evaluate the COTS FPGAs that they wanted to use in their satellite designs. The analyses included parts stress screening and derating, signal and power integrity, reliability, worst case circuit, FMECA, radiation total-ionizing-dose, radiation events, and solder joint fatigue analyses [27]. From a testing standpoint, GSFC performed printed wire board coupon, thermal vacuum and vibration qualification, electromagnetic interference and compatibility, and life testing to establish confidence that the COTS FPGA would work for the required mission lifetime [27]. This is a good example to mimic when developing a COTS RMF and risk evaluation processes. NASA GSFC's process is like the one developed to assess the COTS in the exemplar battery.

5. COTS-BASED SPACE HARDWARE RISK MANAGEMENT FRAMEWORK

Managing COTS-based space hardware risk differs from established space industry RM processes that are grounded in standards-based hardware design, development, and qualification protocols. This historic hardware development process is typically measured in years which could be potentially reduced if using COTS hardware is embraced [12]. Two differences are how aleatory and epistemic uncertainties are uncovered and how risk assessment techniques and mitigations differ from those that typically are accomplished in traditional hardware development and qualification routines. This is the reason for the development of the risk management framework (RMF) as illustrated in Figure 28. This framework is used as a guide to evaluate COTS for use in space hardware applications. It is also used as the foundation to build COTS specific risk management evaluation processes that are tailored to assess specific COTS-based hardware. These are described in this section and were used to answer Research Question No. 3 which was: *What type of industry risk management methods can be tailored to assess COTS-based hardware designs?*

5.1 COTS PERFORMANCE UNCERTAINTY TYPES

Based on the lessons learned extracted from the technical literature review and the generic RM model shown in Figure 2, a COTS specific RM strategy was created to establish a baseline RMF as illustrated in Figure 28. This framework was used as a template to create RM evaluation processes designed to uncover risk uncertainties during the evaluation of a COTS-based secondary lithium-ion battery earmarked for use in a fleet of DoD LVs and SVs. Successful use of these proposed COTS RM processes depends on understanding additional RM concepts that

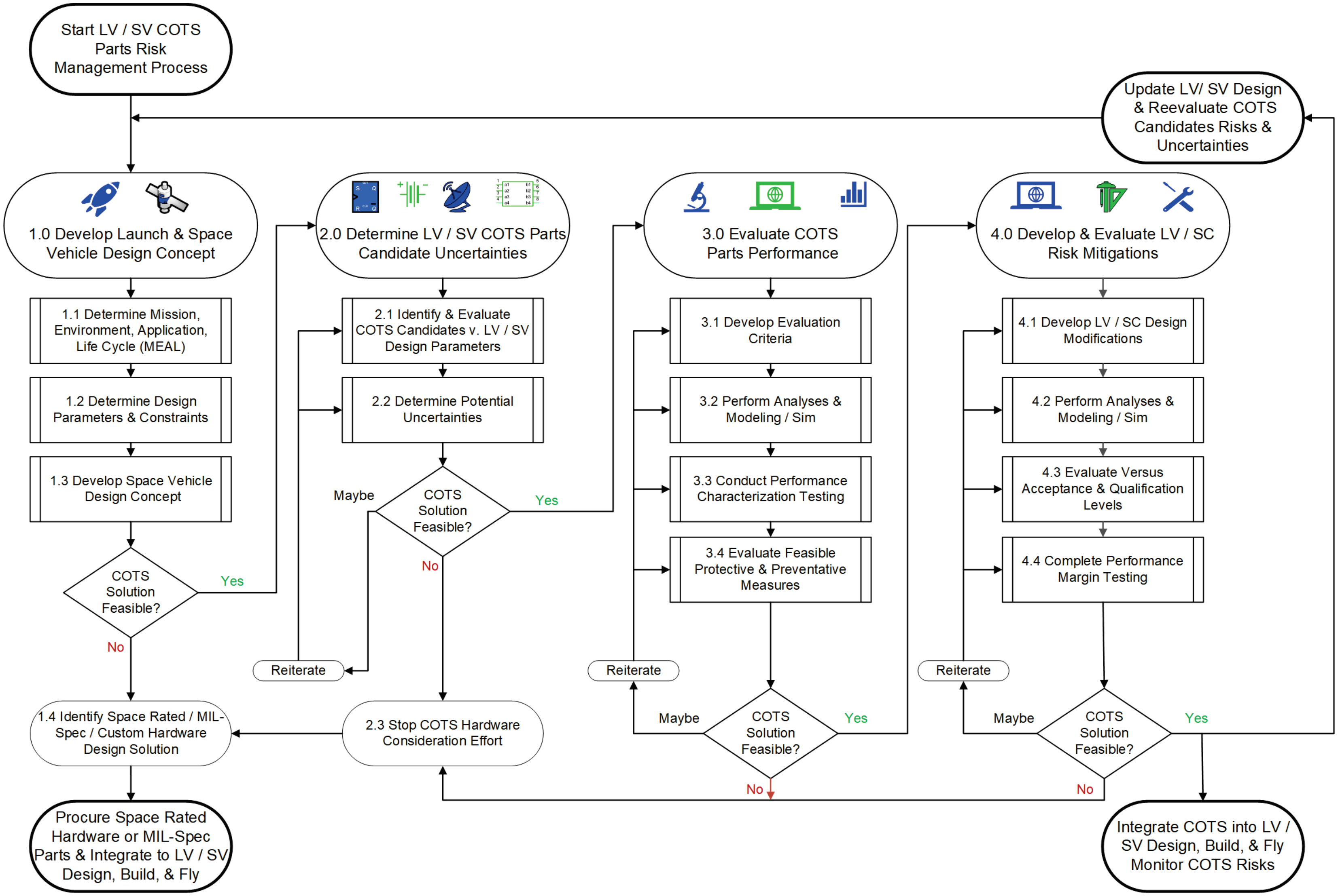

Figure 28. COTS RMF is used to determine if COTS candidates are feasible for LV / SV designs.

explain two types of uncertainties. These are called aleatory and epistemic uncertainties as defined by the NASA Risk Management Handbook [24]. This effort builds upon the uncertainties as discussed in the Introduction and Background section and is meant to refine the uncertainty concept. As exemplified in this study, aleatory and epistemic uncertainties should be fully understood because the distinct types of uncertainties require diverse types of mitigations and treatments. Specifically,

> *"Aleatory uncertainties are random or stochastic in nature and cannot be reduced by obtaining more knowledge through testing or analysis. Epistemic uncertainties are not random in nature and can be reduced by obtaining more knowledge through testing and analysis." [24]*

Aleatory uncertainties exist when insufficient objective evidence is available to define the COTS behavior under stressful conditions or if reliability and resiliency performance is reduced from uncontrollable lot-to-lot manufacturing and other variables. This is an extension of Meyer's and Renier's [21] risk uncertainty Types I – III as presented earlier.

Quantifying aleatory risks is not straightforward. For example, predicting the effects of space weather to electronics embedded in an SV is extremely difficult. Radiation susceptibility, thermal gradients, and electromagnetic effects on the SV can be modeled and simulated. But space weather is dynamic. As a result, the models developed to predict these environments are routinely updated based on data that is continuously collected from Earth and space-based sensors.

Epistemic uncertainties are those that can be reduced through modeling and simulation, analysis, non-destructive evaluations, and destructive testing and assessments. For example, COTS space hardware can be exposed in the laboratory to environmental conditions such as radiation, thermal, shock, vibration, or acoustic stimuli to characterize how a component, unit, sub-system, or system will react when exposed to a variety of use and worst-case scenarios. The data collected during these activities can significantly reduce epistemic uncertainty to determine whether the hardware will meet design requirements.

In general, classifying sources of risk as aleatory and epistemic uncertainties is not commonly performed when managing risk throughout the space industry. This is typically the case because the rigid space-grade criteria largely eliminate sources of epistemic uncertainty [2]. Whereas conventional guidance consulted to reduce risk in LV / SV designs has traditionally concentrated on reducing aleatory uncertainty through screening and testing [28], but the weaknesses of these methods are evident when the LV / SV architects consider using any parts that are not statistically process controlled, used outside of their rated bounds, or not produced by an ILPM. To paraphrase a discussion about aleatory uncertainties with the NASA Goddard Chief Engineer for Safety and Mission Assurance, "*…you cannot test in reliability and resiliency, it must be addressed in the design and manufacturing processes*" [79]. The COTS that fall into this category will only perform as originally designed for their native application. When this is the case, reevaluating designs and doing pre-production assessments will help to determine if the candidates can be used if positioned or operated differently than originally planned. These are methods to address aleatory and epistemic uncertainties.

5.2 ASSESSING AND MANAGING COTS-BASED SPACE HARDWARE RISK

As per the NASA COTS definition, the LV / SV designer, by definition, does not have input into COTS designs, testing, manufacturing, or product assurance processes. Uncertainties in the product's performance that would be acceptable in the product's native applications will have to be identified, examined, and evaluated for use in space applications. The management of the risks associated with these uncertainties must commence before the LV / SV designs are complete. But the sheer number of COTS to select from could be immense requiring a structured and pre-planned COTS filtering and selection process. An example method to select potential candidates is proposed by Garg [80]. He proposed to employ a fuzzy modified distance-based approach (FMDBA) as a method to select the best COTS candidates that would be used for fiduciary transaction hardware. In his paper, Garg describes the use of fifty-six COTS attributes. These attributes are a mixture of aleatory and epistemic uncertainties. He continues by categorizing each attribute to one of seven "*linguistic variables*" [80] that he has defined. These are similar to weighting values or metrics used in systems engineering analyses of alternatives. Once categorized, the attributes are reduced using linear algebra to identify the most preferred candidates based on the method's defined grading criteria.

Garg's method is highlighted because regardless of the COTS comparison and selection methods employed, eventually the aleatory and epistemic uncertainties of the refined subset of COTS will still require disposition. This could be quite laborious if there are numerous decision attributes used as decision criteria. Therefore, using NASA's COTS and RM definitions and the Figure 2 RM process as starting points, a more detailed COTS RMF was developed to provide structure on how to evaluate a small subset of potential COTS that were down selected from a larger candidate pool. This is what was presented in Figure 28.

The entire goal behind the COTS RMF is to identify aleatory and epistemic uncertainties. To do this requires a combination of COTS evaluation methods that can be used to determine what the uncertainties are and how incumbent risks can be treated. This is what is represented in Figure 28's process steps 1 through 4. Figure 28's process includes a decision cycle that contains three options based on four distinct points so an initial set of risk levels and consequences can be established. This is appropriate because a monitoring and review cycle is a cornerstone of RM.

As it is executed three options are presented for consideration. The first option is to completely abandon the notion of using COTS altogether because the preliminary assessment proved that the candidate was not a viable choice. The second option is to repeat the process because even though the initial screening assessment showed promise, there remains some doubt in the COTS performance; therefore, a decision cannot be made yet and evaluations should continue. The third option is integrating the COTS into the design because the evaluation process proved that the hardware's performance and its form, fit, and function were considered sufficient. But, before these decisions can be made, the COTS need to be subjected to an evaluation process which will be described in follow-on sections.

5.3 COTS CANDIDATES RISK MANAGEMENT FRAMEWORK EXPLAINED

Overall, the COTS RM Framework, Figure 28, contains four cardinal steps. Step 1 illustrates how the LV / SV design process is used to determine if COTS should be considered. It is meant to represent the '*Context*' of the Figure 2 RM strategy. Step 1 evaluates the LV's / SV's *mission, environments, application, and lifetime (MEAL)* [2], performance parameters, and constraints.

Step 2 is used to identify and cull COTS candidates that appear to meet Step 1 criteria and to determine where performance gaps and uncertainties exist as compared to the LV / SV design requirements. Step 2 coincides with Figure 2's '*Identify*' and '*Analyze*' blocks. This is the starting point to investigate the COTS' pedigrees. This step is used to refine the COTS candidates' potential for integration into space hardware applications. It compares the COTS performance in their native applications against the space hardware's requirements. This is done to determine if performance gaps exist. During this initial portion of the COTS evaluation process, uncertainties are identified, and the methods needed to characterize the COTS performance are starting to be defined. A sample gap analysis was illustrated in Figure 7.

Based on Step 2's output, development of tailored evaluation criteria, the selection of the modeling and simulation (M&S) techniques, analyses (i.e., sneak circuit, derating, radiation susceptibility, reliability, etc.), and characterization tests (non-destructive, destructive, X-ray computed tomography, etc.) needed to characterize the COTS capabilities and limitations are completed. Once this is accomplished, and if necessary, mitigations are considered that will protect or prevent the COTS from being degraded by hazardous stimuli. These actions are illustrated in Figure 2's Step 3 to address Figure 2's '*Evaluate*' box. Examples of protective and preventative measures may include shielding the COTS to lessen radiation exposure, modifying the LV / SV environment control system (ECS) to afford a more conducive thermal environment, or modifying the hardware's position and orientation in the LV or SV. Other examples include using software to control when the COTS are required to function thus making the COTS less susceptible to single event upsets or by adding redundant parts to increase the system's reliability.

Mitigations like these (examples are not all inclusive) are done to manage the aleatory and epistemic uncertainties as hypothesized in Step 2. Obviously, based on the uncertainties as previously defined, COTS M&S, analyses, and testing evaluations provide insight into epistemic uncertainties which are preferred because the output is objective and characterizes the COTS performance. However, doing this can consume considerable resources. Therefore, being aware how the COTS technical evaluation tasks could impact schedules and cost needs to be closely monitored so that design development efforts do not induce unwanted schedule or programmatic risk. Thus, the RM process needs to be factored into design efforts early in the program vice later when technical, schedule, and cost risks increase as the LV / SV design matures and hardware is being built.

Based on the information and data collected in Steps 1 through 3, if required, design modifications at the LV / SV system, subsystem, or unit levels can be accomplished which is depicted in Step 4. This step corresponds with the Figure 2 RM strategy's '*Treat*' block which leads to decisions that are made in the '*Communicate and Consult*' and '*Monitor and Review*' blocks. This tailored RM process incorporates decision points after each step to ensure effective communications between stakeholders and designers are built in. These actions are used to represent reiterations required as the technical evaluations uncover COTS limitations and the corrective actions that need to be taken. These are additional examples of Figure 2's '*Communicate and Consult*' and '*Monitor and Review*' blocks in action.

Returning to any of the steps affords the opportunity to reevaluate the risk posture, which is an RM best practice. These decision points prompt the COTS evaluators to decide if the COTS solutions remain feasible. The decision points are continuously repeated until is determined either to abandon the COTS consideration, to return through the process to collect more data, or to exit the process altogether to integrate the COTS into the baseline design.

This entire process, as presented in Figure 28, represents a tailored and amplified version of the Figure 2 fundamental RM process and a significant expansion of Katz's roadmap as exhibited in Figure 6. It was used to develop a series of risk management evaluation processes. These processes start to expand Figure 28's Step 1's *Develop Launch and Space Vehicle Design Concept* and Step 2's *Determine LV / SV COTS Parts Candidate Uncertainties.* These are used to characterize launch and space vehicles architectures, the most likely places in those architectures that COTS has been shown to be used, the hazardous stimuli that could affect their performance, and the life cycles associated with various space vehicle types. This information is important because it helps to establish the context as illustrated in Figure 2's generic RMF.

5.4 COTS RISK MANAGEMENT EVALUATION PROCESSES

Figure 28 RMF was developed to outline the factors LV / SV designers and RM stakeholders need to address when considering COTS candidates for integration into designs and / or how designs need to be modified to use COTS. Figure 29 illustrates a process that is used to expand the COTS-based space hardware RMF. This roadmap shows how the spacecraft type, its overarching top-level design requirements, the hazardous stimuli that could affect its performance, and how preventative or protective measures can factor into the decision to use COTS. This methodology is called, "*COTS Risk Management Process A: Assessing COTS Candidates*." This will dictate the types of COTS parts (candidates) that are being considered for use. Because there are many COTS choices, this process will assist in culling a large list of parts into a subset of items that have promise.

The first step is establishing the risk management context. This is initially completed by identifying the LV / SV types, their purpose, how long the LVs / SVs need to function, and where in space it is required to operate. Space positioning is examined separately in a subsection because it dictates the stresses placed on the COTS hardware.

Referring to Table 8, presented again as Table 22, it categorizes five space vehicles based on their mission, how long the LVs / SVs typically must function, and the hazardous stimuli that could impact the hardware's performance during launch or while it is operating in space. This is followed by Step 2 which identifies five attributes that are needed to continue developing

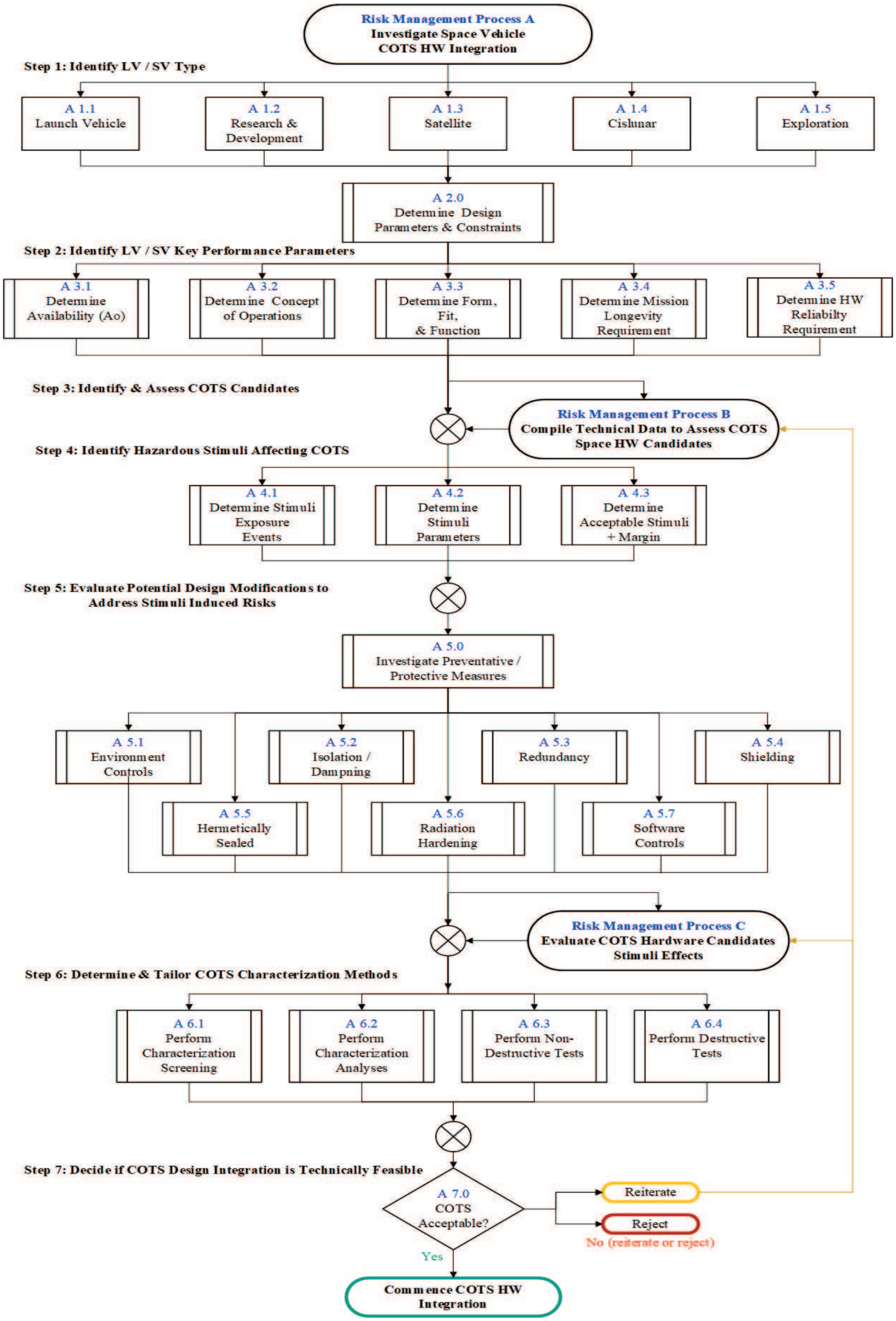

Figure 29. COTS Risk Management Process A: Assessing COTS Candidates

the COTS candidate assessment criteria. These are the LV's / SV's availability, concept of operations, form-fit-function, mission life cycle, and reliability and resiliency requirements. Once these are known, a preliminary COTS risk assessment can be performed as illustrated in Figure 30, "*COTS Risk Management Process B: Determine Uncertainty Risk Level*" (Step 3).

Table 22. Space Vehicle Categorization by Type, Mission, & Longevity

Space Vehicle	**Mission**	**Longevity**	**Hazard**
Launch Vehicle	Transport SV to space	< 100 hours	Acceleration Acoustic Atmospheric Drag Charged Particles Electromagnetics Gravity Pressure Micrometeorites Radiation Shock Space Debris Space Weather Thermal Vibration
Research & Technology Development	Space vehicle or hardware development	< 2 years	
Cislunar	Designed to support scientific research to support travel and operations related to the moon	< 5 years	
Satellite	Consumable products (i.e., cartography, communications, defense, meteorology, surveillance, etc.)	<15 years	
Exploration	Scientific research	1 to 'n' years	

Using the information collected in Process A to this point, a gap assessment of the LV / SV requirements, applicable space industry standards, statutes, and regulations versus COTS hardware provenance data can be accomplished. The gap assessment is the initial point at which risk will be uncovered. As illustrated in Figure 7, an examination of the requirements and pedigree material is imperative to determine if COTS can be used. As depicted in the diagram, there are at most four unions. This concept was explained in the Introduction and Background chapter but is presented again for continuity purposes.

