NASA/TM–20205011579
NESC-RP-19-01490

# Recommendations on Use of Commercial-Off-The-Shelf (COTS) Electrical, Electronic, and Electromechanical (EEE) Parts for NASA Missions


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December 2020

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December 2020

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# NASA Engineering and Safety Center
# Technical Assessment Report

## Phase I

## Recommendations on Use of Commercial-Off-The-Shelf (COTS) Electrical, Electronic, and Electromechanical (EEE) Parts for NASA Missions

**October 27, 2020**

# Report Approval and Revision History

NOTE: This document was approved at the October 27, 2020, NRB.

| | | |
|---|---|---|
| Approved: | TIMMY WILSON Digitally signed by TIMMY WILSON Date: 2023.02.08 18:21:55 -05'00' | |
| | NESC Director | Date |

| Version | Description of Revision | Office of Primary Responsibility | Effective Date |
|---|---|---|---|
| 1.0 | Initial Release | Mr. Robert Hodson, NASA Technical Fellow for Avionics, LaRC | 10/27/2020 |
| 1.1 | Added GSE list to Appendix A.6 | Mr. Robert Hodson, NASA Technical Fellow for Avionics, LaRC | 11/30/2020 |
| 2.0 | Minor updates to Sections 4.0 and 7.10.7. Section 8.3 (removed NESC Recommendations and pointed the reader to the Phase II final report). Added Appendix C, Use of COTS Practices from Centers. | Mr. Robert Hodson, NASA Technical Fellow for Avionics, LaRC | 2/08/2023 |

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# Technical Assessment Report

## 1.0 Notification and Authorization

Dr. Peter Majewicz, NASA Electronic Parts & Packaging Program Manager, requested an independent assessment to summarize Commercial Crew Program (CCP) and NASA Centers' current and best practices, and lessons learned, on use of commercial-off-the-shelf (COTS) for all mission risk classifications, and provide recommendations that could lead to future NASA Electronic Parts and Packaging (NEPP) Program and/or Agency guidance on COTS parts.

The key stakeholders for this assessment included Dr. Peter Majewicz, NASA Electronic Parts & Packaging Program Manager, Dr. Jonathan Pellish, NASA Electronic Parts Manager, EEE parts managers/leads/engineers at NASA Centers, program/projects managers, and the NASA Engineering and Safety Center (NESC).

## 2.0 Signature Page

Submitted by:

Dr. Robert F. Hodson Date

Significant Contributors:

| | |
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| Mr. Erik C. Denson Date | Ms. Kristen T. Boomer Date |
| Angela Thoren 11/16/20 | 16 Nov 2020 |
| Ms. Angela P. Thoren Date | Dr. Jesse A. Leitner Date |
| Peter Majewicz 17NOV20 | |
| Dr. Peter J. Majewicz Date | |

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

## 3.0 Team List

| Name | Discipline | Organization |
|---|---|---|
| **Core Team** | | |
| Robert Hodson | NESC Lead, NASA Technical Fellow for Avionics | LaRC |
| Yuan Chen | Technical Lead, Parts Eng. and Reliability | LaRC |
| Carlton Faller | Parts Engineering | JSC |
| Ron Hodge | Parts/Packaging/FA | MSFC |
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| Erik Denson | Electrical Chief Engineer | KSC |
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| **Assessment Support** | | |
| Melinda Meredith | Project Coordinator | LaRC/AMA |
| Linda Burgess | Planning and Control Analyst | LaRC/AMA |
| Erin Moran | Technical Editor | LaRC/AMA |

## 4.0 Executive Summary

The Phase I of the Technical Assessment has two primary goals. The first was to capture the NASA Centers' current practices, best practices, lessons learned and Center-proposed recommendations on use of commercial-off-the-shelf (COTS) electrical, electronic, and electromechanical (EEE) parts in spaceflight systems, and COTS EEE parts and assemblies in critical ground support equipment (GSE). The second was to provide recommendations on use of COTS, including a set of current best practices based on the Centers' current and best practices and the NESC team's discussions. Eight NASA Centers participated in the assessment: Ames Research Center (ARC), Glenn Research Center (GRC), Goddard Space Flight Center (GSFC), Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), Kennedy Space Center (KSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC).

The Phase I report included eight NASA Center reports on each NASA Center's current practices and lessons learned on use of COTS, risk context of use of COTS parts, current and best practices on COTS parts selection, verification, application, radiation hardness assurance, and a list of common COTS concerns with the NESC team's comments. There are a number of NESC findings, observations and recommendations, and some key findings and recommendations are highlighted in the executive summary.