The ideal situation is for all four sets to converge. This means that there would be minimal work required to assess and manage any risk. However, where the number of unions decreases, the COTS hardware will have to undergo an increased amount of scrutiny. This means more risk would be incurred and the risk management efforts would increase. This is depicted using the colored symbols in Figure 7. As previously explained the area where the green star resides shows the four areas meeting where the pedigree data demonstrated compliance to all the requirements and can be interpreted as baseline risk. The yellow diamond showing three unions would be

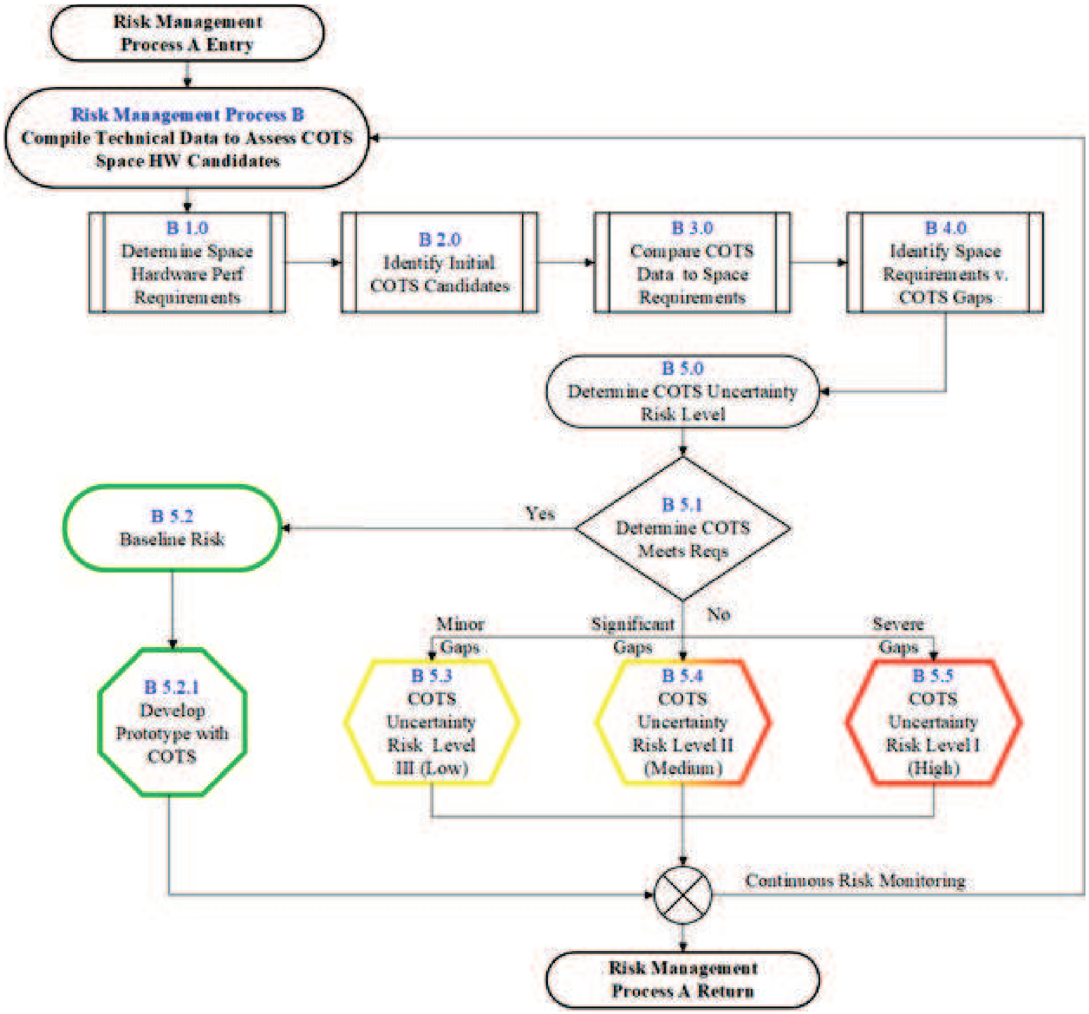

Figure 30. COTS Risk Management Process B: Determine Uncertainty Risk Level

considered low risk. The orange triangle showing two unions equates to medium risk. The red circle denotes high risk with its zero unions. This is then translated further into the RM Process B. Baseline risk can be interpreted to mean that the COTS hardware meets the LV / SV performance requirements and can be integrated immediately into the design's architecture. The low, medium, and high risks are identified based on the level of uncertainty that exists (i.e., performance limitations). This is described by Meyer and Reniers who state that there are three types of uncertainties (listed below) used to characterize risks [21]. It is also dependent on whether the uncertainties are considered aleatory or epistemic as previously described.

- *Type I* *Historical data is available,*
- *Type II* *Little or extremely little historical data is available,*
- *Type III* *No historical data is available. [21]*

So, using Meyer's and Reniers' generic risk identification scheme, three levels of uncertainty can be established and used to qualitatively measure the span between the LV / SV's requirements and the COTS hardware's capabilities. The presence of aleatory uncertainty could play a significant factor as well. If there is an abundance of aleatory uncertainties, risk management protocols will need to be defined to bound these. This is not as simple as identifying the modeling and simulation, analyses, or tests that are accomplished to understand epistemic uncertainties. An example of how aleatory and epistemic uncertainties were addressed during the exemplar validation process is explained in follow on sections.

These uncertainties can be further classified as Uncertainty Risk Levels (URL) I, II, or III. These are initially dependent on the extent of the issues discovered from the gap assessment. Once the uncertainties are identified and classified, the information compiled is funneled back to the RM Process A so Step 4 can be accomplished. This step determines the types of hazardous stimuli that can affect the COTS hardware. For example, if the gap assessment concluded that the

COTS candidate was never subjected to radiation exposure testing, it can be proposed that how it will respond in such an environment is questionable. Thus, a risk was uncovered and methods to characterize the COTS in a radiation environment will need to be coordinated. Continuing, the methods to characterize the COTS hardware need to be established to uncover weaknesses, risk likelihoods, consequences, and severities (Step 5). This process is illustrated in Figure 31 which depicts the evaluation of COTS hypothetical performance when it is subjected to hazardous stimuli and if design modifications, protective protocols, or preventive measures would address the COTS' shortcomings. This is the *COTS Risk Management Process C: COTS Candidates Utilization Decision Point*. This work includes predicting how the components would respond to worst case conditions. Once completed, a decision point is reached on whether to reject the COTS or to continue to pursue its potential use. If the decision is to continue, then the data collected from RM Process C is routed back to RM Process A to move to Step 6 in the roadmap.

Step 6 is executed to determine the types of screenings (i.e., derating), analyses (i.e., thermal, reliability, etc.), and tests (i.e., shock, radiation susceptibility, etc.) that can be used to evaluate the hardware's capabilities and limitations. At this point, additional risk management processes would need to be developed that are unique to the COTS candidate under evaluation and the URL. A URL I would indicate that greater characterization efforts would be required compared to those categorized at a URL III. Completion of this step leads to another significant decision point. As the Risk Management Process C is executed, it eventually leads to stakeholders having to determine if the COTS-based design solution truly does work, if it reduces cost, and conserves schedule. If the answer is yes, then efforts to commence COTS formal assessments start as depicted in Step 7. However, if the answer is no, then the COTS candidate is rejected for use.

Completing Step 7 of the COTS candidates initial assessment establishes the groundwork needed to examine the candidates deemed worthy for more in-depth evaluations. Once this is accomplished, then the COTS evaluation process is tailored to the parts selected. This tailoring process is an example that the space industry can use to develop their own COTS RM strategies.

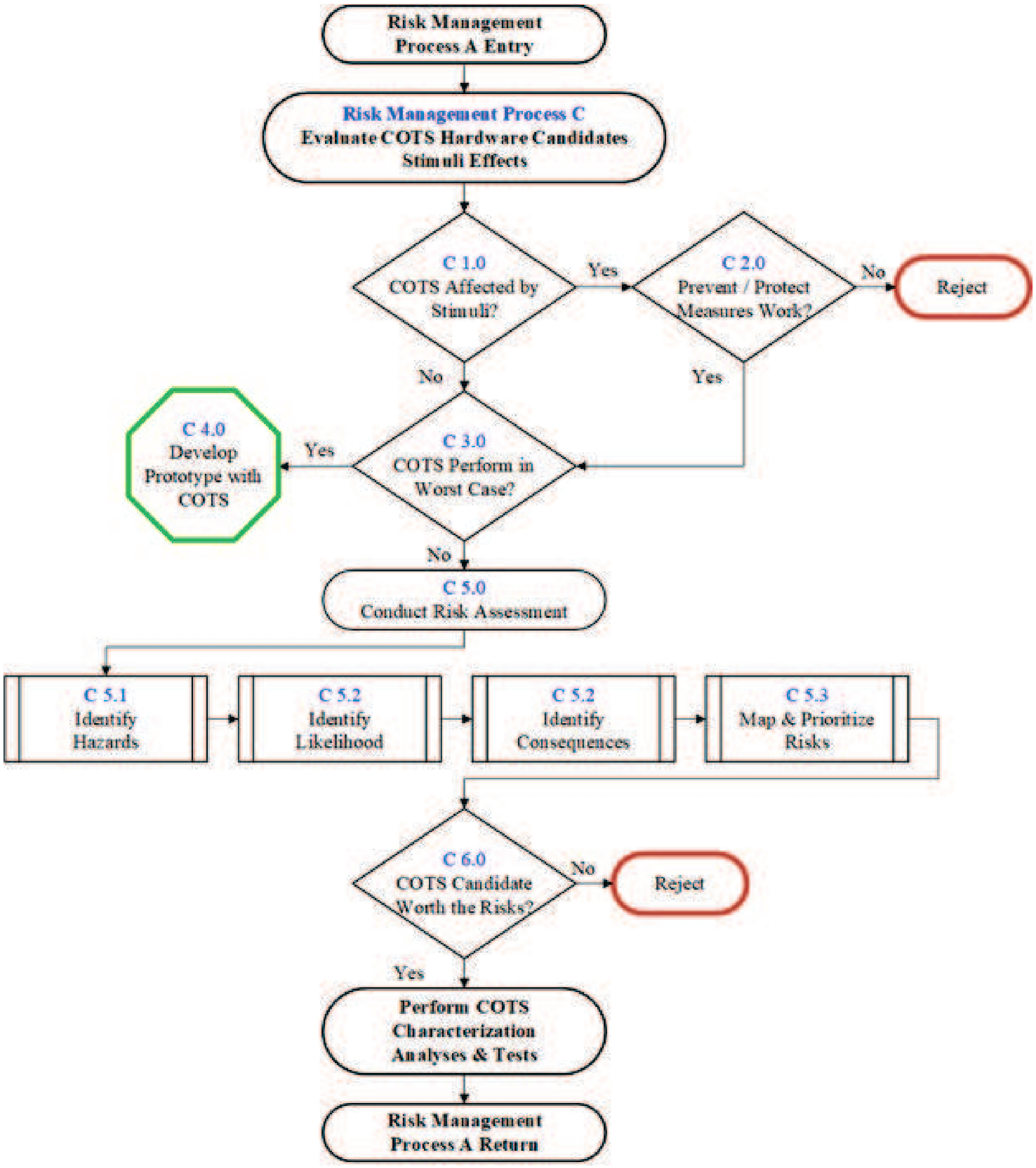

Figure 31. COTS Risk Management Process C: COTS Candidates Utilization Decision Point

Proof that a tailored COTS systems engineering RM process is useful is presented in the next sections. These will illustrate and exemplify how the proposed COTS risk management process was successfully executed to evaluate a space-grade secondary battery built with COTS lithium-ion battery cells.

5.5 RISK MANAGEMENT FRAMEWORK SUMMARY

This chapter's purpose was to present information to answer Research Question No. 3 which was, "*What type of industry risk management methods can be tailored to assess COTS-based hardware designs?*"

To answer this question, four RMF processes were developed and presented in this chapter. These processes show a tiered hierarchy that can be used to make decisions on whether COTS should be considered for use in a space system. As the processes migrate through each step, more information is collected to make informed decisions. These can be considered expansions of the rudimentary RMF and COTS evaluation roadmap as shown in Figures 2 and 6. In this case, the RMF presented here established the risk context, starts to identify where aleatory and epistemic uncertainties and risks reside, and starts to lay the groundwork to evaluate and treat the risks. After the uncertainties are uncovered it can then be determined if there is a feasible path to characterize the capabilities and limitations of COTS candidates being considered for use. If the decision cycles determine that the risks, costs, and schedule impact are too severe then the costly and time intensive path to develop custom space-grade hardware may be the only alternative. But, if the initial assessments demonstrate a feasible path exists, then risk management evaluation processes can be created. These would be tailored to evaluate the COTS candidates at a more robust level. This is what will be explored and demonstrated in the next chapter. Specifically, the next chapter explains how material presented up to this point was used to create risk management evaluation processes which were used to guide the examination of the COTS used to build a space-grade secondary battery.

6. COTS RISK MANAGEMENT FRAMEWORK EXEMPLIFIED[3]

This section illustrates an example on how aleatory and epistemic uncertainties were exposed and how associated risks were successfully reduced during the development of a LV / SV twenty ampere-hour (Ah) secondary lithium-ion battery built with COTS cells, a PCB, and EEE components. This example shows how the Figure 28 COTS RMF was tailored into a unique evaluation process designed to expose aleatory and epistemic uncertainties. The data collected was used to determine risk levels, consequences, mitigation methods, and hardware design solutions.

The next sections will show how the RMF proved critical to the evaluation of the COTS used to build the battery to the point that enough data was compiled to reduce and mitigate risks enough to fly the batteries into space in support of numerous missions on board a fleet of LVs and SVs. The accomplishment of these processes was used to answer Research Questions No. 4 which was: *What COTS analyses, modeling, and tests can be used to validate COTS-based space hardware risk management strategies?*

6.1 BATTERY RISK MANAGEMENT FRAMEWORK VALIDATION

Lithium-ion battery (LIB) use has increased dramatically over the last thirty years, including those used in a variety of space-related applications. LIBs are used to power LV / SV avionics,

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[3] This chapter is derived from an adaptation and expansion of the work previously published or submitted* for publication as noted in the following references:
E. W. Herbert, "Launch Vehicle Lithium-Ion Battery Development Using Commercial-Off-the-Shelf Cells," in *30th Aerospace Testing Seminar*, El Segundo: The Aerospace Corporation, 2017.
E. Herbert and T. Bradley, "Managing Commercial-Off-the-Shelf (COTS) - Based Space Hardware Risk," in *33rd Aerospace Testing Seminar*, El Segundo, 2023.
E. Herbert, R. Sega, J. McGraw and T. Bradley, "Risk Management for Commercial-Off-the-Shelf Parts Based Space-Rated Hardware," *Systems Engineering Journal,* 2023.*

navigation-guidance-control systems, flight termination systems, communication and telemetry systems, computers, and other portions of the LV's / SV's architecture. The increased energy density combined with its reduced mass and footprint makes it an ideal power source because it yields more specific energy and power, has longer cycle life, and exhibits increased cell voltage potential.

Figure 32 illustrates how LIB has become the preferred solution as compared to legacy battery designs. LIBs contain superior energy and power density, weigh less, and consume less footprint in a LV / SV when compared to legacy chemistries like silver-zinc, nickel-cadmium, and lead-acid. This makes LIB use in launch and space vehicles' power energy application an attractive alternative to heritage designs. However, LIBs are not tolerant to abuse or improper operation.

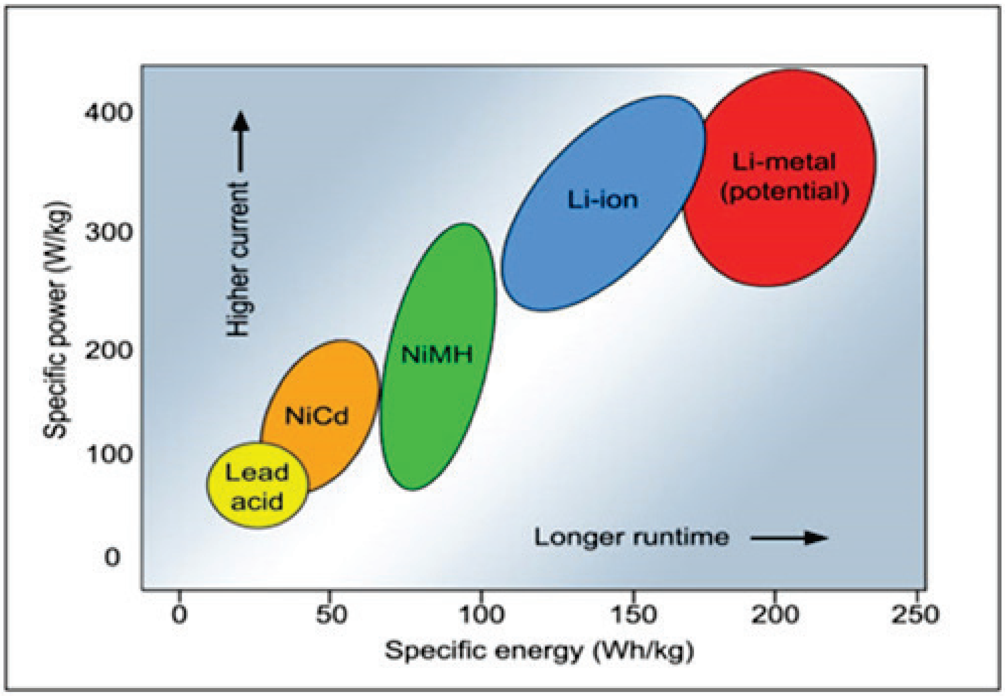


Figure 32. Battery specific energy versus specific power comparison demonstrates LIB performance over legacy chemistries [81].

Ensuring that a LV's / SV's lithium-ion battery is safe and reliable requires detailed knowledge about its chemistry, construction, performance, charging / discharging operations, maintenance cycles, and packaging, handling, storage, and transportation protocols.

LIB designs come with a unique set of engineering challenges. Battery engineers take into consideration characteristics such as mass, weight, footprint, capacity, maximum and minimum current, operating voltage range, temperature ranges, rechargeability and number of cycles, and survival in maximum predictable environments. Designers must also recognize that lithium-ion cells are not tolerant to overcharge, over-discharge, exposure to heat, or excessive cell damage; so, a BMS that monitors cell performance and responds to off-nominal conditions is mandatory. As such, battery evaluations, if conducted correctly, will expose failure modes that could occur during integration, launch, and mission operations. Implementing a robust and efficient battery development philosophy will mitigate the failure modes and ensure that LIBs can be produced within budgetary and schedule constraints.

This research's section documents how the RM processes developed from RM controls, enablers, and the RMF discussed in the previous chapters were used to guide the development of the COTS-based battery risk evaluation work. This section will present the decision criteria, M&S, analyses, and testing used to establish confidence in the COTS and the battery's overall performance. It also illustrates how aleatory and epistemic uncertainties were exposed and how the associated risks were successfully reduced during the LIB's development. This led to the battery's design being fully qualified and deemed safe in accordance with numerous safety and transportation requirements. The results from this effort demonstrated that a high reliability LV / SV battery can be built with COTS parts if a defined RM strategy is used.

6.2 NOMINAL SPACE-GRADE LITHIUM-ION BATTERY QUALIFICATION

During traditional LV / SV design and development processes, space-grade hardware units are delivered to LV / SV providers based on the requirements communicated to their suppliers. The provider relies upon hardware vendors to do their due diligence to ensure that the units meet specifications and to deliver compliant hardware. The hardware is always subject to acceptance (AT) and qualification tests (QT). These are performed to evaluate hardware workmanship and to verify that the design will perform in space at maximum predicted environments (MPE) plus an established margin. For lithium-ion batteries, AT typically includes performance (functional) tests before, during, and after AT events, wear-in, leakage, vibration, thermal cycles, and thermal vacuum tests. QT typically includes additional performance (functional) tests, leakage, shock, vibration, thermal, pressure, life, and burst pressure tests at elevated levels. Other tests such as acceleration, climatic, and static load testing typically require an evaluation to determine if those are required based on their MEAL. The ATs and QTs completed are based on the battery type and test criteria that reside in various space hardware standards.

Due to the cell lithium-ion chemistry numerous qualification, transportation, and safety requirements standards were applicable during this battery development effort. The requirements are levied upon lithium-ion batteries based on their composition, power density, and operational sensitivity. These come from different stakeholder organizations such as the Underwriter's Laboratory (UL) [82], United Nations (UN) [83] , US Department of Transportation (DoT) [84], and US Department of Defense (DoD) [85] [86] [87] [88] [89] [90] [91]. These are to ensure the battery is safe to operate, handle, store, and transport via civil, commercial, and government ground, air, sea, and rail conveyances.

6.3 COTS-BASED SPACE-RATED SECONDARY BATTERY DESCRIPTION

During the development of a new launch vehicle and a new (separate) space vehicle (payload), a secondary lithium-ion (Li-ion) battery was designed to power communications, command and control, guidance, flight termination, instrumentation, and attitude control system electrical loads. Figure 33 is a one-line diagram of the lithium-ion battery system architecture.

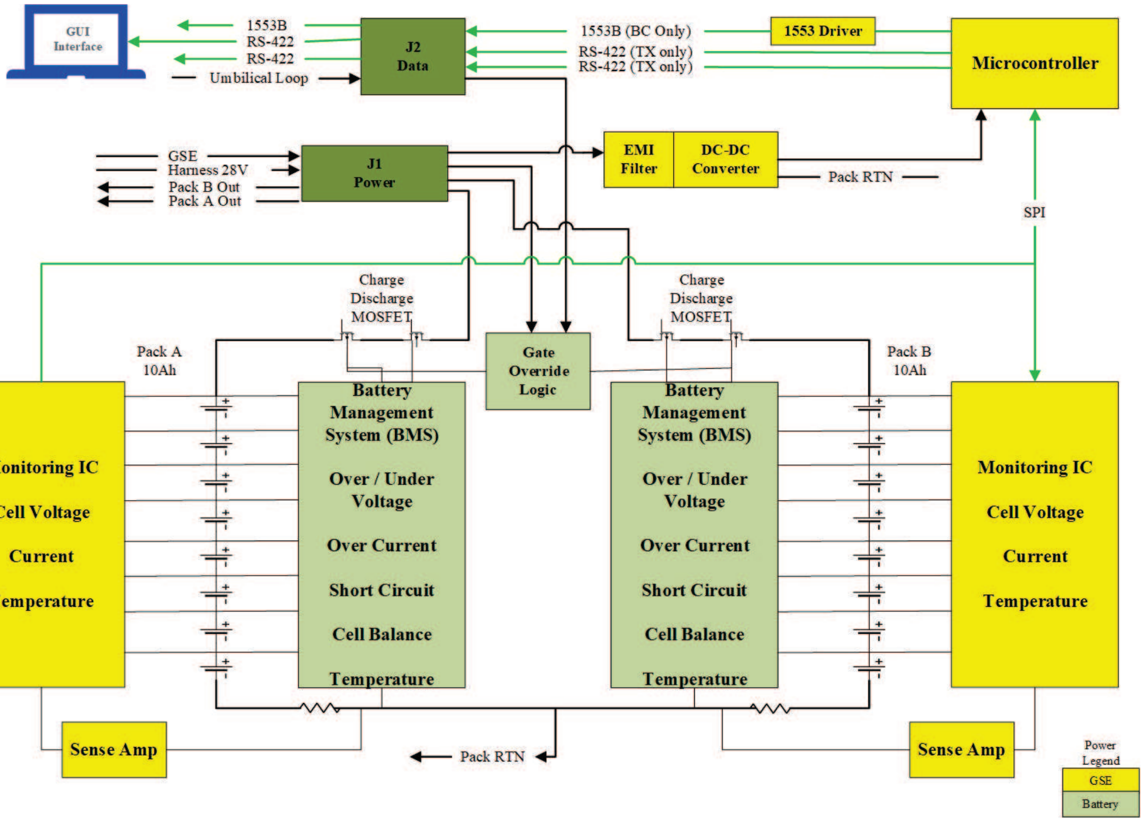


Figure 33. COTS-based secondary lithium-ion battery single line diagram developed for a launch and space vehicle program [46].
Courtesy of the Space Information Laboratories

The battery contains COTS Li-ion pouch cells made by an international vendor, a domestically produced COTS printed circuit board (PCB) which contained an electrical circuit populated with COTS electrical-electronic-electromechanical (EEE) components, a COTS microcontroller with firmware that controls a battery management system (BMS), instrumentation, internal and external ground support equipment (GSE) interface connections, wiring, and an aluminum housing. The battery contains eight cells wired in series in a pack with two packs wired in parallel. The cells are a soft pouch design with a nominal ten ampere-hours capacity with a charge cutoff identified as 4.2 volts and discharge cutoff as 2.75 volts. The cell, displayed in Figure 34, is 159 mm long, 60 mm wide, and 9.8 mm thick. The BMS was designed to monitor the battery's performance, cell state of charge, balancing, charge and discharge operations, and safety features that are initiated if an off-nominal state is detected. The battery was designed for fifty charge / discharge cycles and is rated at 20 ampere-hours (Ah) capacity.

Figure 34. Commercial-Off-the-Shelf lithium-ion polymer cell used to produce a space-grade vehicle battery [46].
Courtesy of the Space Information Laboratories

6.4 LITHIUM-ION BATTERY RISK DISCOVERY

During the initial assessment for use in the LV and SV applications, the COTS hardware was used to construct engineering design units (EDU) and flight-ready batteries that would be subjected to design evaluation and qualification testing. Prior to integration at the battery system level, the cells, as per industry best practice, were evaluated to determine their internal resistances, self-discharge rate, and capacities to verify electrical similarity. Matched cells were made into 8-cell packs and assembled into batteries which would be subjected to electrical performance, functional, development (DT), acceptance (AT), qualification (QT), safety, and charge / discharge tests.

The batteries were built based on vendor Certificates of Compliance (CoC). These CoC stated the COTS cells complied with Underwriter's Laboratories, *Standard for Safety: Lithium Batteries* [92] and United Nations *Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria Tests* [93] safety and transportation requirements. Additionally, the units were built with PCBs that were certified as being built and evaluated in accordance with IPC rigid printed board standards [88].

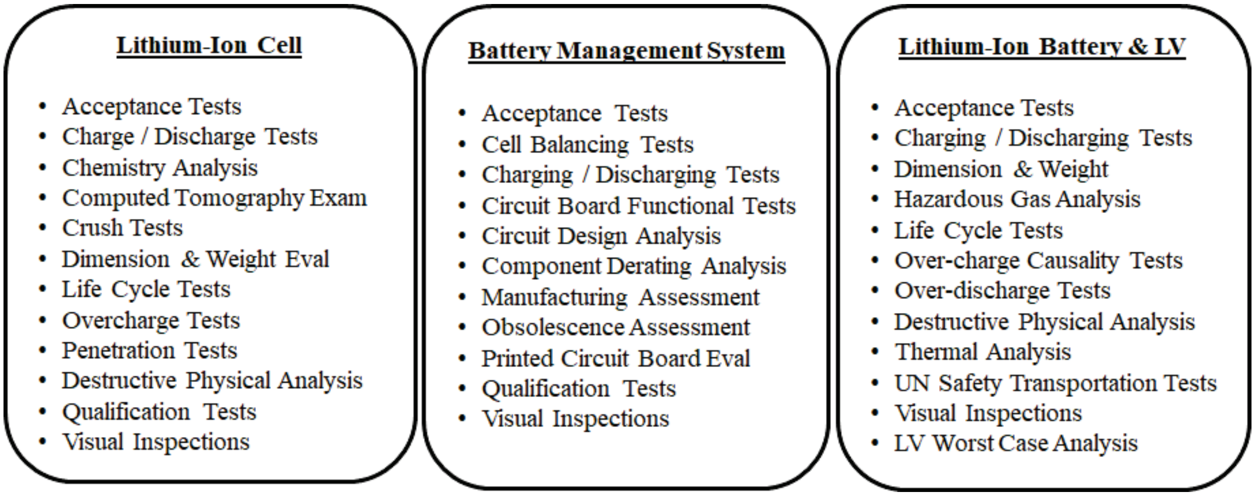
In this case, the program followed hardware development processes that used the vendor's CoC as sufficient evidence needed to incorporate the COTS into the battery's design. But reliance on the CoC instilled false confidence in the parts' performance capabilities and the batteries were unable to meet the standards of compliance that were asserted by the vendor's CoC. During battery evaluation tests, unexpected responses during charge / discharge tests were observed indicating the battery transitioned to an off nominal and unsafe state. Posttest analysis revealed that little was known about the battery's COTS components. It was at this point that the determination that an Uncertainty Risk Level I existed was made. This lack of technical data and confidence in the COTS pedigrees was the catalyst necessary to develop a tailored COTS and battery RM evaluation processes based on that illustrated in Figures 2 and 28 through 31.

Description of the tailored RM processes, the aleatory and epistemic uncertainties exposed, and how those were successfully mitigated are described in the next sections. The overall process evaluated the LIB's cells, PCB, and EEE components. Once these were completed, the evaluations were completed at the BMS and then at the battery level. This was accomplished to garner as much information as possible to mitigate aleatory and epistemic uncertainties discovered during the research. In support of these efforts several assumptions were developed to guide the design assessment. These were:

- COTS lithium-ion cells are generic in design and not application specific.
- Lithium-ion cell manufacturers protect their proprietary manufacturing techniques which limit the amount of pedigree data released to the consumer.
- Regardless of application, in the United States, lithium-ion cell and battery manufacturers are required to conduct testing to demonstrate compliance to domestic and international safety, performance, and quality requirements regardless of whether COTS or custom-built cells are used.
- Custom-built space-grade batteries are manufactured in limited quantities and are expensive to produce.
- Enough cells and batteries are required to support the design, testing, launch and payload fleet allocation and sparing.
- The batteries are required to operate reliably, safely, and with appropriate power margin to satisfy mission objectives.
- The batteries are required to comply with statutory battery safety and qualification standards.
- Special tooling, support equipment (i.e., charging hardware), storage, handling, and transportation should be included in the assessment.

Table 23 specifies the cell, PCB, EEE components, BMS, electrical circuit design, and battery evaluation activities performed. Risk management processes were developed from these to focus the COTS evaluations and to validate the RMF. These are discussed in depth in the sections that follow.

Table 23. COTS-based Lithium-ion Battery Risk Evaluation Analyses and Tests Performed to Uncover Aleatory and Epistemic Uncertainties



Lithium-Ion Cell

- Acceptance Tests
- Charge / Discharge Tests
- Chemistry Analysis
- Computed Tomography Exam
- Crush Tests
- Dimension & Weight Eval
- Life Cycle Tests
- Overcharge Tests
- Penetration Tests
- Destructive Physical Analysis
- Qualification Tests
- Visual Inspections

Battery Management System

- Acceptance Tests
- Cell Balancing Tests
- Charging / Discharging Tests
- Circuit Board Functional Tests
- Circuit Design Analysis
- Component Derating Analysis
- Manufacturing Assessment
- Obsolescence Assessment
- Printed Circuit Board Eval
- Qualification Tests
- Visual Inspections

Lithium-Ion Battery & LV

- Acceptance Tests
- Charging / Discharging Tests
- Dimension & Weight
- Hazardous Gas Analysis
- Life Cycle Tests
- Over-charge Causality Tests
- Over-discharge Tests
- Destructive Physical Analysis
- Thermal Analysis
- UN Safety Transportation Tests
- Visual Inspections
- LV Worst Case Analysis

6.5 LITHIUM-ION CELL RISK EVALUATION PROCESS

To manage the COTS cell risks, a six-step risk evaluation process, Figure 35, was created to provide a structured method to assess if the cells could comply with the LV's / SV's electrical performance, management, and safety requirements. This six-step process identifies the IOP activities required per the controls and enablers discussed in Chapter 3.

The battery was required to provide no less than fifty charge / discharge cycles of service and to be rated at 20 Ah capacity. The life cycle requirement was calculated by summing the times associated with the LV / SV integration activities that require battery power (i.e., production testing), storage, transportation, maintenance activities, launch site electrical power and

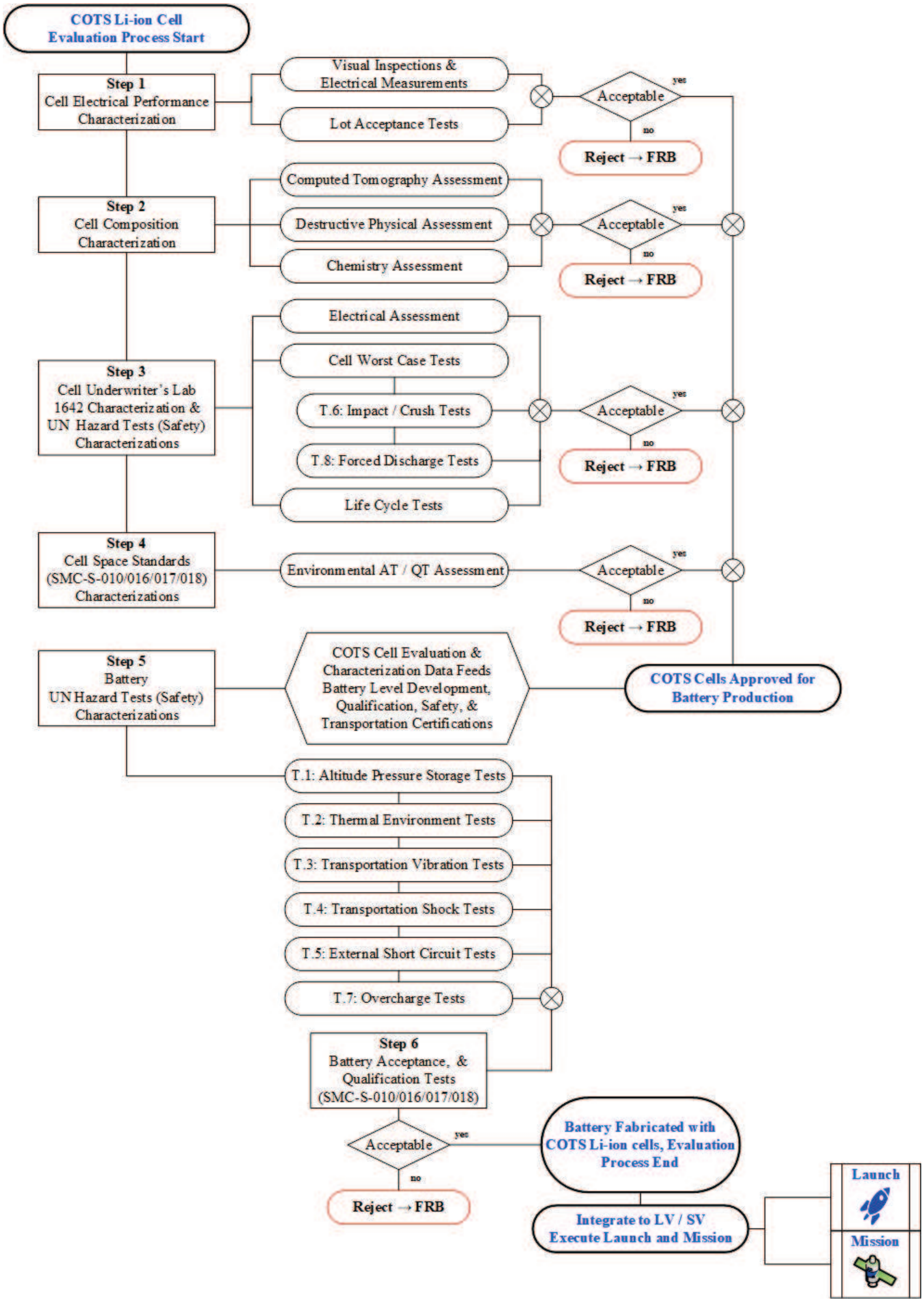


Figure 35. COTS cell uncertainty characterization and evaluation process used to manage risk.

distribution system testing, and the supply of power to the LV / SV loads during launch, deployment, and operational events. Additional design requirements had to consider what would happen if the Li-ion batteries were mistreated, damaged, or if the units experienced a thermal runaway event.

Because Li-ion battery thermal runaways can be quite destructive and difficult to contain the Li-ion cells and batteries had to demonstrate compliance to UL, UN, DoD, and DoT safety and transportation requirements, none of which could be waived. These requirements established the context as illustrated in Figure 28's Step 1, '*Develop Launch and Space Vehicle Design Concept*'.

Once this context was established, the tailored COTS cell systems engineering risk management process exhibited in Figure 35 was developed and implemented. At this point in the program no other COTS cells were under consideration which correlates to and satisfies Figure 28's Step 2's task to "*Identify & Evaluate COTS Candidates v. LV / SV Design Parameters*". However, a contingency was developed to locate a potential space-grade battery vendor that could provide a battery that would suit the program's requirements.

The next objective was to identify aleatory and epistemic uncertainties to determine quickly if other cell candidates needed to be considered. This triggered Figure 28's formal technical evaluation of the COTS Li-ion cells. The COTS cell technical evaluations started with Figure 35's Step 1 labeled "*Cell Electrical Performance Characterization*". Figure 35 Steps 1 through 6 are tailored representations of Figure 28's Steps 2 through 4 "*Determine LV / SV COTS Candidates' Uncertainties, Evaluate COTS Performance*, and *Develop and Evaluate LV / SV Risk Mitigations*" sub-processes.

6.6 LITHIUM-ION CELL TECHNICAL EVALUATION

The discussion that follows encompasses Figure 28's COTS RM SE process Steps 2 through 4 which focuses on identifying uncertainties, completing analyses and characterization tests, and the development of feasible risk mitigations. This tailoring of Figure 28's RM process is reflected in the six steps illustrated in Figure 35. Specifically, various evaluation activities were performed at the cell and battery levels. Unique evaluation criteria and test plans were developed to expose and address aleatory and epistemic uncertainties to the maximum extent possible.

As shown in Figure 35, after each evaluation step was completed, the data collected was evaluated to determine if the results demonstrated that the cells or batteries met requirements or if additional design reviews had to be convened. These COTS cell uncertainty characterization and evaluation processes were used to manage risk and to determine if mitigations could be developed. Once the uncertainties were identified and characterized, methods to treat those were successfully developed and executed. This included slightly modifying the battery's case design and reconfiguring its orientation inside the LV and SV. This portion of the process coincides with Figure 28's three decision options on whether to abandon the use of the COTS part, to continue with the evaluation process, or to conclude that the COTS part had enough uncertainties resolved to allow it to be incorporated into the LV / SV design. These options also correlate with the risk management options to either accept, avoid, control, mitigate, or transfer the risk [20].

As illustrated in Figure 35's Step 1, the process started by visually and electrically inspecting 243 cells from two lots made by the same vendor. This was an example of performing Figure 28's Steps 3.1 through 3.4. The visual inspections were performed to determine if each cell was dimensionally alike and if any external damage was noticeable. This evaluation determined that the Lot 2 cells' height was slightly larger than the Lot 1 cells. Next, electrical evaluations were performed to determine if the cells met the open-circuit voltage, resistance, cell matching, capacity, and state-of-charge requirements. These confirmed that the Lot 1 cells had a 9.8 Ah capacity as compared to the Lot 2 cells that met the vendor's advertised 10 Ah capacity. Additionally, a small subset of the two lots were subjected to life cycle tests to determine if the cells would meet the fifty charge / discharge cycle requirement. The data collected during Step 1 is considered information used to quantify epistemic uncertainties.

Figure 35's Step 2 included subjecting all cells to x-ray computed tomography (CT) imaging. Because there was minimal data on the cell's manufacturing process, its testing, or how reliability was established, evaluation criteria had to be developed. The criteria developed were a qualitative assessment and was used to develop an understanding of aleatory uncertainty. The criteria included an assessment of the CT images to determine if there were any indications of material variabilities that could limit cell life or have the potential to cause internal short circuiting such as electrode misalignment, presence of non-native material, foreign object debris, internal damage, or breaches. As a result of the assessments, 25% (61 of 243) of the cells were rejected for use. Figure 36 shows examples of two cells that were rejected due to tears and wrinkling observed in the CT images. It was unknown whether damage such as this could potentially cause a tear in the separator leading to an internal short circuit and possible thermal runaway. As a conservative risk mitigation effort, such cells were rejected. An alternative option of populating a battery with the worst looking cells and subjecting those to qualification level testing was rejected due to cost and schedule constraints.

Following the CT imaging, a small subset of cells was subjected to energy dispersive x-ray spectroscopy (EDX), scanning electron microscope imaging (SEM), and destructive physical assessment (DPA). The EDX and SEM verified that the cathode was made with lithium cobalt oxide ($LiCoO_2$) applied onto aluminum, and the active anode material was composed of carbon applied onto copper. The vendor's technical specification stated that the electrolyte salt was lithium hexafluorophosphate ($LiPF_6$). Verification of the electrolyte's chemistry was not done.

Three Lot 1 cells and two Lot 2 cells were subjected to destructive physical assessment (DPA). Under disassembly, it was verified that the Lot 2 cells, which met the 10 Ah rated capacity, had an additional cathode and anode pair relative to the 9.8 Ah Lot 1 cells. This additional cathode / anode pair caused enough dimensional difference that an eight-cell pack constructed from Lot 2 cells was now too large to fit in the existing battery housing. This caused the battery manufacturer to redesign the battery housing. This observation is a good example of NASA's COTS definition in action. Here, the cell vendor did not have any obligation to inform their customers that they added an additional cathode / anode pair, but this small lot-to-lot difference caused a significant battery case redesign.

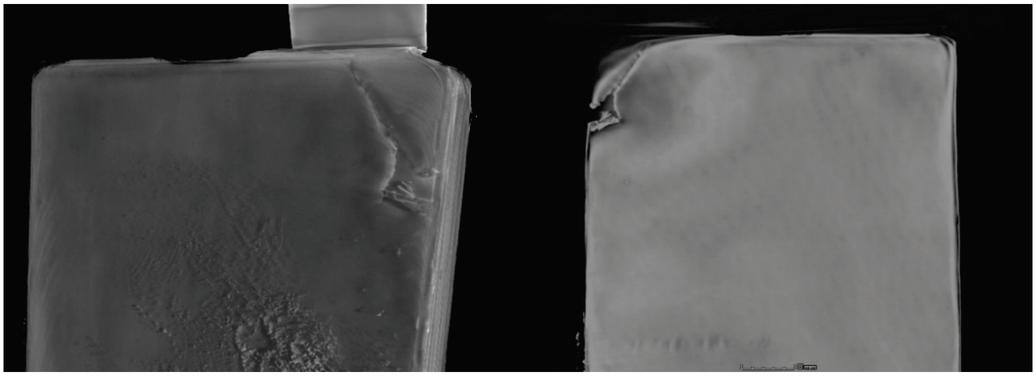


Figure 36. Damaged COTS cells rejected based on x-ray computed tomography imaging [46].
Courtesy of the Space Information Laboratories and The Aerospace Corporation

The findings are examples of how Figure 28's Steps 3.4, "*Evaluate Feasible Protective and Preventative Measures*" and 4.3 "*Develop LV / SC Design Modifications*" were being applied. As a result of the data collected in Steps 1 and 2, enough information was obtained to proceed to

Step 3. This initiated the commencement of experiments designed to produce data to determine if the COTS cells would meet UL Standard of Safety requirements.

To determine how cells would respond to abuse, a test configuration was built based on UL's techniques [94]. Specifically, seven cells were subjected to penetration and crush tests to characterize the abused cells' reaction. A test chamber was constructed that subjected cells to needle point penetration and crushing pressure. The test chamber design was manufactured and modified based on a design created by the Underwriters Laboratories [94]. Figure 37 depicts the test chamber designed to withstand high thermal reactions; vent toxic gas safely, and to collect video and thermal data. Indentation tests using metal and ceramic tips were conducted on the broad and narrow edges of the test cells. Crush (pinch) tests used a metal spherical ball against the cell's broad face. Both tests were designed to evaluate the cell's performance if damage was afflicted to the cell. The first tests were intended to drive the cells to complete failure. A second test was conducted to inflict damage, without forcing it to fail, followed by cycling the cells to characterize the degradations in performance. The damaged cell charge / discharge cycling performance was like those conducted on the non-damaged cells except for one cell in which the

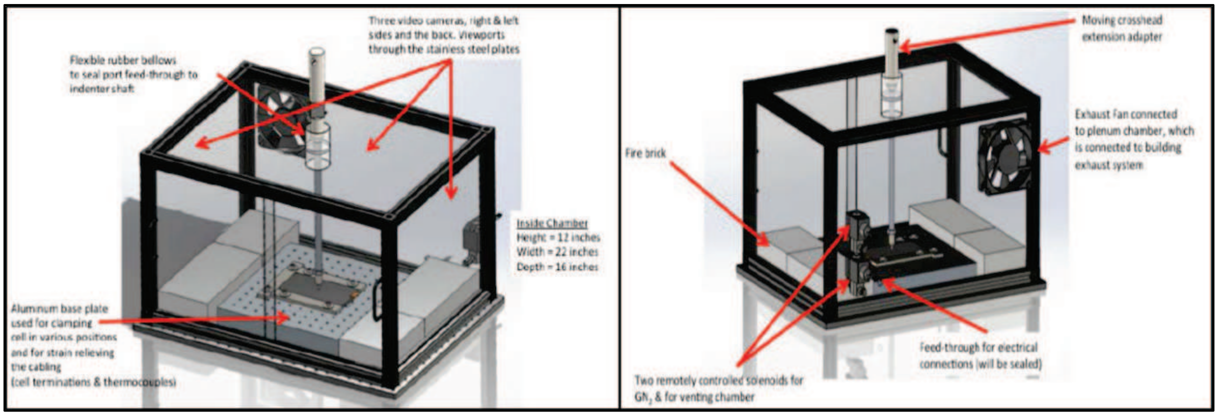


Figure 37. Test chamber developed to conduct pinch and crush tests [46].
Courtesy of the Space Information Laboratories and The Aerospace Corporation

pouch was breached. Figure 38 has photos taken during the UL penetration tests while the cells were in the test chamber.

Upon the completion of Step 3, a subset of Lot 1 and 2 cells were subjected to Step 4, *Cell Space Standards Testing*. In this case the cells were subjected to battery-level thermal acceptance and qualification tests [55]. Subjecting the cells to battery-level environmental tests provided information to reduce epistemic uncertainties associated with the battery's performance under launch and space environments. The cells performed nominally during the functional checks prior to, during, and after the test events. This activity instilled confidence that batteries built with the screened Lot 1 and 2 cells could survive battery-level AT, QT, safety, and transportation tests.

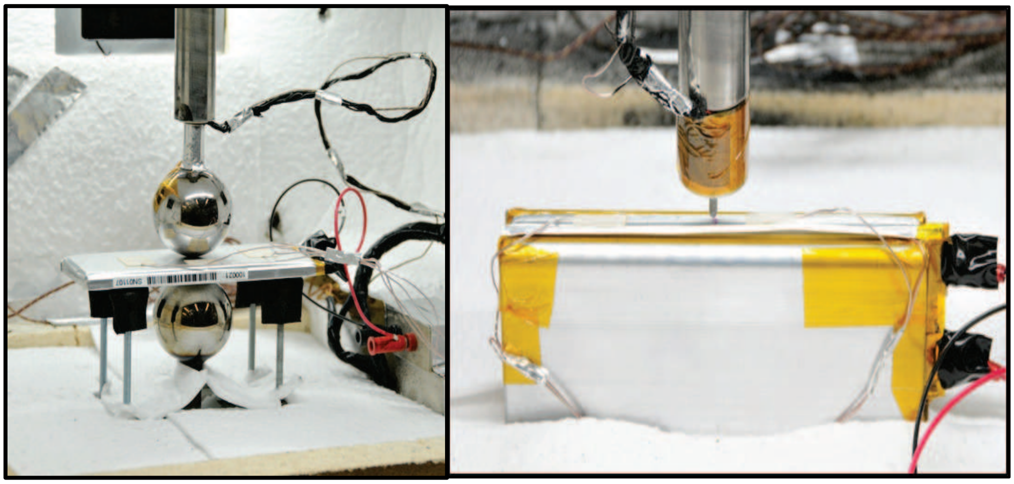


Figure 38. COTS cells subjected to abuse to determine cell stability per UL safety criteria [46].
Courtesy of the Space Information Laboratories and The Aerospace Corporation

The next section discusses the evaluation of the batteries PCB. Separate risk management processes were developed for this which will be explained. The results of the analyses and tests completed will be presented. Following this, battery level tests were performed which were conducted in accordance Figure 28's Steps 5 and 6.

6.7 PRINTED CIRCUIT BOARD EVALUATION

Figure 39 is the RM process developed and executed to evaluate a COTS printed circuit board (PCB) populated with EEE components and the BMS electrical circuit design destined for use in the secondary lithium-ion battery. The PCB is critical to the battery management system which is used to keep the lithium-ion cells stable, balanced, and to interrupt electrical operations if safety thresholds are exceeded.

The evaluation started on the PCB that was used in the battery design that exhibited off-nominal behavior during the initial development tests. Using the gap assessment technique as previously described, it was quickly determined that the PCB fell into a URL I (severe gaps / high risk) category. Though a CoC was provided by the manufacturer stating it was produced at a space-grade level, the vendor provided minimal documentation to prove the claim. This lack of compliance data compelled the need to acquire additional data to gain confidence in the PCB's functionality. Thus, the eleven step BMS Printed Circuit & Electrical Design risk management process, as depicted in Figure 39, was created and executed.

Similar to the cell risk evaluation process, the battery level evaluations Steps 9 through 11 were completed once the COTS components were characterized and any modifications required were completed. The battery level test results will be presented in the next section.

As depicted in the figure, EEE component screening and derating, thermal, and sneak circuit analyses were completed. Additionally, material coupon examinations, manufacturer process evaluations, and an IPC Class III (space-grade) requirements compliance assessment were completed. Following these, the PCB was subjected to functional, workmanship thermal, acceptance and qualification thermal cycles, and cell charge management tests. Though

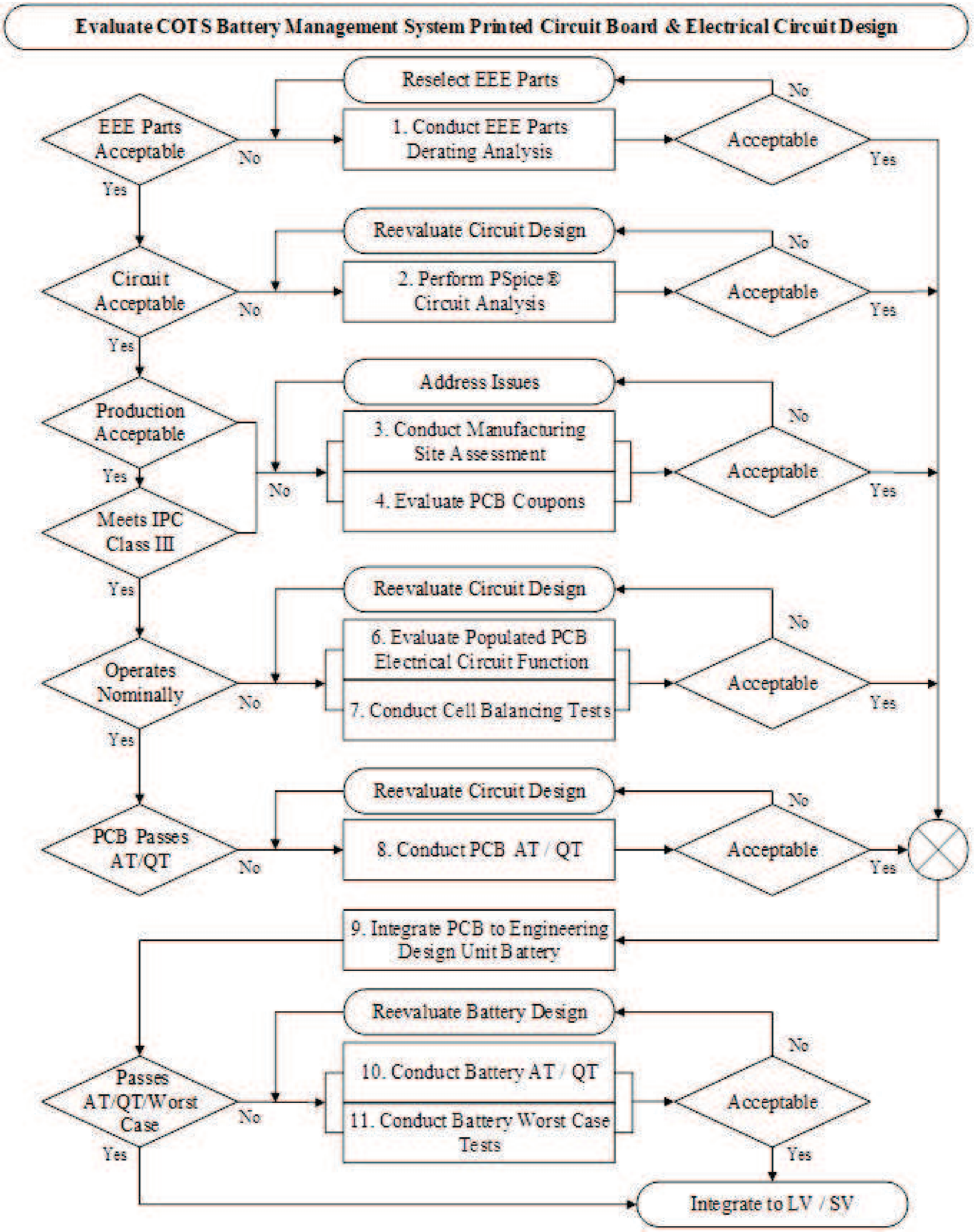


Figure 39. COTS printed circuit board (PCB) evaluation process performed to characterize its ability to perform in space environments and battery management functions.

not required, the PCB thermal tests subjected the PCB to battery level acceptance and qualification thermal tests levels as detailed in SMC-S-016 [55] and -018 [95] . Once these were accomplished and an approved PCB design was obtained, the PCB was exposed to battery level environments which is what is reflected in Figure 40's fifteen step process. Testing the PCB at these levels was done to establish confidence in the PCB design to prove it could pass the tests before it could be integrated into a battery. Thermal tests were used because they are the most perceptive in uncovering parts infant mortality, outgassing, epoxy issues, and PCB resiliency.

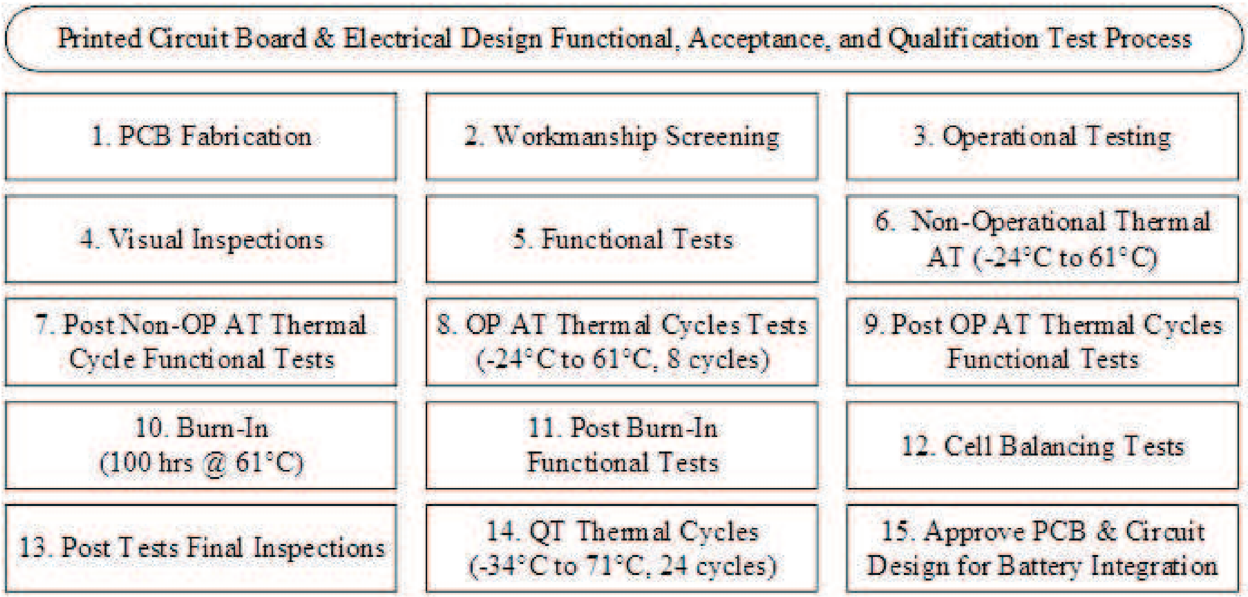


Figure 40. Printed circuit board and electrical design functional, acceptance (workmanship), and qualification (design verification) tests performed to characterize its performance in space thermal environments. [55] [95]

The COTS PCB risk evaluation process evaluation started with Figure 39's Step 1 that determined that the EEE parts included in the design were appropriate. However, during the Step 2 circuit evaluation a sneak path was discovered using the PSpice® circuit design modeling tool. If this sneak path were activated during a battery off-nominal condition it could circumvent the battery's BMS. If this happens then the probability for battery thermal runaway increased which could lead to catastrophic damage. As a result, the circuit design was modified to remove the sneak path. [Data collected during this circuit modeling is not presented because it would reveal proprietary electric circuit design methodology.]

Additionally, while the PCB evaluation was underway, manufacturing, and electric circuit design subject matter experts visited the vendor's manufacturing facility to evaluate its production and quality assurance processes which corresponds to Figure 39's Steps 3 and 4. Though the vendor did have established quality assurance processes these were considered the bare minimum required. It was also learned that the PCB's design material coupons were not available for assessment. The performance of the EEE parts derating analysis and vendor site visit was considered a way to address aleatory uncertainty while performing the PSpice® modeling provided data used to mitigate epistemic uncertainty associated with the BMS electrical circuit design.

The PCB evaluation continued by executing Figure 39's Steps 6 through 8 and Figure 40's Steps 1 through 14. The latter is an amplification of Figure 39's processes. These were carried out to determine how the PCB would respond to thermal environments.

The first PCB thermal test was performed as shown in Figure 40's Step 6. The PCB and its electrical circuit were dormant during these tests. After the PCB was visually inspected and functionally operated per Figure 40's Step 7 it was subjected to eight cycles of thermal testing (Step 8) to prove that workmanship was adequate. After this was accomplished, the PCB was examined again and subjected to functional tests per Figure 40's Step 9. This was followed by a 100-hour burn-in period (Step 10) to expose latent defects to the PCB or EEE parts. Step 11 functional tests completed proved the PCB could successfully perform the BMS cell management functions (Step 12). After this, the PCB was subjected to twenty-four thermal test cycles at QT temperatures (Step 14). During QT, the PCB was operated at predefined points in accordance with SMC-S-016 and -018 test criteria. This was followed by visual and functional performance assessments to determine if the PCB met the qualification criteria.

The thermal tests conducted on the original PCB design showed that board layer delamination occurred. Additionally, using microscopic tools it was discovered that the PCB's electrical conduit displayed significant workmanship issues. Figure 41 displays a sample of the etching, cracking, and smearing issues discovered. Figure 42 displays the PCB layer delamination discovered. Because of the workmanship issues and the delamination, the original PCB was rejected for use which was an example of Figure 28's decision cycle in action. This led to a search for an alternate supplier whose product could pass the criteria and whose manufacturing processes demonstrated acceptable production and quality assurance methods. During this process, the program received board coupons for evaluation. The coupons were

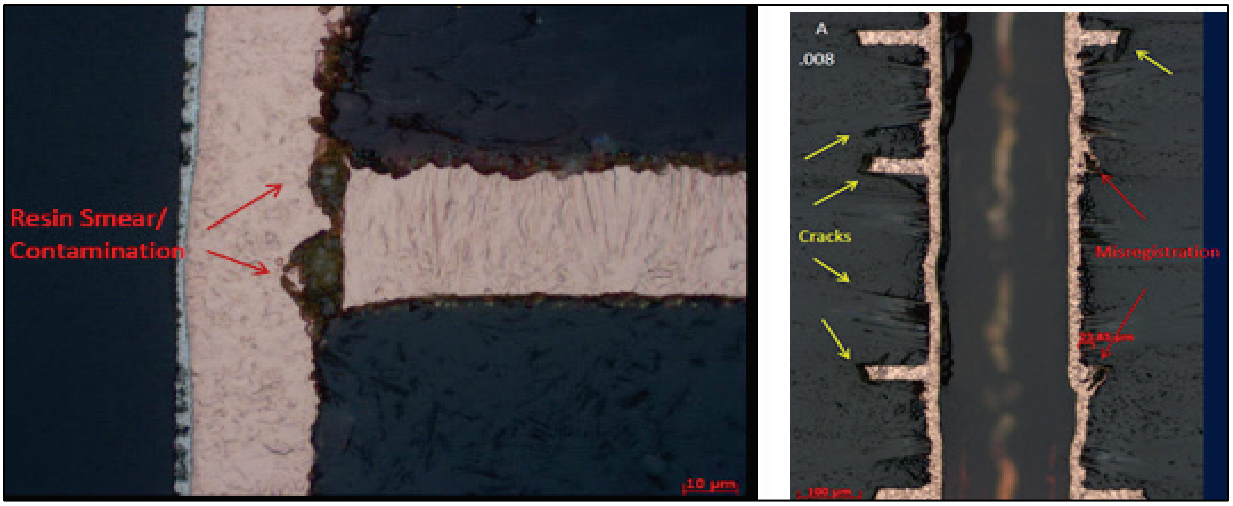


Figure 41. Lithium-ion battery COTS printed circuit board workmanship issues discovered using proactive RM processes [51].

Courtesy of the Space Information Laboratories and The Aerospace Corporation subjected to visual, microscopic evaluation, and thermal testing. The coupons samples were determined to be acceptable. Based on these results, new PCBs were ordered from the new vendor and subjected to Figures 39 and 40 risk evaluation processes. The results from these tests were acceptable and were proven to meet the IPC rigid board production and circuit design requirements. The new PCB also met all burn-in, AT, and QT requirements. This PCB was approved for integration into a set of battery EDUs. These were built to undergo battery level development, acceptance, qualification, and safety compliance testing. This testing is reflected in the cell and PCB RM processes as shown in Figure 39's Steps 5 and 6 and Figure's 40's Steps 9 through 11. The results of these battery level RM process evaluation steps are presented in the next section.

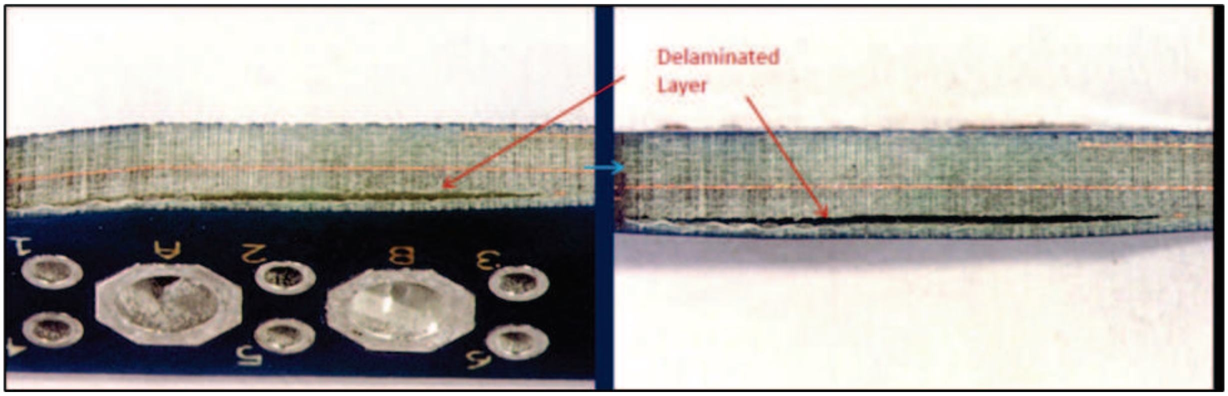
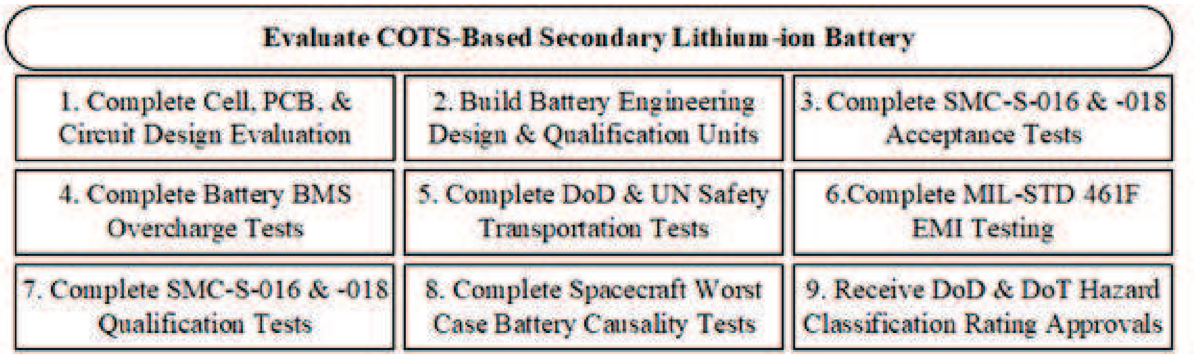


Figure 42. Lithium-ion battery COTS printed circuit board layer delamination discovered using proactive RM processes [51].
Courtesy of the Space Information Laboratories and The Aerospace Corporation

6.8 LITHIUM-ION BATTERY QUALIFICATION AND WORST-CASE TESTS

Once the lithium-ion cell and BMS designs were evaluated, the efforts then focused on proving if the battery could meet LV / SV qualification and safety requirements. This was completed based on the nine tasks exhibited in Figure 43.

After the COTS cell, PCB, and EEE parts were successfully evaluated, twelve batteries were built to support battery testing. This testing included AT, QT, electromagnetic interference and compatibility (EMI / EMC), safety, and battery causality tests. These were accomplished to demonstrate compliance with the United Nations, DoT, and DoD transportation and safety requirements. These battery level tests were those referred to in the cell and PCB risk evaluation processes as shown in Figure 28's RM framework and Figures 29 - 31 and 39 RM processes.



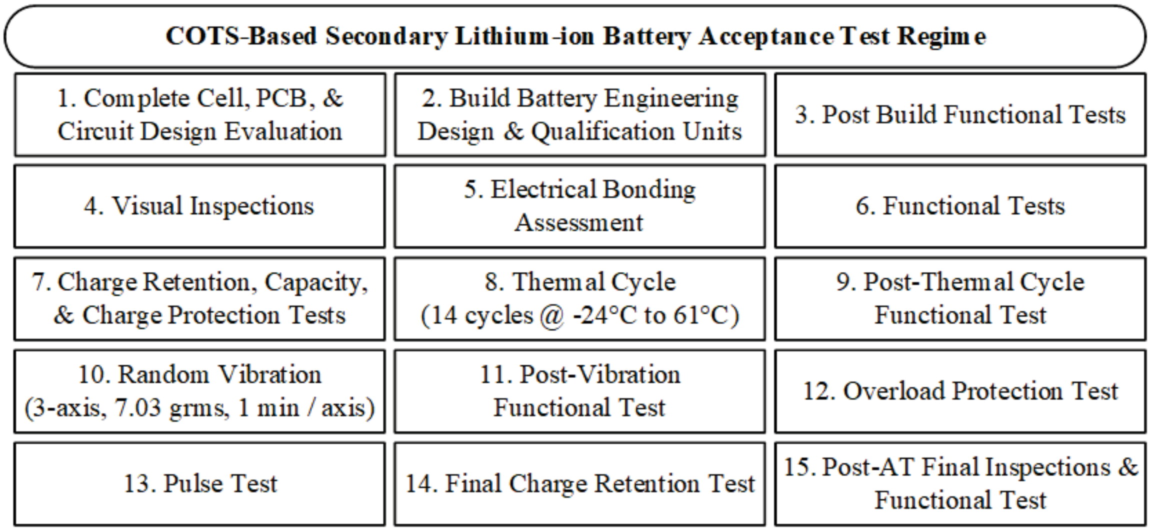
Evaluate COTS-Based Secondary Lithium-ion Battery

1. Complete Cell, PCB, & Circuit Design Evaluation	2. Build Battery Engineering Design & Qualification Units	3. Complete SMC-S-016 & -018 Acceptance Tests
4. Complete Battery BMS Overcharge Tests	5. Complete DoD & UN Safety Transportation Tests	6.Complete MIL-STD 461F EMI Testing
7. Complete SMC-S-016 & -018 Qualification Tests	8. Complete Spacecraft Worst Case Battery Causality Tests	9. Receive DoD & DoT Hazard Classification Rating Approvals

Figure 43. COTS-based battery level evaluation tests were conducted to verify it could meet space, safety, and transportation requirements.

The AT, QT, and EMI/EMC tests were conducted in accordance with SMC-S-016, SMC-S-018, and MIL-STD 461F criteria. Two batteries were allocated to the AT, QT, and EMI / EMC tests to satisfy launch range safety requirements [90] [91]. Eight were allocated to the safety tests and two were dedicated to the worst-case causality testing. Additionally, during battery production, the Defense Contracting Management Agency (DCMA) was employed to conduct third party inspections during the battery assembly process to verify workmanship prior to sealing the battery after the cell packs were integrated.

Figures 44 list the AT conducted. As part of the AT, the batteries were subjected to electrical performance assessments, exposure to fluctuating thermal environments, and vibration testing. The electrical performance assessments included performing functional tests before, during, and after the thermal cycles, electrical bonding inspections before and after the AT, charge, discharge, retention, and overcharge tests. EMI testing was successfully performed prior to doing the QT.



COTS-Based Secondary Lithium-ion Battery Acceptance Test Regime

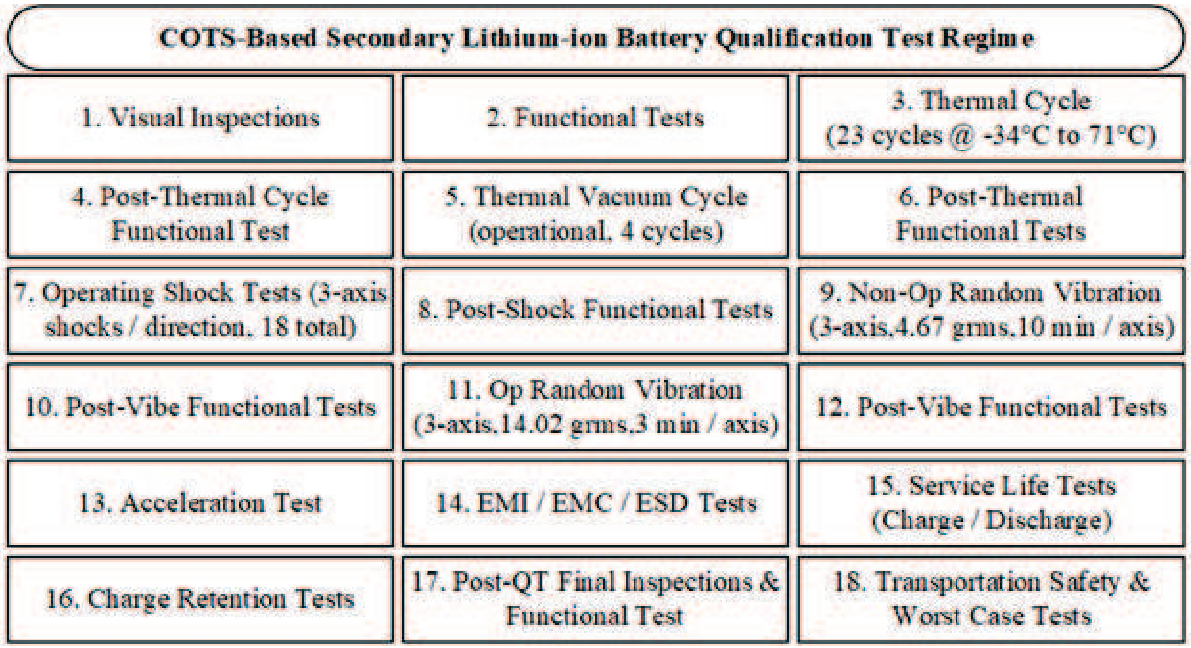
1. Complete Cell, PCB, & Circuit Design Evaluation	2. Build Battery Engineering Design & Qualification Units	3. Post Build Functional Tests
4. Visual Inspections	5. Electrical Bonding Assessment	6. Functional Tests
7. Charge Retention, Capacity, & Charge Protection Tests	8. Thermal Cycle (14 cycles @ -24°C to 61°C)	9. Post-Thermal Cycle Functional Test
10. Random Vibration (3-axis, 7.03 grms, 1 min / axis)	11. Post-Vibration Functional Test	12. Overload Protection Test
13. Pulse Test	14. Final Charge Retention Test	15. Post-AT Final Inspections & Functional Test

Figure 44. COTS-based battery level acceptance tests (AT) performed to workmanship.

These were completed to demonstrate that the battery functioned as designed, that it was properly built, and that the BMS would safely manage the battery's operations. No issues were observed indicating off-nominal performance.

After AT was completed, the tests shown in Figure 45 were accomplished to qualify the battery's design. Like the AT, functional tests and visual external and internal inspections were performed prior, during, and after the test events. As compared to the AT, the thermal cycles during QT were increased to twenty-three cycles and with the temperatures increased and decreased by 10°C. This was followed by four thermal vacuum cycles. Eighteen shock events were completed to make sure that the battery was exposed the stimuli from all six axes (±X, ±Y, ±Z). Once functionality was verified after the thermal and shock tests, vibration tests were performed at the levels and durations listed in Figure 45. This was followed by acceleration testing. Additionally, as part of the QT, the batteries were subjected to one hundred charge / discharge cycles to prove that the battery would meet its service life requirements. The batteries performed nominally.

Following QT, transportation and safety tests were conducted to demonstrate that the battery was safe to be transported via air, sea, and ground commercial or military convenience. The tests used eight batteries as specified in the United Nations Manual of Test [83]. Deemed a small battery per the standard, the tests required were the Test 1 (T1) - Altitude Simulation,
Test 2 (T2) - Thermal Exposure, Test 3 (T3) - Vibration, Test 4 (T4) - Shock,
Test 5 (T5) – External Short Circuit, and Test (T7) 7 - Overcharge. The UN Test 6 was not required for this battery; thus, it is not listed.



COTS-Based Secondary Lithium-ion Battery Qualification Test Regime

1. Visual Inspections	2. Functional Tests	3. Thermal Cycle (23 cycles @ -34°C to 71°C)
4. Post-Thermal Cycle Functional Test	5. Thermal Vacuum Cycle (operational, 4 cycles)	6. Post-Thermal Functional Tests
7. Operating Shock Tests (3-axis shocks / direction, 18 total)	8. Post-Shock Functional Tests	9. Non-Op Random Vibration (3-axis,4.67 grms,10 min / axis)
10. Post-Vibe Functional Tests	11. Op Random Vibration (3-axis,14.02 grms,3 min / axis)	12. Post-Vibe Functional Tests
13. Acceleration Test	14. EMI / EMC / ESD Tests	15. Service Life Tests (Charge / Discharge)
16. Charge Retention Tests	17. Post-QT Final Inspections & Functional Test	18. Transportation Safety & Worst Case Tests

Figure 45. COTS-based battery level qualification tests (QT) performed to evaluate the COTS-based hardware design.

Pass / Fail criteria for T1 through T4 stated that the battery could not exhibit any leakage, venting, disassembly, rupture, fire, and could not exhibit more than a 10% drop in its open-circuit voltage immediately after the tests were completed.

T5 Pass / Fail criteria stated the battery could not exhibit an external temperature > 170°C nor could it exhibit any disassembly, rupture, or fire within six hours after the test.

The T7 Pass / Fail criteria stated the battery could not exhibit any disassembly during the test nor within seven days after the overcharge was applied. All the batteries passed the UN tests.

The last task completed was to subject the battery to off-nominal conditions to characterize its performance during a worst-case scenario. These battery causality overcharge tests were conducted on two batteries to collect response data if a cell went into thermal runaway and what, if any, risk mitigations could be taken. The unique tests helped answer whether thermal runaway propagated to neighboring cells and if the battery housing could contain an off-nominal event. The test data was used to validate a LV / SV thermal model created to predict effects to the LV / SV structures and integrated hardware. This is considered an example of Figure 28's Step 4.4, "*Complete Performance Margin Testing*" task.

Each battery was instrumented with thirty-two thermocouples positioned on the battery housing and the test fixture mounting plate. One cell was configured to drive it to thermal runaway by charging it at a fast rate (twice the normal charging rate) without a charge cut off limit. During the first battery overcharge test, the battery was oriented with the two interface connectors and cables below the battery box. As expected, the overcharged cell transitioned to thermal runaway. The battery housing exhibited deformation caused by the internal pressure created by the thermal runaway. This created an escape path for effluent to pass via the battery housing-to-lid seams. This effluent ignited the external cabling overwrapping and the flames rose and impinged on and around the battery housing. Additionally, the test results were used to validate LV and SV internal thermal model predictions which is an example of Figure 28's Steps 3.2 and 4.2 "*Perform Analyses and Modeling/Sim*" being executed.

The data collected from the causality tests and thermal modeling led to two modifications to the LV and SV which corresponds with Figure 28’s Step 4.1, “*Develop LV / SC Design Modifications*.”

The first modification changed the battery’s orientation inside the LV / SV. This was done to prevent effluent and thermal energy from impinging on sensitive components and structural areas inside the LV / SV. The second modification changed the battery’s external cable positioning and incorporated flame-retardant cable overwrap. Once completed, the battery causality test was repeated. Figure 46 is a photo of the second battery test as thermal energy and effluent exited the battery’s case. As in the first test, high pressure created by the cell thermal runaway caused the battery housing to deform. Just like before, this path allowed effluent and thermal

Figure 46. COTS-based secondary lithium-ion battery purposely subjected to cell overcharge to observe its reaction and to provide data to validate a thermal model [46].
Courtesy of the Space Information Laboratories

energy to escape from the battery housing. However, even though the thermal energy did escape the battery housing again, the posttest inspections and thermal modeling showed that it was no longer considered a danger to the LV's / SV's internal components or structure. This time, the cable overwrap material did not ignite, proving that the overwraps were indeed flame retardant even after being exposed to extremely elevated temperatures and flames. Both modifications were incorporated as formal changes to the battery's interface and integration design.

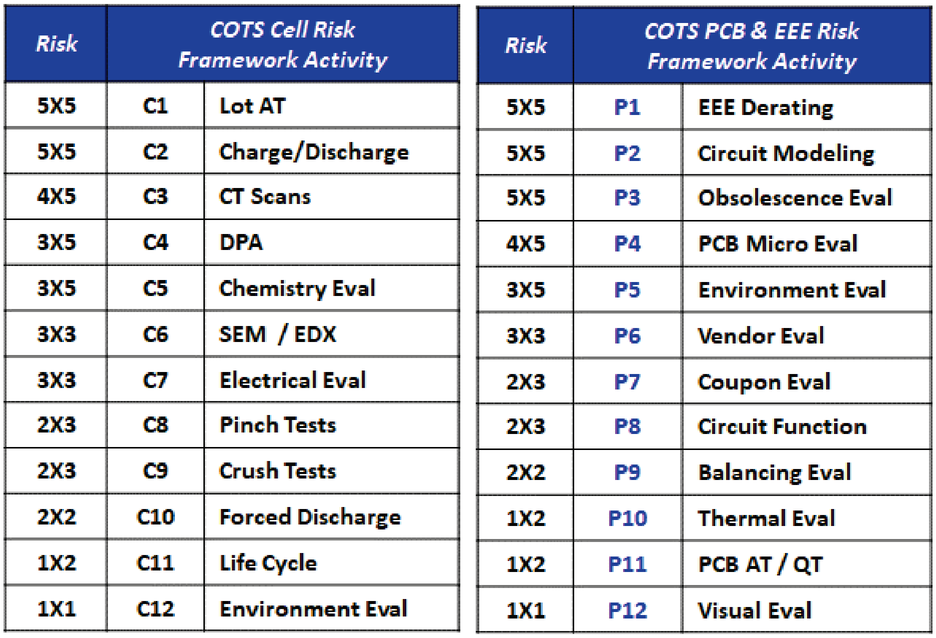
6.9 RISK MITIGATION BURN-DOWN

As described in Section 1.4, risk matrices are used to communicate risk likelihood, severity, consequence, and magnitude as illustrated in Tables 3 through 6. Besides using the matrices to display the initial risks, the matrices are good tools to track if the mitigations are working. It is burn-down plans such as these that are methods used to communicate progress and status to decision authorities and stakeholders.

Figures 47 and 48 matrices are conceptual illustrations like those used during the actual COTS-based Li-ion battery development, characterization, and evaluation project. However, these risk burn-down paths are not the same to ensure the integrity of non-disclosure agreements. The activities listed are those that correspond to those shown in Figures 34, 35, 39, 43 – 45, and Table 23 risk evaluation processes. These are the activities that were developed from the various controls and enablers as described in Section 3.2.

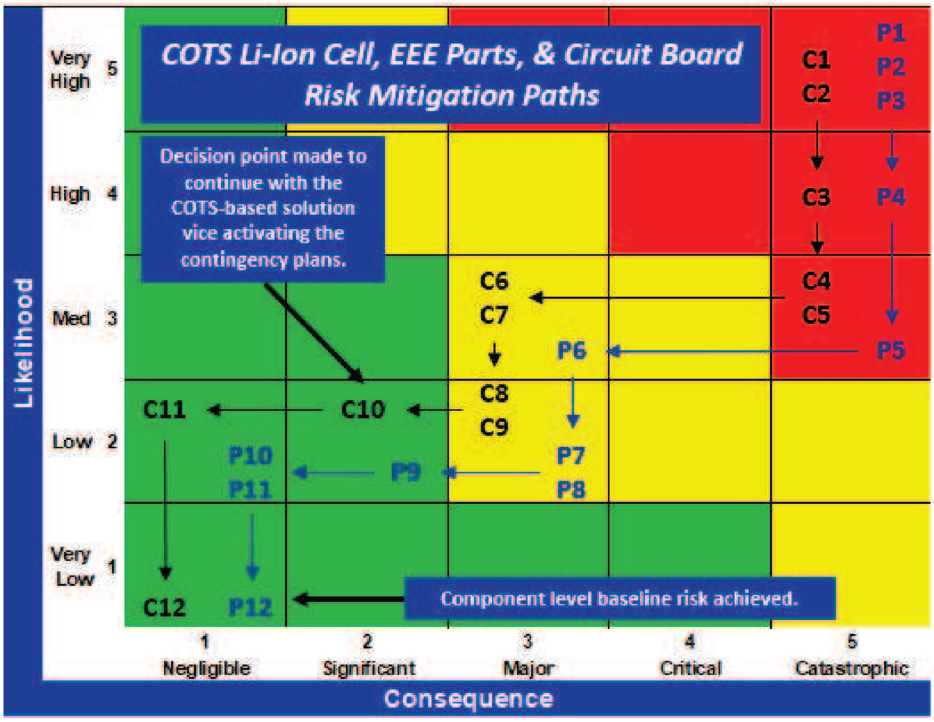
The matrices highlight the risk mitigation activities executed per the risk evaluation processes as presented in the previous sections. Figure 47 contains the risk burn-down paths associated with the COTS Li-ion cells, EEE parts, and PCB. Table 24 contains the Likelihood

Table 24. COTS Lithium-ion cells, EEE parts, and Printed Circuit Board Risk Burn-Down Matrix



Risk	*COTS Cell Risk Framework Activity*	
5X5	C1	Lot AT
5X5	C2	Charge/Discharge
4X5	C3	CT Scans
3X5	C4	DPA
3X5	C5	Chemistry Eval
3X3	C6	SEM / EDX
3X3	C7	Electrical Eval
2X3	C8	Pinch Tests
2X3	C9	Crush Tests
2X2	C10	Forced Discharge
1X2	C11	Life Cycle
1X1	C12	Environment Eval

Risk	*COTS PCB & EEE Risk Framework Activity*	
5X5	P1	EEE Derating
5X5	P2	Circuit Modeling
5X5	P3	Obsolescence Eval
4X5	P4	PCB Micro Eval
3X5	P5	Environment Eval
3X3	P6	Vendor Eval
2X3	P7	Coupon Eval
2X3	P8	Circuit Function
2X2	P9	Balancing Eval
1X2	P10	Thermal Eval
1X2	P11	PCB AT / QT
1X1	P12	Visual Eval



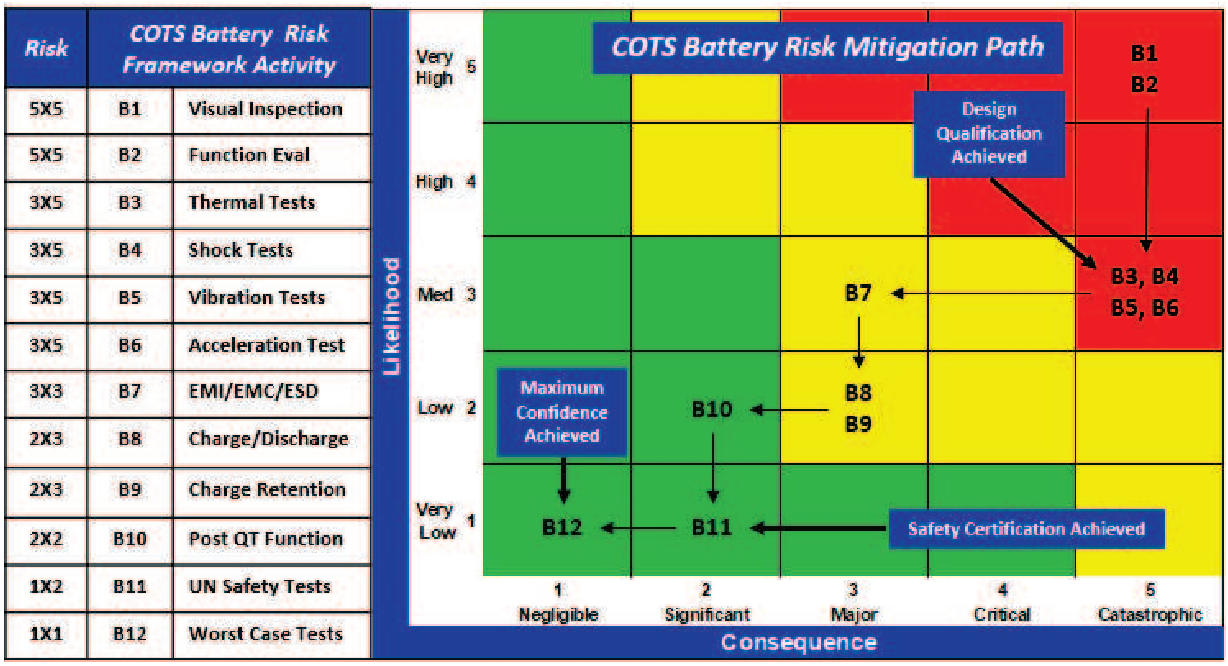
COTS Li-Ion Cell, EEE Parts, & Circuit Board Risk Mitigation Paths

Decision point made to continue with the COTS-based solution vice activating the contingency plans.

Component level baseline risk achieved.

Figure 47. Sample COTS component-level risk burn-down matrix illustrating risk mitigation progress.

versus Consequence (i.e., 5 X 5) risk numerical representations from the initial risk assessment. The burn-down path continues until the lowest risk level was achieved. In this example, the Li-ion cells risk levels and activities are labeled with a **C** followed by a number. The same is done for the PCB and EEE parts activities but are labeled with a **P** followed by a number. The alpha-numeric codes are positioned on the risk matrix with arrows used to represent the burn-down path achieved. For example, the Li-ion cell path started in the 5 X 5 position which decreased as the various activities were completed. In this case, the risks were reduced significantly after the cell CT scans, DPA, chemistry analysis, and pinch / crush tests were completed. All these activities can be traced back to the Figures' 35 and 39 risk evaluation processes. Moreover, it was at the C10 point where elevated confidence in the cell's performance was achieved. This corresponds to when the cell pinch and crush abuse tests were



Risk	COTS Battery Risk Framework Activity	
5X5	B1	Visual Inspection
5X5	B2	Function Eval
3X5	B3	Thermal Tests
3X5	B4	Shock Tests
3X5	B5	Vibration Tests
3X5	B6	Acceleration Test
3X3	B7	EMI/EMC/ESD
2X3	B8	Charge/Discharge
2X3	B9	Charge Retention
2X2	B10	Post QT Function
1X2	B11	UN Safety Tests
1X1	B12	Worst Case Tests

Figure 48. Sample COTS unit-level risk burn-down matrix illustrating risk mitigation progress.

completed. This is the point when the program decided not to activate the contingency plans because enough confidence was achieved to make an informed decision.

As previously explained, Figures 35 and 39 were the activities used during the risk evaluation processes. Once the component level risk evaluation processes were completed, the battery level risk mitigations started where were tracked separately using a similar burn-down process. Figure 48 illustrates the burn-down path and the activities tracked during the battery level risk evaluation process. The risk burn-down process followed the same labeling and tracing process as described for the component burn-down matrix. The battery activities were coded alpha-numerically again with a **B** prefacing the number to represent a battery activity.

These tools proved to be extremely effective in communicating the COTS-based battery development process to stakeholders. This assisted in having technical and programmatic decisions made in a timely fashion so as not to induce cost, schedule, or mission risks.

6.10 COTS RISK MANAGEMENT FRAMEWORK EXEMPLIFIED SUMMARY

The modeling and simulation, analyses, and tests as described in this chapter were used to answer Research Question No. 4 which was, "*What COTS analyses, modeling, and tests can be used to validate COTS-based space hardware risk management strategies?*". The activities described were conducted based on the risk management evaluation processes shown in Figures 35 and 36 which were based on the RMF as illustrated in Figures 28 through 31. These processes were used as the guide to develop methods that were outside the normal hardware development and design qualification boundaries to evaluate a COTS-based secondary lithium-ion battery destined for use in a fleet of launch and space vehicles. The processes used were essential to uncover aleatory and epistemic uncertainties associated with the battery's cells, printed circuit board, electrical design, and integration of the battery into the LV and SV structure.

For example, the X-ray computed tomography non-destructive testing used to examine 243 cells proved there were manufacturing and quality control issues with 25% of the cells evaluated. The CT scans uncovered numerous issues with the cell's workmanship that normally would not have been known if the vendor's CoC was trusted. Because the cells were inexpensive, the loss 61of the 243 cells was deemed acceptable. In addition, the cell destructive physical assessment proved there were significant cell lot-to-lot configuration differences. In this case, the addition of an anode / cathode pair caused enough dimensional differences that the battery case had to be redesigned.

Seven COTS cells were subjected to penetration and crushing force tests. However, on a positive note, the crush and penetration tests demonstrated that the COTS cells could withstand a great deal of punishment while continuing to provide potential and without going into thermal runaway.

The battery management system's electrical circuit, EEE components used, and the printed circuit board evaluation revealed several issues. In this case, the COTS evaluation processes were instrumental in uncovering a sneak path and flaws in the PCB. The flaws discovered during the PCB evaluation process is another example of the COTS definition at work. In this case, the original PCB vendor provided CoCs that stated the PCB met design requirements to be used in space. It did not need to disclose its manufacturing and quality control processes, provide any data that supported the CoC, or maintain test coupons after it completed its production run. This combination of poor PCB design practices combined with poor manufacturing and a lack of robust quality assurance practices made the COTS product not reliable enough for use in space. However, the RM evaluation processes proved to uncover and address all the aleatory and epistemic uncertainties discovered during the evaluation processes.

The methods used to discover the issues are good examples of Figure 28’s Steps 2, 4, 6 and 7 of the *COTS Risk Management Process A: Assessing COTS Candidates* risk management strategy at work. As a result, the electrical circuit was redesigned, and the PCB production and testing processes were improved to reduce the risks from an URL I to a baseline level.

Battery-level tests consumed twelve units during qualification, safety, and worst-case overcharge tests which qualified the battery’s design for space use. The battery design met all qualification criteria. However, during the battery causality tests, it was discovered that if the battery experienced thermal runaway severe damage would be inflicted to surrounding hardware inside the LV / SV structures. As a result, it was determined that the battery’s orientation inside the LV had to be modified to prevent effluent and heat (fire) from impinging on neighboring hardware and the LV’s structure. Additional measures were taken to replace the battery’s external cable overwraps with those made from flame retardant material.

In summary, the modeling and simulation, analyses, and tests proved that a safe and reliable secondary lithium-ion battery could be built with COTS. The tailored RMF and processes employed proved highly effective in exposing and mitigating aleatory and epistemic uncertainties discovered at the component, subsystem, and system levels. Accordingly, it can be concluded that the presented RM framework and evaluation processes were successfully validated using the lithium-ion battery as an exemplar. As a result, a battery design that was originally riddled with uncertainty and classified at an Uncertainty Risk Level 1 was transformed into a robust, safe, and reliable unit qualified for use in space. The lithium-ion battery design that was used as an exemplar to validate this research’s hypotheses and qualified for flight was successfully flown on a fleet of launch and space vehicles over the last eight years.

7. RESEARCH DISCUSSION

7.1 RESEARCH DISCUSSION

Following the generic RMF as exhibited in Figure 2, the first step in the RM process was to establish the context to determine where uncertainties exist. To establish this context, a common RM and COTS lexicon was established to focus the research's attention. This was followed by a detailed examination about aleatory and epistemic uncertainties, controls, and enablers, and that there exists a lack of guidance on how to effectively assess if COTS could be good candidates for integration into space system hardware. Additionally, it was demonstrated how important it is to understand a LV's / SV's MEAL [96] before COTS candidates could be selected. Based on these premises, a COTS-based space hardware risk management framework and complimentary risk evaluation processes were developed based on fundamental RM theory. These were then used and validated using a COTS secondary lithium-ion battery as an exemplar. All this work was done to answer Research Questions 1 through 4. Now, the final task that remains is to address Research Question No. 5 which was, "*What lessons can be learned from this effort that can benefit the space industry and what recommendations can be made to further the research?*"

The following sections are presented to answer Research Question No. 5. Specifically, a discussion will be presented on how the categorization of risk into the two types, aleatory and epistemic, are instrumental in uncovering risk and developing mitigation methods. Following this, a discussion on how risk profiles are dependent on the space environment and how uncertainties will differ as those dynamic attributes change as a function of a LV's / SV's MEAL [96] is presented.

The next topic also presents the lessons learned during this research. Special emphasis is placed on the controls and enablers extracted from the initial literature review and how those were used to create the processes and select the activities used to identify, analyze, evaluate, and treat risks. Lastly, a series of topics are provided that recommends additional research that can be done to further the exploration of using COTS to build space hardware.

7.2 QUANTIFYING UNCERTAINITY IN COTS RISK MANAGEMENT

Evaluating and managing risk associated with using COTS to build space hardware is dependent on understanding and addressing sources of uncertainty in COTS performance. As proposed by NASA and as discussed in this study [24], uncertainties were divided into two categories, aleatory and epistemic. This differentiation among types of uncertainties was evident and proved beneficial during the evaluation of COTS lithium-ion battery cells, a printed circuit board, and EEE components. Epistemic uncertainties and risks were mitigated using the set of modeling and simulations, analyses, and tests that provided the data needed to determine the capabilities and limitations of the cells, PCB, EEE parts, and the battery. In contrast, screening all the cells in the inventory to determine if they met requirements to build batteries was a means to manage aleatory uncertainty. Another example was the assessment of the PCB vendor's factory to examine their manufacturing processes and quality assurance practices. The observations made contributed to the decision to locate a new PCB vendor.

Because aleatory uncertainties are those that cannot be evaluated or mitigated by M&S, analysis, or test, aleatory uncertainty was a source of unresolved doubts about the cell's reliability. In automotive or electronics industries, reliability can be established using probability and statistical based predictions because there is ample data to support such an assessment.

Moreover, industries such as these practice statistical process control routinely during their manufacturing processes which reduces variability and increases quality assurance. This is counter to the space industries' low-volume hardware production model which does not allow it to practice these high yield manufacturing techniques. As such, aleatory performance uncertainty for COTS components should be identified, and managed separately from other sources of uncertainty.

For example, this research described how a method to mitigate aleatory uncertainty was created to evaluate the Li-ion cells internally without causing any damage to the cell's soft pouch construction. Using the qualitative criteria to evaluate CT images of the cell's internal structure provided the battery development team with the ability to judge good versus bad cells. Out of 243 cells subjected to the CT scanning, sixty-one were rejected for use. These were rejected even though the cells had passed the electrical tests at the beginning of the evaluation process. Based on this information it was determined that the program could afford to lose approximately 25% of its inventory because there were enough acceptable cells to manufacture the quantity of batteries required by the program. This decision was made easier because the cells were relatively inexpensive due to their COTS nature, and that the cost was worth it to reduce epistemic uncertainty in system performance.

Regarding epistemic uncertainty, a combination of modeling and simulation (i.e., PSpice® circuit modeling), analyses (i.e., thermal analysis), and testing (i.e., causality tests) activities were accomplished to obtain data which was used to better understand how the cells, BMS, and battery would perform during nominal and off-nominal scenarios. For example, the battery level worst case causality tests results were used as the basis to reposition the battery when it was integrated into the launch and space vehicle. This modification was completed to prevent effluent and heat (fire) produced during a battery thermal runaway event to damage the internal structure or neighboring components. Another example is the discovery during cell destructive physical assessment that there was an additional cathode / anode pair added to the second lot of cells purchased. This realization was what caused the need to redesign the battery case to accommodate a slightly larger 8-cell pack. Both were examples of identifying epistemic uncertainty and mitigating the risks associated with them using objective evaluation methods that were not part of the original design-build philosophy.

With this discussion about uncovering aleatory and epistemic uncertainties in mind, the question on whether the processes used as documented in this research are any different than those normally used in space hardware development differ is valid. To answer this question, it is appropriate to discuss the reasons for developing the COTS RMF and the evaluation processes used. Some reasons why relate back to the definition of COTS as defined in the Chapter 1 discussion and restated below.

> *"A part for which the manufacturer solely establishes and controls specifications for configuration, performance, quality, and reliability. This includes design, materials, processes, assembly, and testing with no Government-imposed requirements (i.e., no Government oversight). COTS typically are available on a manufacturer's catalog (e.g., website) or from various distributors." [2]*

In this case, the research has shown that insufficient Li-ion cell and printed circuit board technical information was available to remove concerns about the COTS components' performance only after an off-nominal event was observed during the initial battery engineering design unit testing. Because of this, an examination to determine what was really known about the hardware was initiated. It was concluded that little was known about the cell and PCB manufacturers' design, test, and manufacturing processes. So, unique methods to characterize the hardware's performance were required. This is an example of how Figure 9's organization's policies, processes, procedures, decision register, risk register, quality assurance register, and traceability mapping had to be modified to obtain the data needed to demonstrate that COTS could be used to build the exemplar battery.

For example, even though the PCB manufacturer stated that the products they delivered were compliant to space-grade standards, a closer examination based on a variety of unique tests proved the opposite. The results from these tests led the design team to question the vendor's manufacturing and quality control processes which were found woefully inadequate. As such, because there was scant technical information available about the Li-ion cell and PCB, both proved to epitomize the COTS definition.

Additionally, referring to Table 10, "COTS-based hardware benefits and risks", it could be concluded that many of the items listed under the "Risk" column were realized such as "Supplier production processes changed without insight" and "Lack of manufacturing quality control requires mitigation". It is because of these risks being realized that the unique COTS risk evaluation techniques were developed. The techniques were based on methods used and documented in various forms of scientific literature not those contained in any space hardware standard or guide. Granted, the final evaluations performed were used to demonstrate that the final battery design could be qualified in accordance with space hardware requirements; however, most of the assessments (i.e., cell CT scans), analyses (i.e., cell chemistry), and tests (i.e., cell crush and pinch) completely deviated from the nominal battery building process. It was the lack of technical data and historical performance data that drove the need to collect the data to mitigate the multitude of aleatory and epistemic uncertainties uncovered.

Based on this discourse, the next question that would rightly be posed would be if the choice of COTS in this case was a good one. To answer this, referring to Figure 5, "Hypothetical COTS versus custom space hardware development comparison" and Figure 28, "COTS Risk Management Framework used to determine if COTS candidates are feasible for LV / SV designs", it can be said that there was a point when proceeding with the COTS-based battery design was questioned.

Referring to Figure 5, there are two paths shown. The first is the typical space-grade hardware development process. The second path illustrates a path using COTS. For this battery, the issues discovered with the initial battery design came during the typical hardware development process phase. It was at this point, when a decision as reflected in Figure 28's step 2.3 was made to continue the path of using the COTS-based design. This was made based on the results from an assessment based on Step 2.2's determination that the cell was the critical path. It should also be known that the evaluations of the of the cell, electrical circuit, and PCB were done in parallel vice in a serial fashion. Completing the evaluations as depicted in Figures 35 and 39 simultaneously proved to be advantageous because these could be completed in time to keep pace with the overall LV / SV design schedules. Meanwhile as these were being accomplished a contingency plan to determine if a different battery could be developed to support LV / SV schedules was underway. A decision to reject this contingency was made after the cells completed Figure 35's Steps 1 through 3 evaluations. It was at this point that higher confidence was achieved because, by this time, the sneak path and PCB workmanship issues had been resolved. Once this was realized, the likelihood that the battery would not be able to pass the qualification, transportation, and safety tests was significantly diminished.

Besides the technical rationale given to continue with the COTS-based design there were two other reasons. The first was that there was a significant investment already sunk into the COTS-based design. The second reason was based on the procurement of the contingency space-grade battery. Like any other unit identified as part of the baseline architecture, there would still have been costs, time, and resources dedicated to an alternate battery's procurement, development testing, manufacturing, and the like. So, a final decision was made that proceeding with the COTS-based design was the most prudent and affordable. But this decision to accept the risk instead of transferring the risk was made from an informed perspective based on the execution of Figure 28's Steps 3 and 4. It was also bolstered by the continuous risk monitoring cycles as depicted in Figures 29 – 31 COTS Risk Management Processes A through C. Doing so and as reflected in Figure 30's "COTS Risk Management Process B: Determine Uncertainty Risk Level", the COTS-based battery design effort receded from a COTS URL I (High) to a baseline risk. This was accomplished by developing and executing the robust systems engineering COTS risk management concepts as presented in this research.

7.3 MISSION RISK PROFILES

Not explicit (but recognized) in this formulation of a RMF for COTS is the understanding that different LV / SV missions have different risk profiles, and as the levels of risk acceptable will vary according to the mission requirements (represented in Figure 28, Step 1.0). NASA recommends that these types of considerations be factored in when using COTS in space hardware designs through the concept of the MEAL [2] (mission, environment, application, and lifetime). Launch and space vehicles differ in type, size, purpose, orbit, and environments. They therefore also differ in the amount of risk the LV / SV stakeholders are willing to accept. For reference, two of the largest space hardware users are the US DoD and NASA. Both organizations separate their risks into four classes of space vehicles. Recalling that Table 25 is from the US Air Force's (USAF) Mission Assurance Tailoring Guide [36] which is the policy

Table 25. USAF [USSF] Space Vehicle Risk Class Attributes [36]

	Class A **(Typically ACAT I/II Programs)**	**Class B** **(Typically ACAT II Programs)**	**Class C** **(Typically ACAT III Programs)**	**Class D** **(Typically Experimental Programs)**
Risk Acceptance	Lowest	Low	Moderate	High
National Significance	Extremely Critical	Critical	Not Critical	Not Critical
Payloads	Operational	Operations demonstrates operational utility; May become operational	Typically Experimental	Typically Experimental
Acquisition Cost	Highest	High	Medium	Lowest
Development Time	May take 4 or more years	May take 3 or more years	May take 2 of more years	May take 1 or more years
Mission Life	Long, greater than 5 yrs, typically 8-10 years	Medium, up to 5 years	Short, less than 2 years	Short, less than 1 year
Launch Constraints	Critical	Medium	Few	Few to none
Specifications and Standards Compliance	Specs/Stds fully incorporated as compliance documents with no to limited tailoring of requirements. All practical measures taken to minimize risk to mission success.	Specs/Stds required as compliance documents with minor tailoring in application to maintain a low risk to mission success.	Medium risk of achieving mission success may be acceptable. Reduced mission assurance requirements with tailoring acceptable.	Higher risk acceptance of achieving mission success. Reduces set of mission assurance requirements acceptable.

document that communicates payload (space vehicle's) attributes. (NASA used a similar categorization. NASA's are labeled Class 1-4 vice A-D.) Foremost in the guidance is the risk level that is considered acceptable for each payload class. After this, the policy describes other factors such as reliability, cost, development time, mission life, and mission types. As shown in Table 25, the Class C and D space vehicle risks are moderate to high and experience development timelines between one to two years. Use of COTS is endorsed for Class C and D missions because these are more likely to be research and development operations to assess new space hardware performance in the harsh space environments. On the other hand, Class A and B payloads have little tolerance for risk because the payloads are required for national security objectives. With the Table 25 attributes and the new USAF / USSF acquisition policy mentioned previously [4] in mind, it can be deduced that the current mission assurance and risk tolerance levels will need to be amended if the new three-year acquisition policy to field Class A and B payloads is to be realized. One of the only ways to achieve these accelerated payload acquisition development timeline goals is to embrace COTS or determine other methods to quicken the production of unique space-grade parts. This will be the case to support the increase in LV / SV demand as discussed in Chapter 1. Another example where the need for space hardware will increase are the NASA Gateway [63] and Artemis [65] missions. Both will require a great deal of hardware and money to support the sustained missions on or around the Moon. COTS are a useful source, but methods need to be developed and matured to quickly evaluate if COTS parts can sufficiently substitute space-grade parts.

7.4 CONTROLS, ENABLERS, AND LESSONS IN PRACTICE

The RMF and evaluation processes as illustrated in Figures 28 – 31, 35, and 39 were developed based on the information extracted from the literature reviewed during this research. Referring to Section 3.2's Figure 9 that illustrated a generic input-process-output diagram, it was evident that many of the Technical, Process, and People attributes presented in Tables 14 – 16 needed to be applied to instill confidence that a COTS-based secondary lithium-ion battery could be built while staying within design, schedule, and budgetary constraints. However, a major obstacle that had to be overcome was what the INCOSE Systems Engineering Guide refers to as *Cognitive Bias* [39]. As the Guide explains, *"...stakeholders (individual or groups) are subject to cognitive biases when interpreting uncertain information*" [39]. In the case of using the COTS battery cells and PCBs, the overarching biases that had to be overcome were that methods could be developed to quickly gain knowledge to make informed decisions. These biases were well founded especially because during the time this battery was being developed there were numerous examples in news reports of lithium-ion batteries catching fire and causing severe damage (airplane, automotive, mobile phones, electric scooter, etc.). So, to solve this the RMF had to be carefully framed, or as INCOSE says it depends on "*[H]ow we ask the question or describe the decision matters"* [39]. Therefore, the following controls and enablers as exhibited in Tables 14 – 16 were built into the RMF and evaluation activities as illustrated in Figure 9. The activities:

- Determined quickly where uncertainties resided by performing a robust gap analysis. (Requirements versus COTS performance data comparison) [51]

- Determined that minimal data was available that would provide confidence in the COTS cells and PCB performance; thus, exposing the need to independently collect performance data. (CoCs lacked demonstrable evidence) [46] [51] [97]

- Determined points within the COTS assessment process that a decision had to be made on whether to continue with the COTS-based design or to withdraw from the campaign to seek another alternative. (Post cell CT scans and pinch & crush tests) [34]

- Carefully selected the assessment, screenings, analyses, and tests methods that were grounded in experimental evidence documented in technical literature. (Cell CT scans, DPA, pinch & crush tests; PCB microscopy, thermal exposure) [28]

- Closely examined the LV's / SV's mission profile to determine exactly how long the batteries needed to provide nominal performance. (Short yet highly risk adverse duration missions) [96]

- Determined methods to collect data on how the COTS cells would respond when subjected to worst case situations such as being abused or overcharged. (Battery worst case tests) [27]

- Evaluated manufacturing processes (PCB) to be certain that the hardware could function in the MEAL environments. (Manufacturer site visits, coupon assessments) [96]

- Kept lines of communication open amongst all stakeholders to demonstrate mitigation strategies were achievable. (Regular briefings based on data collected) [39]

- Identified and completed design modifications quickly. (Battery case, battery orientation) [34]

- Evaluated the EEE parts to determine if those would be operated outside of the specification thresholds and assessed if any EMI / EMC or radiation would affect their operations during associated with the MEAL. (Derating analysis) [31]

- Evaluated the predicted environments to determine if the COTS would function and to determine if the qualification levels were overly conservative. [66]

Additional lessons that were identified during this research are as follows:

- Learned that controlling the operation of electrical circuits and EEE parts can substantially reduce effects from radiation exposure to forestall or limit single event upsets and total ionization dosage (TID). [27] [33]

- Learned that early architecture design awareness when considering COTS is to determine if protective and preventative measures could be incorporated that could eliminate or significantly reduce the likelihood of damage from environmental exposure. [28] [48]

- Learned that the selection of the COTS manufacturer is extremely important. The manufacturer should be able to demonstrate proven reliability based on high volume control by robust quality assurance practices such as statistical process control to reduce lot variability, automated production with limited human touch time, practices robust verification methods that spans across lots, and that defects are quickly addressed and removed from distribution to the market. [96]

- Learned that vendor Certificates of Compliance should be scrutinized to determine if the claims being made can be backed up with data. The lack of test and / or historical performance data is an indicator that a COTS candidate will have to be subjected to some level of evaluation by the space program to uncover uncertainties. Requesting the assistance of unbiased third parties (i.e., FFRDCs (Aerospace Corporation) or government In Service Engineering Agents (ISEA)) to liaison with the vendor to broker a way manufacturing, test, and performance data can be evaluated without exposing proprietary provisions is a good practice to routinely adopt. The use of non-disclosure agreements (NDA) is a useful mechanism to facilitate trust between the independent evaluator and a hardware vendor. [46] [51] [97]

- Learned there are numerous stakeholder interests involved across the space hardware development process can be significantly taxing. Stakeholder involvement will be more intensive if an energetic device (i.e., battery) is being built vice a benign device that does not have the ability to cause a catastrophic event. Close communication with stakeholders could allow for performance evaluations to be done in parallel vice serially to meet their requirements. This would allow for conservation of funds and time. [46] [51] [97]

- Learned to closely examine a design’s build of material to distinguish between active and passive parts. Identification of active parts, where they reside in the hardware’s system level design, and how those will be used are important because resources can be focused on COTS that would be considered at risk. [75]

- Learned that there are data repositories that exist that have cataloged COTS that have demonstrated their use in space environments and that performance data coupled to the COTS is readily available which helps to reduce uncertainty. [98] [99] [100]

- Learned that there is a considerable amount of data that shows that SVs partially built with COTS have surpassed their expected lifetime which indicates that those were overdesigned. The need to closely examine where design trades can be made to allow for COTS to be incorporated should be an entering design practice. [44]

- Learned that evidence exists that shows COTS-based SV failures were attributed to design incongruities and not associated with the COTS failing to perform. [101]

- Learned that space hardware test facilities perform the same tests on the same hardware for numerous customers. In order not to compromise competitor proprietary design methodology it would be prudent to request assistance from neutral third parties (i.e., FFRDCs, UARC, government sponsors) to determine if the COTS were already tested. This would save resources without violating a company's design structures. [18]

All the controls, enablers, and lessons listed are equally important. However, the last lesson documented is important because this can improve the current COTS body of knowledge available to space hardware designers. As such, this topic is amplified in the next section. The expansion of the existing COTS data repositories will benefit the space industry especially if it wants to incorporate modern technologies, reduce costs, and to reduce fielding times.

7.5 COTS COMPONENT PERFORMANCE DATA SHARING

One of the challenges of using a quantitative RMF such as the one proposed in this work, is that it is often difficult to accurately predict a space-grade part's reliability without demonstrated performance in the space environment. So, it is left to the space hardware design teams to determine how sufficient data will be collected to determine if a COTS candidate (or even a new space-grade or MIL-Spec part) can be used in a space application. One way to accelerate the development and adoption of risk management frameworks for COTS equipment is to develop space industry wide data repositories where all can access COTS evaluation data.

A collective COTS data repository is a means to enable reduced uncertainties around the performance of COTS parts through data sharing. For example, there are COTS related databases currently being maintained by NASA, the Aerospace Corporation and the University of Colorado, and the Naval Sea Systems Command (NAVSEA) Naval Surface Warfare Center Crane Division (NSWC Crane). These are extremely useful tools to identify COTS for space hardware applications but access to the technical data available is limited.

NASA is currently proposing a capability called the Parts Evaluation and Assessment Laboratory (PEAL) [98]. PEAL will support a database for parts that are assured directly by their combination of being produced by an Industry Leading Parts Manufacturer, those that practice high-volume statistically process controls, or manufacturers that test 100% of their parts [98].

Another example is the Aerospace Corporation's collaboration with the University of Colorado facilitating an on-line parts data repository called PMPedia™ (https://pmpedia.space) [99]. This database is an open-source collection that contains EEE parts' technical data that have been evaluated for space radiation effects.

The third example is led by NSWC Crane which is the DoD's Technical Execution Lead for the Strategic Radiation Hardened Electronics Council (SRHEC). One of SRHEC's purposes is to "*Coordinate with strategic/space programs to identify and quantify needs for radiation-hardened (RH) components and systems; identifying common needs, priorities, and leveraging opportunities"* [100].

All three of these resources are good tools to identify COTS candidates for space hardware designs, but the only one that is open to the industrial community is the Aerospace / University of Colorado PMPedia™ database. Another limitation is that these databases only focus on parts that have been assessed from a radiation susceptibility aspect.

Despite their limited focus, these repositories can be considered good models to enhance and to foster increased collaboration amongst academic, civil, commercial, and government communities. The repository files could include COTS parts performance data in space environments, COTS test and evaluation data, the methods used to evaluate the COTS, and any historical evidence that demonstrates the hardware's performance in space. Expanding and synchronizing databases such as these will allow the space industry to conserve cost and schedule instead of devoting resources to repeating expensive and time-consuming COTS parts evaluation tests that may have already been completed at the same test facilities by other activities. This type of expansion and sharing of COTS data can enable the use of systems-engineering derived and quantitative risk management frameworks such as those proposed here.

One known current activity to address these discontinuities is being sponsored by the Aerospace Corporation, a Federally Funded Research and Development Center (FFRDC). The Aerospace Corporation is facilitating a joint study between government, civil, and commercial stakeholders to develop COTS EEE parts use guidance, establishing co-joined COTS databases, and the development and publishing of COTS risk management strategies such as those presented in this research [18].

FFRDCs and University Affiliated Research Centers (UARCs) are in unique positions because of their not-for-profit charters, strong ties working in the various industries, and their commitments to protect proprietary data. It makes these organizations the logical choice to charter such efforts. However, as can be imagined, developing COTS parts guidance that is agreed upon by space industry agents can take considerable time and effort to gain consensus. Therefore, research efforts like what was presented in this study fill a gap while formal and accepted guidance to the space industry is published.

Another example is NASA's recent work which seeks to communicate guidance to the COTS user space community. Currently, NASA is working to publish a COTS use policy document which is focused on high level commercial procurements such as full spacecraft and standard products and components such as star trackers and reaction wheels [101]. It is titled, "*Guideline for Usage of Commercial Off the Shelf Products*" [28] which is currently going through the final review process. Despite NASA's policy not being published yet and the Aerospace Corporation's cross-industry facilitation efforts in its infancy, it does show that there are space industry champions working to lead efforts like those listed above. Having industry leaders encouraging and supporting the use of COTS is imperative for the use to be accepted by an extremely risk adverse industry.

These efforts prove that the space industry is actively seeking to use COTS parts and figuring out the best methods to assess their performance. The sharing of data and collaboration to develop COTS use policies are good steps to enable increased use of COTS products in space hardware designs. The sharing of COTS relevant technical performance data will enable more robust and timely COTS risk management decisions to be made that mitigate aleatory and epistemic uncertainties. Thus, the development and fielding of space hardware will be able to keep pace with demand through increased use of COTS in space hardware designs.

7.6 FUTURE WORK

The information presented in the previous sections naturally leads to a discussion about future work. As presented, there are significant aerospace industry partners working together to develop guidance that can be used to utilize COTS when building space hardware. Their goals are to convince a hesitant and risk adverse community that COTS can be used in specific applications. The goal would be to advertise and to advocate to have it become a best practice to expend the resources needed to demonstrate that due diligence is being accomplished to accept COTS into space hardware designs. This is one area where a vast amount of work needs to be done. As described, the various organizations chartered to develop methods to evaluate COTS are focused on EEE parts with special emphasis on radiation susceptibility. This area is ripe for future research to expand the library of knowledge.

For example, like the research presented here, additional research can be done at the hardware unit or sub-system level. For example, an SV’s communications system (as described in Table 18) that includes computer processors, transmitters, receivers, antennas, motors and controllers, encryption equipment, mixers, amplifiers, and filters all could be evaluated to determine if COTS can be used in their designs. Some work that could be accomplished would be like that shown in Appendix B, Table 27. All the hardware listed above contain circuits that are built with EEE parts. A BOM, like that shown in Table 27, is evaluated to determine where COTS can be used instead of space-grade parts is a good start. Another option would be to assess a unit such as a transmitter to determine where exactly COTS parts would reside and to determine how these would be exposed to the various environments as discussed in Chapter 4. This type of examination could identify where exposure to radiation is minimized or eliminated all together by the incorporation of a modicum of shielding that would not impact the spacecraft's SWaP.

Another opportunity for future work would be to use the databases above to reexamine how parts, units, sub-systems, and systems are qualified for space. Anecdotal evidence was presented in this research that indicates that high value, low risk spacecraft are over designed as depicted in Appendix A and Tables 7 – 8. This work would include conducting an intensive survey of space vehicles' MEAL to determine if their operation exceeded the cited lifetime. This survey should also examine what caused its failures. As suggested by the data presented in this research and during discussions with GSFC [101] many of the failures can be better attributed to design issues vice the parts that were selected to build the hardware.

Building on the suggested work above and considering an entering assumption that spacecraft are overdesigned, an evaluation of the current space hardware qualification standards is appropriate. Since the qualification standards currently being used in industry were compiled over 30+ years ago and the fact that parts reliability and resiliency has drastically improved over the last five decades, a case could be made that studies should be encouraged to reexamine the basis of the qualification standards. The improvement in parts performance using statistical process control and manufacturing optimization techniques has increased the likelihood that some COTS parts are more than sufficient for space applications.

Further research needs to be accomplished to develop risk management processes for other hardware units. For example, RM processes like those exhibited in Figures 35 and 39 could be developed and validated in the same fashion as demonstrated in this research. RM processes are needed to assess an entire space craft suite of avionics units such as antennas, inertial measurement units, receivers, solar panels, star trackers, and transmitters to name a few. Once enough of these COTS RM evaluation processes are developed and validated these can be collected and published in a document that can be made available to industry for use as a guide when considering using COTS in a design.

An additional suggestion is to develop methods to improve hardware testing efficiency. Because there is a finite number of facilities that can perform the various and specialized types of tests (i.e., EMI / EMC, radiation susceptibility) required to characterize and qualify hardware, optimization of these resources would increase the pace that testing can be accomplished. For example, the same COTS part may be under consideration by numerous commercial or civil organizations to use it in their spacecraft design. These organizations would perform the same test as another but be completely unawares. Plus, data from the tests performed is not routinely shared amongst the wider aerospace industrial community. This results in the testing facilities repeating the same tests on the same hardware, which is not efficient. It also increases hardware development time because testing opportunities are not readily available. One way to alleviate this is to expand the charters of the groups attempting to develop COTS guidance for consumption by the aerospace community. These or activities like these (i.e., NSWC Crane) could further engage and survey industry to determine what design choices they are making and what parts they are considering. Coordinating the testing of one unit is much more efficient than repeating the activity over and over again. Then, this data could be shared across the aerospace community without exposing the proprietary nature of the upper-level design. This type of research would benefit the increased need for qualified space parts which are in demand now and will be in greater demand when the colonization of the Moon and other areas (i.e., Mars) is realized.

Since many COTS components being considered for use in space hardware come from industries (i.e., automotive, aviation, medical) that require just as reliable and resilient hardware as the aerospace industry does, investigations on how those industries develop their hardware would be a good topic to research. Like this research the examination of those industries could yield additional controls, enablers, and best practices that can be used to build space hardware. One such method is increasing the use of additive manufacturing which can be used in rapid prototyping. Because additive manufacturing can quickly produce a prototype, experiments and developmental testing can be done quickly to expose flaws in designs which can then be rapidly addressed. Being able to discover design flaws early can economize resources and increase a design's robustness. This relates to the observation noted in this research that spacecraft system failure is attributed more times than not to how a part is used in a design and operated outside its advertised boundaries. The proper use and application of the part can be readily evaluated if it is introduced early in the design phase.

7.7 RESEARCH DISCUSSION SUMMARY

The purpose of this chapter was to answer Research Question No. 5 which was, "*What lessons can be learned from this effort that can benefit the space industry and what recommendations can be made to further the research?*"

Answering this research question was accomplished by summarizing how systems engineering controls and enablers were extracted from the literature review and used to create a risk management framework for use when considering using COTS in space system hardware.

To communicate how the controls and enablers influenced the COTS assessment activities a series of methods that were adopted and employed during the COTS-based battery evaluations was presented. These methods were used to practice Risk Informed Decision Making [22] which is an overarching goal for developing and tailoring the appropriate risk management framework.

This was followed by a discussion about how there is a great deal of interest in this topic within the industry and what action is currently underway. However, there remains a significant amount of work to be done to mature the development of guidance that can be agreed upon within the space community. Lastly, examples were provided that described future work that could be accomplished and how further collaboration could be accomplished.

8. CONCLUSIONS

The aerospace industry is experiencing a significant increase in the development and launching of spacecraft to service numerous academic, civil, commercial, and government demands. An example of this increased space operations tempo is NASA's Gateway [63] which will be used as a way station to support the ARTEMIS [65] project to establish a permanent presence on the Moon. Another example is SpaceX's LEO based Starlink satellite constellation [58] that provides internet services to all points on the Earth. A third example is the accelerated development and fielding of low risk, high value satellites to support a revised DoD policy.

Using Commercial-Off-the-Shelf (COTS) components to build space-grade hardware is a method the space industry is embracing. Their use has enormous potential to increase performance, reduce cost, and to shorten design, production, and fielding schedules. But incorporating COTS into hardware designs requires the management of risk early in the design phase. Doing so requires knowledge about the hardware's design, how it will be used, the environments it will be exposed to, and its expected lifetime.

8.1. RESEARCH AGENDA SUMMARY

The objective of this research was to develop a risk management framework that could be used to evaluate Commercial-Off-the-Shelf parts for use in launch and space vehicle designs. The RMF will provide the aerospace industry with a model to use when they are considering incorporating COTS into their hardware designs. This model fills a gap that currently exists in the space industry's standards and policies. The five research questions posed to meet this objective are restated below.

- Research Question No. 1: What are the controls, enablers, and activities of a risk management strategy for COTS-enabled space system hardware?

- Research Question No.2: What are the missions, space vehicle types, and environments that need to be considered when evaluating COTS components for integration into LV / SV architectures and designs?

- Research Question No. 3: What type of industry risk management methods can be tailored to assess COTS-based hardware designs?

- Research Question No. 4: What COTS analyses, modeling, and tests can be used to validate COTS-based space hardware risk management strategies?

- Research Question No. 5: What lessons can be learned from this effort that can benefit the space industry and what recommendations can be made to further the research?

The research questions were used to divide the research into discrete tasks. The tasks to answer these were completed and used to develop a robust RMF as illustrated in Figure 28 and validated during the development of a COTS-based secondary lithium-ion battery. Having performed these tasks to answer the research questions above, the research contributions of this dissertation can now be summarized. This research has contributed to the advancement of the state of the art in systems engineering by:

- Developing and communicating an understanding of industry examples, and COTS best practices for the design and build of hardware to be integrated into a LV or SV. This review of literature and industrial practice classified the attributes of current risk management practice in terms of systems engineering controls and enablers, which were adapted and translated into a comprehensive COTS risk management process. This understanding included the adaption of the NASA concept of the LV's / SV's mission, environments, applications, and lifetime (MEAL) [96] to COTS risk management, and assessment of the effect that MEAL would have on space hardware with COTS as part of the design architectures.

- Developing and instantiating a novel systems engineering risk management framework and evaluation processes based on the best practices identified and in response to calls for systems engineering innovation from industry and researchers. These methods identify where aleatory and epistemic uncertainties resided to effectively manage COTS use risk. These methods were exemplified and tailored to evaluate a COTS-based secondary lithium-ion battery so that as many aleatory and epistemic uncertainties and their associated risks could be identified, analyzed, evaluated, and treated (mitigated).

- Performing the modeling and simulation, analyses, and tests required to collect the data that feeds the proposed COTS RMF. The successful execution of the RMF and evaluation processes using a secondary lithium-ion battery built with COTS serves as example and validation case for the effectiveness and value of a systems engineering approach to COTS risk management in LV / SV systems.

This research program has produced the following publications:

- E. W. Herbert, "Launch Vehicle Lithium-Ion Battery Development Using Commercial-Off-the-Shelf Cells," in *30th Aerospace Testing Seminar*, El Segundo: The

Aerospace Corporation, 2017.

- E. Herbert and T. Bradley, "Managing Commercial-Off-the-Shelf (COTS) - Based Space Hardware Risk," in *33rd Aerospace Testing Seminar*, El Segundo, 2023.
- E. Herbert, R. Sega, J. McGraw, and T. Bradley, "Risk Management for Commercial-Off-the-Shelf Parts Based Space-Rated Hardware," *Systems Engineering* Journal*,* 2023[4].

8.2 RISK FRAMEWORK VALIDATION SUMMARY

The methods and procedures proposed and exemplified in this study significantly expanded the process proposed by Katz [37] to evaluate COTS in space hardware designs. The RMF and evaluation processes were developed to expose aleatory and epistemic uncertainties. Once these uncertainties related to COTS were discovered, robust risk management activities were initiated to mitigate the likelihood and consequences to acceptable levels. The RMF and risk evaluation processes, as exhibited in Figures 28 - 31, 35, 39, 40, 43, 44, developed and used in this research provided actionable roadmaps to guide the collection of data needed to demonstrate how COTS risks could be effectively identified, analyzed, evaluated, and treated.

These RMF and risk evaluation processes were constructed using data mined from technical literature that contained information on how COTS were successfully used in space. This

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[4] The *Systems Engineering* Journal submission has been approved by the International Council on Systems Engineering (INCOSE) on 7 February 2024 but has not yet been published. Minor edits to the orignal submission are being made and will be resubmitted to INCOSE for final approval per their submission requirements.

literature review identified significant controls, enablers, and activities that were incorporated into the RM framework and processes.

The RMF developed and illustrated in Figure 28, is a four-step process that identifies the context that COTS could be used in, the methods to identify COTS candidates, how to evaluate their performance in the design application, and how to use this information to make a risk informed decision. This RM framework baseline was expanded further as shown in Figures 29 - 31. These RM roadmaps charted the paths to clarify the type of spacecraft the COTS could be used on, the importance of understanding what the key performance parameters are, and how the space environments, missions, and applications will dictate a spacecraft's architecture.

The three risk management processes provided step-by-step methods to identify how severe the risks using COTS could be. This is important because COTS cannot be used in all applications. There will always be a need for custom and unique space hardware that only a dedicated engineering process can accomplish. However, when an opportunity exists to incorporate less expensive and more readily available non-space-grade parts, it should be examined closely. From the execution of these three processes, a firmer understanding of what the risk levels was postulated. For this research, the phrase Uncertainty Risk Level was proposed, defined, and utilized based on existing RM theory [21].

In support of the development of the RM framework, this research presented material related to the importance of understanding a spacecraft's purpose as it relates to its mission, environment, applications, and lifetime (MEAL) [96]. This information was presented in Chapter 4. This chapter established the RM context which is a fundamental RM tenet as exhibited in Figure 2. The three space segments needed to perform a mission, orbits, environmental hazards, and information related on how to assess the impact of each on spacecraft design were presented.

After the RMF and evaluation process baselines were developed, these were used as the templates to create evaluation processes which would be used to examine a secondary lithium-ion battery partially made with COTS. This battery was used as an exemplar to validate the framework's utility. Specifically, two risk management evaluation processes were created to outline the steps to characterize COTS battery cells, a printed circuit board, EEE components, an electrical circuit design, and the battery. The processes were designed to obtain the data needed to address aleatory and epistemic uncertainties discovered as the evaluations progressed.

The RMF and evaluation processes validation started by completing a gap assessment, as proposed by Katz [37], between the COTS and battery requirements. It was quickly understood that the battery in its current state of design was considered to fall under the Uncertainty Risk Level I (high risk) category. As such, a thorough design and parts level assessment was deemed necessary to characterize the COTS lithium-ion cells, PCB, EEE components, and its electrical circuit design. After the individual assessments were completed using the RM processes, the battery proved to be reliable, qualified for space and safe for use.

During the evaluations, numerous issues were observed and corrected. The first issue discovered was that COTS vendor CoCs should be examined with skepticism. The lack of detailed technical data should have been a signal that triggered a need for a more thorough examination of the parts before integrating them into a battery.

COTS cell issues observed included those discovered when performing a cell lot-to-lot comparison which uncovered differences in electrical performance, dimensions, and in cell construction. The RM evaluation processes used determined that the first cell lot lacked one anode / cathode pair as compared to the second lot. The lack of this anode / cathode pair was the reason the first lot performed slightly below the manufacturer's stated capacity. The addition of the anode / cathode pair in the second cell lot increased the width of the cell. This dimensional difference was enough to induce the need to redesign the battery housing because the eight cell packs would not fit in the housing's original design.

Additional cell issues were discovered when 243 cells were examined using x-ray computed tomography. This non-evasive technique and the evaluation criteria developed were used to reject sixty-one of the 243 cells evaluated. The cells were rejected and deemed not fit for service due to internal construction issues that could have the potential to underperform or worse when subjected to the harsh space environment. However, because enough cells were available to produce the batteries needed to support the program, the loss of ≈ 25% of the cell inventory was not considered significant, especially since the cells were inexpensive.

PCB issues discovered were that the board design did not meet IPC space-grade standards even though the vendor's CoC stated it was. PCB electrical conduit workmanship issues were discovered when the PCB was examined using microscopic techniques. Additional issues were discovered when the boards were exposed to thermal environments. The exposure to the thermal gradients caused the PCB layers to delaminate. As a result, this COTS vendor's PCB was rejected for use and a replacement vendor who could produce an acceptable PCB had to be identified.

Besides the issues associated with PCB manufacturing, a sneak path was discovered during PSpice® modeling of the PCB's battery management system electrical circuit. If left unchecked, this sneak path could have circumvented the BMS which would have negated the protective features designed into the battery. Thus, there was a pathway for unrestrained battery charging to occur which could cause a thermal runaway. The discovery of the sneak path led to a modification of the BMS electrical circuit that would be populated on the new PCB design.

Lastly, the processes described in this research provided information needed to treat and mitigate performance uncertainties at the COTS lithium-ion battery system level when it was integrated into the LV and SV. The safety, transportation, handling, DT, AT, QT, and battery hazard casualty tests provided the information needed to determine how the battery would perform in space and how it would react to off-nominal conditions.

During the battery worst case (causality) tests it was discovered that if the battery were to go into thermal runaway, effluent and heat would impact surrounding hardware and structures. The tests also showed that the cable overwrapping used would ignite if exposed to effluent and thermal energy escaping from the battery. As a result, the battery's orientation inside the LV and SV was modified and flame-retardant overwraps replaced those previously used.

As a result of the RMF and RM evaluation processes used, numerous issues were discovered, and the appropriate design modifications were instituted. This was all accomplished while meeting schedule and budget constraints. The battery built with COTS parts was deemed qualified for use by the internal and external stakeholders (Table 13). This battery design was successfully flown without any anomalies observed numerous times on the LV and SV it was originally intended for. The success was so good that the battery is now considered a reliable product and the processes developed during this have been integrated into the battery vendor's design, manufacturing, testing, and mission assurance processes.

Based on the results achieved in this research and during the development of the battery for use on an active space program, this research finds that the RMF and risk evaluation techniques employed were successful in uncovering aleatory and epistemic uncertainties. This research finds that risks were successfully identified, analyzed, evaluated, and treated. Because of this a conclusion can be drawn that utilizing a COTS-centric risk management framework and evaluation processes such of those presented in this research that space-grade hardware can be developed successfully when the appropriate assessment techniques and activities are employed to evaluate space hardware built with Commercial-Off-the-Shelf parts.

This research presented risk management roadmaps that can be used as a guide to build space hardware with COTS components and assemblies. The risk management strategies demonstrated that space hardware design, development, production, and fielding efforts need to take into consideration the LV's / SV's purpose, its location in space, the environments to which it will be subjected to, and the time the LV / SV is required to perform its mission. Moreover, the use of COTS is not just a technical problem. The current risk management processes and the culture surrounding the use of COTS components will undoubtedly have to evolve.

8.3 SYSTEMS ENGINEERING AND INDUSTRY CONTRIBUTIONS

8.3.1 INDUSTRY CONTRIBUTIONS

The risk management framework and evaluation processes proposed in this research benefits the aerospace systems engineering and industrial community because it provides guidance on how to evaluate COTS for use in space systems hardware designs. As discussed in earlier chapters, space system stakeholders encourage the use of COTS to build space system hardware but do not provide the methods to evaluate their performance to meet mission, environment, application, and lifecycle requirements. The RMF and evaluation processes developed in this research start to fill a gap that exists in the standards and policies that dictate how space system hardware is designed and tested. This gap exists because COTS are parts that are available on the open market but typically do not have the established pedigree that space-grade parts do. So, to decide if COTS can be used in select hardware designs, different activities than those found in existing standards are needed to characterize COTS performance.

8.3.2 SYSTEMS ENGINEERING CONTRIBUTIONS

The RMF proposed in this research leverages the practices documented in the space industry standards which are used as a benchmark to assess COTS against. It is also recognized that the COTS being considered will still need to show that their performance will meet space system mission, environment, application, and lifetime goals [54]. To do this, the COTS RMF differs from the legacy approach because it focuses on:

- Evaluating the LV / SV development from a mission needs perspective vice an overarching concept grounded in an overly conversative requirements-based methods.

- Evaluating COTS limitations based on their native application which leads to tailored evaluation processes used to uncover where risks truly reside so that effective and feasible mitigation strategies could be developed based on the LV's / SV's specific mission, application, environment, and lifetime (mission risk) vice a design solution (design risk) that blankets a wide range of uncertainties that may or may not be germane.

- Expanding the risk evaluation activities to assess the COTS impact at the unit, subsystem, and system levels instead of solely concentrating assessments at the part (component) level.

- Challenging the current standards-based space hardware qualification philosophy that is rooted in decades old data and that does not take into consideration parts manufacturing and mission assurances improvements made over the last few decades.

To accentuate this point Table 26 is a compilation of the differences between the characteristics of traditional COTS hardware development processes and the processes proposed in this research. The utility of developing a COTS specific RMF, such as what was presented in this research, is acknowledged as a recognized need amongst the aerospace commercial and civil

Table 26. Legacy Space Hardware Development Versus COTS-Based Space Hardware Development Comparison

Legacy Space-Grade Hardware Development Processes*	**COTS-Based Risk Management Process** (This research product)
Anchored to requirements-based hardware development.	Technical requirements are challenged, which opens the trade space to decide if design constraints can be relaxed.
Hardware architects are held accountable to rigid requirements compliance, which stifles design creativity.	Opens the design space for alternative yet just-as-effective design solutions.
Standards levied tend to be overly conservative.	Challenges the legacy standards development and testing criteria.
Space-grade hardware development processes are extremely long, which prevents the incorporation of modern technological advances.	Shortens the development timeline by tailoring the test and evaluation cycle to what is needed based on the LV's / SV's MEAL not what is dictated in a legacy standard or policy.
Stakeholder community adheres to legacy hardware development concepts.	Challenges any biases associated with using COTS and uses RMF as a method to assuage stakeholder concerns.
Standards provide specific and rigid processes on how space-grade hardware should be developed and tested.	Unique evaluation activities are defined on how best to evaluate the COTS or how design modifications can be made to support COTS integration.
* References acknowledged: [11] [33] [55] [85] [96] [102] [103] [104] [105]	

community. This was proven based on the work that is currently underway by major space industrial partners to develop a RMF and risk evaluation processes such as those presented here. However, the scope of this research goes beyond what those stakeholders are working on. Specifically, this research proposes to expand how COTS are evaluated to the subsystem and system levels and not just at the part level.

This concept was demonstrated using the COTS-based lithium-ion battery as a research subject. In this case, the Li-ion battery was considered a micro-system that exists within the spacecraft system of systems architecture. At the onset, the COTS lithium-ion cell, printed circuit board, and the EEE parts were examined at the component level, like current practices. Once this was completed, the cells, EEE parts, printed circuit board, and the battery management system electrical circuit were combined and evaluated at the subsystem level. After this, the battery was assembled and evaluated as a system. Capping these activities off was evaluating the battery's performance using off-nominal scenarios to determine the effects on the LV and SV at the spacecraft systems level. These evaluation processes were unique because they examined COTS performance where the aleatory and epistemic uncertainties existed. It did this by employing unique evaluation techniques that were coupled with those dictated by the space design and test standards. So, by completing the activities as discussed in this research, enough data was collected to make hardware design decisions that alleviated doubts that the hardware would not perform as needed.

In this case, the outcome was positive; however, this may not always be the case. This is why using an RMF such as what was proposed in this research benefits the space industry. Specifically, it provides a roadmap on how to assess COTS hardware to decide if their use can be sanctioned or if another design solution needs to be considered. Therefore, the methods proposed here provided robust methodologies on how to identify, analyze, evaluate, and mitigate aleatory and epistemic uncertainties to acceptable risk levels. So, based on the research completed, it can be concluded that there are methods that can be codified when considering using COTS to design, build, test, and deploy reliable, resilient, and safe space system hardware and that these methods are useful tools that can be employed by the space industry community.

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APPENDIX A NASA COTS-BASED SPACE VEHICLE LONGEVITY DATA[5]

The data contained in Table 27 was provided to the author by the NASA Goddard Space Flight Center. This data compares space vehicle planned operational longevity to what was achieved or its current state. This data is associated with all four of NASA's space vehicle risk classes [24].

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Table 27. NASA COTS-Based Space Vehicle Longevity Data

Missionary	Year	NASA Risk Class	Planned Lifetime (yrs.)	Actual lifetime (yrs.)	Reason SC Ended Mission
EO-1	2000	C	1	21	fuel expended
GOES-L	2000	A	10	10	outdated
TDRS-H	2000	B	11	22+	active
NOAA-L	2000	C	2	13	"critical anomaly"
GOES-M	2001	A	5	12	thruster issues
Aqua	2002	A	6	20+	active
NOAA-M	2002	C	2	11	two instruments failed
TDRS-I	2002	B	11	20+	Valve issue, took 6 months to get to GEO
RHESSI	2002	D	2	16	communication problems
TDRS-J	2002	B	11	19+	active
ICESat	2003	C	3	7	laser failure
Aura	2004	B	6	18+	active
Neil Gehrels Swift	2004	C	2	17+	active (thermoelectric cooler failed shortly into mission, but successful operational workaround was put in place)
NOAA-N	2005	C	2	17+	active
GOES-N	2006	B	10	16+	active (USSF now)
ST-5 (3 S/C)	2006	C	90 days	100 days	demo complete
Fermi (GLAST)	2008	C	5	14+	active
GOES-O	2009	B	10	10	replaced (now on-orbit spare)
NOAA-N'	2009	C	2	13+	active
LRO	2009	C	3	13+	active
GOES-P	2010	B	10	12+	active
SDO	2010	B	5	12+	active
Glory	2011	C	3	0	launch failure
NPP-Suomi	2011	B	5	10+	active
TDRS-K	2013	B	15	9+	active

MAVEN	2013	B	2	7+	active
LandSat-8	2013	B	5	9+	active
LADEE	2013	D	100 days	223 days	objectives completed
TDRS-L	2014	B	15	8+	active
GPM	2014	B	3	8+	active
DSCOVR	2015	D	2	7+	active
MMS (4 S/C)	2015	C	5	7+	active
SMAP	2015	C	3	7+	Primary radar payload failed 7 months into mission – SEGR in the SAA, but team was able to get most science from the radiometer
GOES-R	2016	B	15	6+	active
OSIRIS-REx	2016	B	7	5+	active
ASTRO-H	2016	C	3	0	attitude control failure
NICER	2017	D	1.5	5+	active
JPSS-1	2017	B	7	4+	active
TSIS	2017	C	5	4+	active
TDRS-M	2017	B	15	5+	active
GOES-S	2018	B	15	4+	active
GEDI	2018	C	2	3+	active
ICESat-2	2018	C	3	3+	active
Solar Orbiter	2020	C	7	2+	active
JWST	2021	A	7	0+	active
Lucy	2021	B	12	0+	active
LCRD	2022	D	2	0+	active
GOES-T	2022	B	15	0+	active

APPENDIX B NASA GODDARD SPACE FLIGHT CENTER SOLAR DYNAMICS OBSERVATORY (SDO) BUILD OF MATERIAL DATA[6]

The data contained in this Table 28 was provided to the author by the NASA Goddard Space Flight Center [75]. It was not edited for punctuation, spelling, etc. The data represents the components used to build a unit that resides in the NASA Solar Dynamics Observatory (SDO) which was launched from Cape Canaveral on 11 February 2010 [74]. The SDO's purpose is to collect data on the Sun's activity and how this phenomenon creates Space Weather. The SDO is stationed in a geosynchronous orbit. The satellite's required mission life was five years; however, it still operates and provides a continuous stream of solar data.

The table shown below is a list of parts used to build a unit that is used on the SDO. The data was filtered to remove all manufacturer details. This data is representative of space hardware units that are built with various EEE parts. It is built with parts that were previously used to build space hardware, MIL-Spec, and COTS parts. The parts used are categorized by either being passive or active. Active parts are considered microcircuits and discrete semiconductors.

Per NASA GSFC [79], the percentage of active parts used to build a unit is typically < 10%. In this example, there are 1042 parts used with 5.1% considered to be active and susceptible to radiation damage if not properly protected or utilized. The rest of the 94.9% are passive parts. 1.05% of the 1042 parts are active COTS EEE parts that required a radiation hardening assessment (RHA) prior to being used.

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[6] National Aeronautics and Space Administration , *SDO-PSE-ASD Parts List Data,* Greenbelt: Goddard Space Flight Center, 2023.

Table 28. NASA GSFC GEO Solar Dynamics Observatory Class B Satellite Unit Build of Material List Example

GEO Class B Satellite Build of Material		
Generic PN	**Description**	**Qty**
SR0805X7R104	Capacitor, Fixed, Ceramic, 0.1uF, 25V,	86
SR0805X7R102	Capacitor, Fixed, Ceramic, 0.001uF, 10%, 25V	28
CWR06	Capacitor,Tantalum,Solid,Chip,Fixed,10uF,25V,10%	11
CWR19	Capacitor, Tantalum, Solid, Chip, Fixed, 10uF, 5%,	2
T495	Capacitor, Fixed, Tantalum, Low ESR, 100uF, 10%, 1	2
CKS51	Capacitor,Fixed,Ceramic,470pF,50V,10%,S	1
CKS53	Capacitor,Fixed,Ceramic,0.1uF,50V,10%,S	12
CKS53	Capacitor,Fixed,Ceramic,5600pF,50V,10%,S	2
SR0805X7R103	Capacitor, Fixed, Ceramic, 0.01uF, 25V	41
CDR01	Capacitor,Fixed,Ceramic,100pF,100V,10%,S	1
1N4104	Diode,Zener,10V,400MW,Low Noise	1
1N6638	Diode,Switching,Rectifier,Small Signal,150V,300mA	5
1N4625UR-1	Diode,Low-Noise Voltage Regulator, 5.1V,500mW	1
ISYE-1009RH-Q	Microcircuit,Linear,Radiation Hardened,2.5V Reference	2
1N4619	Diode, Zener Voltage Regulator	1
K2A110FMD	Connector, Electrical, cPCI Connector, Right Angle	2
K2B110FMD	Connector, Electrical, cPCI Connector, Right Angle	1
K2B95FMD	Connector, Electrical, cPCI Connector, Right Angle	1
HD-22	Connector, Electrical, Rect., HD, D-Sub, Recepticl	1
RM0705	Resistor Chip, Fixed, Film, Electrical, Zero Ohm,	6
	Bus wire is used and instructions are on the assem	6
	Bus wire is used and instructions are on the assem	2
	Bus wire is used and instructions are on the assem	18
	Bus wire is used and instructions are on the assem	1
	Bus wire is used and instructions are on the assem	1
IRHNJ9130	Transistor,Rad Hard,Power MOSFET, -100V, P-Channel	1
2N2222AUA	Transistor,Switching,NPN,Low Power	2
RM0505	Resistor,Fixed,Film,3.01K**,1%,50mW,100PPM	1
RM0505	Resistor, Fixed, Film, 2.49K**, 0.1%, 25mW, 25PPM	2
RM0505	Resistor, Fixed, Film, 10**, 1.0%, 25mW, 25PPM	3
RM0505	Resistor,Fixed,Film,10.0KOhm,1%,50mW,100PPM	37
RM0402	Resistor, Fixed, Film, 22.1**, 1.0%, 40mW, 100PPM	112
RM0402	Resistor, Fixed, Film, 49.9**, 1.0%, 40mW, 100PPM	112
RM0402	Resistor, Fixed, Film, 15.0**, 1.0%, 40mW, 100PPM	3
RM0402	Resistor, Fixed, Film, 38.3**, 1.0%, 40mW, 100PPM	1

RM0505	Resistor, Fixed, Film, 8.25K**, 0.1%, 25mW, 25PPM	1
RM0505	Resistor, Fixed, Film, 1.0K**, 0.1%, 25mW, 25PPM	4
RM0505	Resistor, Fixed, Film, 11.5K**, 0.1%, 25mW, 25PPM	2
RM0505	Resistor, Fixed, Film, 4.99K**, 0.1%, 25mW, 25PPM	3
RM0505	Resistor, Fixed, Film, 30.1**, 1.0%, 25mW, 25PPM	2
RM0505	Resistor, Fixed, Film, 10.0K**, 0.1%, 25mW, 25PPM	7
RM0505	Resistor, Fixed, Film, 20**, 1.0%, 25mW, 25PPM	2
RM0505	Resistor, Fixed, Film, 200**, 1.0%, 50mW, 100PPM	13
RM0705	Resistor, Fixed, Film, 1**, 5%, 200mW, 300PPM, SMD	1
RM0705	Resistor,Fixed,Film,11.0K**,1.0%,100mW,100PPM	1
RM0505	Resistor, Fixed, Film, 8.25K**, 0.1%, 25mW, 25PPM	27
RM0505	Resistor, Fixed, Film, 100K**, 0.1%, 25mW, 25PPM	1
RM0705	Resistor, Fixed, Film, 120**, 0.1%, 50mW, 25PPM	4
RM0402	Resistor, Fixed, Film, 69.8**, 1.0%, 40mW, 100PPM	7
RM0505	Resistor,Fixed,Film,1.0KOhm, 1%, 50mW,100PPM	5
RM0402	Resistor, Fixed, Film, 30.1**, 1.0%, 40mW, 100PPM	7
RM0402	Resistor, Fixed, Film, 100**, 1.0%, 40mW, 100PPM	8
RM0505	Resistor, Fixed, Film, 9.2K**, 0.1%, 25mW, 25PPM	1
RM0505	Resistor, Fixed, Film, 2.29K**, 0.1%, 25mW, 25PPM	1
RM0505	Resistor, Fixed, Film, 49.9**, 1.0%, 50mW, 100PPM	4
RM0705	Resistor, Fixed, Film, 33.2**, 1.0%, 50mW, 100PPM	1
RM0705	Resistor, Fixed, Film, 30.1**, 1.0%, 50mW, 100PPM	1
RM0705	Resistor, Chip, Film,49.9**, 1%, 100mW,100PPM	2
RM0505	Resistor, Fixed, Film, 4.32k**, 1.0%, 25mW, 100PPM	1
RM0505	Resistor, Fixed, Film, 10.0**, 1%, 25mW, 100PPM	2
RM0402	Resistor, Fixed, Film, 37.4**, 1.0%, 40mW, 100PPM	2
RM0402	Resistor, Fixed, Film, 16.5**, 1.0%, 40mW, 100PPM	2
RM0402	Resistor, Fixed, Film, 10.0**, 1.0%, 40mW, 100PPM	2
S-311-P18	Thermistor, Insulated, Negative Coefficient	1
54AC2525WRQM LV	Microcircuit,Digital,Minimum Skew Clock Driver	1
HS9-508BRH-Q	Microcircuit,Linear,8-Bit Channel Analog Multiplex	3
RT54SX72SU-1CQ208	Microcircuit, Digital, Radiation Tolerant, FPGA, 7	2
RH1499	Microcircuit,Linear,Precision Rail-to-Rail I/O, Qu	1
RH1013	Microcircuit,Linear,Dual Radhard Op-Amp	1
M914	Resistor Nerwork	11
UT54ACS164245S	Microcircuit,Digital,5V,Bus Transceiver and 5V to	6
BU-61582G6-320	Microcircuit, Hybrid, 1553 Transceiver	1
RH-CF5208	Microcircuit, Microprocessor, Rad Hard Coldfire	1

TST9017	Transformer, 1553	1
HS9-1840ARH	Microcircuit,Linear,Radiation Hardened,Single 16-C	2
HS9-26CLV31RH-Q	Microcircuit,Digital,Radiation Hardened,Quad,Line	1
HS9-26CLV32RH-Q	Microcircuit,Digital,Radiation Hardened,Quad,Recei	1
	Microcircuit, Hybrid, 16Mbit SRAM Module, (4M x 32	1
54ACTQ04LMQB	Microcircuit,Digital,Advanced CMOS logic, Hex Inve	1
54AC08LMQB	Microcircuits,Digital,Advanced CMOS,Quad Two-Input	2
AD9225	Microcircuit, Rad-Hard, 12 Bit A/D Converter, Rad	1
3D_33V_	Microcircuit, Hybrid, EEPROM 256K x 32 module	2
1113R24M0000BF	Oscillator, crystal, Swept Quartz, Rad Hard 24 Mh	1
RT54SX32SU-1CQ208	Microcircuit, Digital, Radiation Tolerant, FPGA, 3	1
HS9-26CT32RH	Microcircuit, Digital, CMOS, Radiation Hardened, Q	1
UT54ACS162245S	Microcircuit, Digital, CMOS, Radiation hardened, S	2
HS9-508BRH	Microcircuit, Linear, 8-Bit Channel Analog Multipl	2
HS9-1840ARH	Microcircuit, Linear, Radiation Hardened, Single 1	4
HD-22	Connector, Electrical, Rect., HD, D-Sub, Receptacl	1
HD-22	Connector, Electrical, Rect., HD, D-Sub, Receptacl	1
HD-20	Connector, Electrical, Rect, Standard Density, D-S	1
AD565ATD/QMLV	Microcircuit, Linear, 12-Bit D/A Converter	1
AD580	Microcircuit, Linear, 2.5V Precision Voltage Refer	1
54ACT244LMQB	Microcircuit,Digital,Advanced CMOS,Octal Buffer/Li	8
RM1206	Resistor, Fixed, Film, 10K**, 0.1%, 125mW, 25PPM	8
RM1206	Resistor, Fixed, Film, 10K**, 1%, 125mW, 25PPM	25
RM1206	Resistor, Fixed, Film, 68.1**, 1%, 125mW, 25PPM	4
RM1206	Resistor, Fixed, Film, 20K**, 1%, 125mW, 25PPM	12
RM1206	Resistor, Fixed, Film, 11.3K**, 0.1%, 125mW, 25PPM	1
RM1206	Resistor, Fixed, Film, 71.5K**, 0.1%, 125mW, 25PPM	2
RM1206	Resistor, Fixed, Film, 21.5K**, 0.1%, 125mW, 25PPM	1
RM1206	Resistor, Fixed, Film, 2K**, 1%, 125mW, 25PPM	2
RM1206	Resistor, Fixed, Film, 4.99K**, 0.1%, 125mW, 25PPM	28
RM1206	Resistor, Fixed, Film, 100**, 1%, 125mW, 25PPM	4
CWR06	Capacitor,Tantalum,Solid,Chip, Fixed,10uF,25V,10%	2
SR0805X7R	Capacitor, Ceramic, Chip 0805, 0.01**F, 25V	15
SR0805X7R	Capacitor, Ceramic, Chip 0805, 0.1**F, 25V	22
CDR01	Capacitor, Ceramic, BP Dielectric, 100pF, 10%, 100	2
CDR01	Capacitor, Ceramic, BP Dielectric, 10pF, 10%, 100V	10
CDR33	Capacitor, Fixed, Ceramic, 47000pF, 50V, 10%	27

TLW-101-05-G-S	Header, Low Profile, 0.025`` Square Post	25
1-102972-0	Header, 10 Positions, Breakaway, Single Row, 0.100	10
S0705CPX000	Resistor Chip, Fixed, Film, Electrical, Zero **, J	1
CDR33	Capacitor, Fixed, Ceramic, 27000pF, 50V, 10%	1
BJ376	Connector, Receptacle, Twianx/Triax, TRB Rear Moun	2
HD-22	Connector, Electrical, Rect., HD, D-Sub, Receptacl	1
CWR19	Capacitor, Tantalum, Chip, Fixed, 10uF, 5%, 35V	4
	Capacitor, Fixed, Ceramic, 68pF, 10%, 100V	12
RM0402	Resistor, Fixed, Film, 49.9**, 1.0%, 40mW, 100PPM	4
RM0402	Resistor, Fixed, Film, 30.1**, 1.0%, 40mW, 100PPM	1
RM0402	Resistor, Fixed, Film, 10**, 1.0%, 40mW, 100PPM	3
RM1206	Resistor, Fixed, Film, 499**, 1.0%, 205mW, 100PPM	4
RM0402	Resistor, Fixed, Film, 10K**, 1.0%, 40mW, 100PPM	36
RM0402	Resistor, Fixed, Film, 33.2**, 1.0%, 40mW, 100PPM	56
RM1206	Resistor, Fixed, Film, 357**, 1.0%, 250mW, 100PPM	1
RM1206	Resistor, Fixed, Film, 2.94K**, 1.0%, 250mW, 100PP	1
RM1206	Resistor, Fixed, Film, 2.43K**, 1.0%, 250mW, 100PP	1
RM0402	Resistor, Fixed, Film, 68.1**, 1.0%, 40mW, 100PPM	12
RCZ0402	Resistor Chip, Fixed, Film, Electrical, Zero Ohm,	9
RH1499	Microcircuit,Linear,Precision Rail-to-Rail I/O, Qu	4
UT28F256LVQLC-65UCA**	Microcircuit, Digital, Radiation Hardened, PROM, 3	2
Sum		**1042**
NASA or ESA RHA = 40 ≈ 3.84%		
COTS RHA = 11 ≈ 1.05%		
Actives without RHA. Total non-RHA and discrete semiconductors (requiring radiation testing or other forms of analysis = 2 ≈ (0.19%)		
Per NASA, typical total active parts are < 10%. BOM example is ≈ 5.1%		
BOM example is made up of ≈ 94.9% passive parts.		

APPENDIX C NATURAL SPACE ENVIRONMENTS AND EFFECTS[7]

Tables 29 and 30 are extracts from the NASA Reference Publication 1390 titled, "*Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment"* [76].

These tables are presented to provide amplifying information on the nine categories of the natural space environment identified by Bedingfield, Leach, and Alexander. This information could be used to develop space vehicle designs that can withstand the environments during the life of the SV. This information should also be used when considering the integration of COTS into the SV design.

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[7] K. Bedingfield, R. D. Leach and M. B. Alexander, *Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment,* Huntsville: National Aeronautics and Space Administration, 1996.

Table 29. Natural Space Environments [76]

	Definition	**Programmatic Issues**
Neutral Thermosphere	Atmospheric density, Density variations, Atmospheric composition (Atomic Oxygen) Winds	GN&C system design, Materials degradation, surface erosion (atomic oxygen fluences), Drag/decay, S/C lifetime, Collision avoidance, Sensor pointing, Experiment design, Orbital positioning errors, Tracking Loss
Thermal Environment	Solar radiation (albedo and OLR variations), Radiative transfer, Atmospheric transmittance	Passive and active thermal control system design, Radiator sizing/material selection, Power allocation, Solar array design
Plasma	Ionospheric plasma, Auroral plasma, Magnetospheric transmittance	EMI, S/C power systems design, Material determination, S/C heating, S/C charging/arcing
Meteoroids and Orbital Debris	M/OD flux, Size distribution, Mass distribution, Velocity distribution, Directionality	Collision avoidance, Crew survivability, Secondary ejecta effects, Structural design/shielding, Materials/solar panel deterioration
Solar Environment	Solar physics and dynamics, Geomagnetic storms, Solar activity predictions, Solar/geomagnetic indices, Solar constant, Solar spectrum	Solar prediction, Lifetime/drag assessments, Reentry loads/heating, Input for other models, Contingency operations
Ionizing Radiation	Trapped proton/electron radiation, Galactic cosmic rays (GCR's), Solar particle events	Radiation levels, Electronics/parts dose, Electronics/single event upset, Materials dose levels, Human dose levels
Magnetic Field	Natural magnetic field	Induced currents in large structures, Locating South Atlantic Anomaly, Location of radiation belts
Gravitational Field	Natural gravitational field	Orbital mechanics/tracking
Mesosphere	Atmospheric density, Density variations, Winds	Re-entry, Materials selection, Tether experiment design

Table 30. Space Environment Effects [76]

SPACE ENVIRONMENTS				
Spacecraft Subsystems	**Neutral Thermosphere**	**Thermal Environment**	**Plasma**	**Meteoroids / Orbital Debris**
Avionics		Thermal Design	Upsets due to EMI from Arcing, S/C Charging	EMI Due to Impacts
Electrical Power	Degradation of Solar Array Performance	Solar Array Designs, Power Allocations, Power System Performance	Shift in Floating Potential, Current Losses, Reattraction of Contaminants	Damage to Solar Cells
GN&C / Pointing	Overall GN&C/Pointing System Design		Torques due to induced potential	Collision Avoidance
Optics	S/C Glow, Interference with Sensors	Influences Optical Design	Reattraction of Contaminants, Change in Surface Optical Properties	Degradation of Surface Optical Properties
Propulsion	Drag Makeup/Fuel Requirement		Shift in Floating Potential Due to Thrust Firings Making Contact with the Plasma	Collision Avoidance, Additional Shielding Increases Fuel Requirement, Rupture of Pressurized Tanks
Materials	Materials Selection, Material Degradation	Material Selection	Arching, Sputtering, Contamination Effects on Surface Properties	Degradation of Surface Optical Properties
Structures		Influences Placement of Thermally Sensitive Surfaces, Fatigue, Thermally Induced Vibrations	Mass Loss from Arcing and Sputtering, Structural Size Influences S/C Charging Effects	Structural Damage, Shielding Designs, Overall S/C Weight, Crew Survivability
Telemetry Tracking & Communications	Possible Tracking Errors, Possible Tracking Loss		EMI Due to Arcing	EMI Due to Impacts
Thermal Control	Reentry Loads/Heating, Surface Degradation due to Atomic Oxygen	Passive and Active Thermal Control System Design, Radiator Sizing, Freezing Points	Reattraction of Contaminants, Change in absorptance/emittance properties	Change in Therma/Optical Properties
Mission Operations	Reboot timelines, S/C Lifetime Assessment	Influences Mission Planning/Sequencing	Servicing (EVA) Timelines	Crew Survivability

Table 30. Space Environment Effects (continued) [76]

SPACE ENVIRONMENTS					
Spacecraft Subsystems	**Solar Environment**	**Ionizing Radiation**	**Magnetic Field**	**Gravitational Field**	**Mesosphere**
Avionics	Thermal Design	Degradation; SEU's, Bit Errors, Bit Switching	Induced Potential Effects		
Electrical Power	Solar Array Design, Power Allocations		Induced Potential Effects		
GN&C / Pointing	Influences Density and Drag, Drives Neutrals, Induces Gravity Gradient Torques		Sizing of Magnetic Torquers	Stability & Control, Gravitational Torques	Effect on GN&C for Re-entry
Optics	Solar UV Exposure Needed for Material Selection	Degradation of Materials			Degradation of Materials Due to Atmospheric Interactions
Propulsion	Necessary Data for Optical Designs	Darkening of Windows and Fiber Optics			
Materials	Influences Density and Drag			Influences Fuel Consumption Rates	
Structures	Influences Placement of Thermal Sensitive Structures		Induces Currents in Large Structures	Propellant Budget	Tether Structural Design
Telemetry Tracking & Communications	Tracking Accuracy, Influences Density and Drag		Locating South Atlantic Anomaly	May Induce Tracking Errors	
Thermal Control	Influences Reentry Thermal Loads/Heating				
Mission Operations	Mission Timelines, Mission Planning	Crew Replacement Timelines			

LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
ACAT	Acquisition Category
ACS	Attitude Control System
ADCS	Attitude Determination and Control System
AFMAN	Air Force Manual
AGP	Alternate Grade Parts
Ah	Ampere-hour
AIAA	American Institute of Aeronautics and Astronautics
AoA	Angle of Attack
AT	Acceptance Test
BMS	Battery Management System
BOM	Build of Material
C&DH	Command and Data Handling
CFR	Code of Federal Regulations
CoC	Certificate of Compliance
Comm	Communications
CONOPS	Concept of Operations
COPV	Composite Overwrapped Pressure Vessel
COTS	Commercial-Off-the-Shelf
CRM	Continuous Risk Management
CSU	Colorado State University
CT	Computed Tomography
CubeSat	Cube Satellite
DAU	Defense Acquisition University
DoD	Department of Defense
DoT	Department of Transportation
DPA	Destructive Physical Assessment
DPPM	Defective Parts Per Million
DT	Development Test
EA	Engineering Agent
ECS	Environmental (or Environment) Control System
EDPS	Electrical Power and Distribution System
EDU	Engineering Design Unit
EDX	Energy Dispersive X-ray Spectroscopy
EEE	electrical-electronic-electromechanical
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference

EMI	Electromagnetic Interference
EPS	Electrical Power System
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulations
FMDBA	Fuzzy Modified Distance-Based Approach
FMECA	Failure Modes, Effects, and Criticality Analyses
GEO	Geostationary Earth Orbit
GNC	Guidance, Navigation, and Control
GPS	Global Positioning System
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
GTO	Geostationary Transfer Orbit
HALT	Highly Accelerated Life Tests
HASS	Highly Accelerated Stress Screening
Hazmat	Hazardous Material
HEO	High Earth Orbit
IATA	International Air Transport Association
IEEE	Institute of Electrical and Electronics Engineers
ILPM	Industry Leading Parts Manufacturer
INCOSE	International Council on Systems Engineering
IPC	Institute for Printed Circuits
IPO	Input-Process-Output
ISEA	In Service Engineering Agent
ISO	International Organization for Standardization
LEO	Low Earth Orbit
LIB	Lithium-ion Battery
Li-ion	Lithium Ion
LSP	Launch Service Provider
LV	Launch Vehicle
M&S	Modeling and Simulation
MA	Mission Assurance
MEAL	Mission, Environment, Application, Lifetime
MEO	Medium Earth Orbit
MIL-Spec	Military Specification
MIL-Std	Military Standard
MRL	Manufacturing Readiness Level
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
NDA	Non-Disclosure Agreement
NESC	NASA Engineering and Safety Center
NOAA	National Oceanic and Atmospheric Administration
NOSSA	Naval Ordnance Safety and Security Activity

NSA	National Security Agency
OP	Operational
PCB	Printed Circuit Board
PEAL	Parts Evaluation and Assessment Laboratory
QMS	Quality Management System
QT	Qualification Test
RCC	Range Commanders Council
RCS	Reaction Control System
RF	Radio Frequency
RHA	Radiation Hardness Assured
RIDM	Risk Informed Decision Making
RM	Risk Management
RMF	Risk Management Framework
RQ	Research Question
SAT	Satellite
SC	Spacecraft
SEM	Scanning Electron Microscope
SIL	Space Information Laboratories
SLS	Space Launch System
SMC	Space Missile Center
SV	Space Vehicle
SWaP	Size, Weight, and Performance
TLYF	Test-Like-You-Fly
TM	Technical Manual
TPM	Technical Performance Measure
TPV	Technical Parameter Value
TRL	Technology Readiness Level
TT&C	Tracking, Telemetry, and Command
UL	Underwriters Laboratories
UN	United Nations
URL	Uncertainty Risk Level
US	United States
USAF	United States Air Force
USN	United States Navy
USSF	United States Space Force