**Key Findings include:**

For safety and mission critical systems on missions with category 1-3 and Class A-C per NPR 7120.5 and NPR 8705.4, respectively, NASA Center current practices typically use NASA-screened COTS parts (F-1a). For non-safety or non-mission critical systems, current Center use of COTS practices range from using NASA-screened COTS parts to the best effort on part-level verification, or using COTS parts without any further MIL-SPEC/NASA screening and qualification at part-level, depending on mission classification level, project requirements and risk posture (F-2). NASA has more than 15 years of using COTS without additional part-level MIL-SPEC/NASA screening and qualification in space systems in sub-Class D missions and some Class D payloads, and other non-critical applications (F-3). Large quantities of COTS parts and equipment are selected and qualified for critical GSE (F-10). Current practice on use of COTS for critical GSE requires full qualification per KSC standards. GSE subsystems undergo a rigorous technical review process and verification and validation testing leading to Design Certification or System Acceptance (F-11).

There is a wide range of differences in current Centers' practices on COTS selection and part-, board-, and system-level verification across the Agency for mission critical systems on Class D and sub-Class D missions (F-1b).

There is a lack of consensus within NASA on the risk of using COTS parts for safety and mission critical applications in spaceflight systems. It varies from feelings of "high risk" when part-level MIL-SPEC/NASA screening and space qualification are not fully performed to "no elevated risk" when sound engineering is used and part application is understood (F-4).

**Key takeaways for COTS parts selection and verification are as follows:**

1. NASA-STD-8739.10 and GSFC EEE-INST-002 are considered in this report to establish the baseline requirements for use of various levels of parts including use of COTS parts. NASA-STD-8739.10 establishes a consistent set of requirements at the Agency level to control risk and minimize the impacts of part selection and usage on reliability in NASA spaceflight hardware and critical GSE, and GSFC EEE-INST-002 (and equivalent parts documents) is used at Agency and Center levels for guidance on parts selection, screening and qualification requirements. Those documents recommend MIL-SPEC parts as the first choice or best practice, and specify 1) different levels of MIL-SPEC parts as baseline parts and 2) detailed MIL-SPEC/NASA screening and qualification requirements on non MIL-SPEC parts. The QML process in which government has control and insight in MIL-SPEC parts, results in parts with high (but not perfect) quality and reliability and full access to part-level verification. Government does not have control or insight into COTS parts, resulting in a major challenge of part-level verification or guaranteed knowledge of COTS parts. However, this does not necessarily imply that COTS parts are low in quality and reliability.

2. The NESC team recognized that government control is not prerequisite anymore for high quality and reliability parts, especially when, in recent years, some manufacturers in commercial industry have developed rigorous process controls driven by advanced technologies and commercial market, often equivalent to or exceeding government controls on MIL-SPEC parts. It is equally important to note that this is not universally the case and may vary from manufacturer to manufacturer.

3. NESC recommended selecting COTS parts that meet project's Mission, Environment, Applications and Lifetime (MEAL) requirements from *Industry Leading Parts Manufacturers (ILPMs).* The NESC team defined an ILPM as a parts manufacturer with high volume automatic production facilities and which can provide documented proof of the technology, process and product qualification, and its implementation of the best practices for "zero defects" for parts quality, reliability and workmanship. The detailed criteria will be addressed in Phase II of the assessment. The NESC recommendations on COTS parts selection, procurement, circuit application, radiation hardness assurance and part-, board- and system-level verification are highlighted in Figure 4.0-1 and detailed in the report.

4. Since there is no Agency requirement or consensus regarding the level of part-level verification that would be sufficient for COTS parts in Class A-C missions without part-level MIL-SPEC/NASA screening and qualification, Phase II of the assessment also intends to provide further guidance on COTS part-level verification and criteria.

5. Parts levels in EEE-INST-002 and equivalent documents do not indicate the level of radiation tolerance, and thus the selection of parts level 1, 2, or 3 does not imply or provide any type of radiation hardness or mitigation of radiation effects. Most

> MIL-SPEC parts and COTS parts are not designed for space applications. Unless parts are specifically designed for space applications, it is unlikely that they were designed to ensure performance in space radiation environments, be those parts MIL-SPEC or COTS. Even MIL-SPEC parts that are designed for atmospheric or terrestrial strategic applications may not perform adequately in space, because the space radiation environment is quantitatively and qualitatively more severe than that of the atmosphere. For instance, MIL-SPEC parts may or may not include a radiation hardness designator signifying TID performance, but may be sensitive to SEE. Radiation threats for COTS parts do not differ from MIL-SPEC parts or any other part fabricated in a similar technology; however, the lot-to-lot variation of radiation sensitivity may be larger for COTS parts, since space radiation tolerance is not designed and optimized for COTS parts. The detailed radiation hardness assurance guideline for COTS parts or any parts is included in NESC-RP-19-01489 "Guidelines for an Avionics Radiation Hardness Assurance".

It is important to note that COTS term has been substantively updated in the Phase II report (NESC-RP-19-01490, Phase II). The Phase I report is maintained for historical context but, for substantive technical details and recommendations, the reader should refer to the Phase II report (available at https://ntrs.nasa.gov/citations/20220018183) and, in particular, any inconsistencies should be dispositioned in the phase II report.

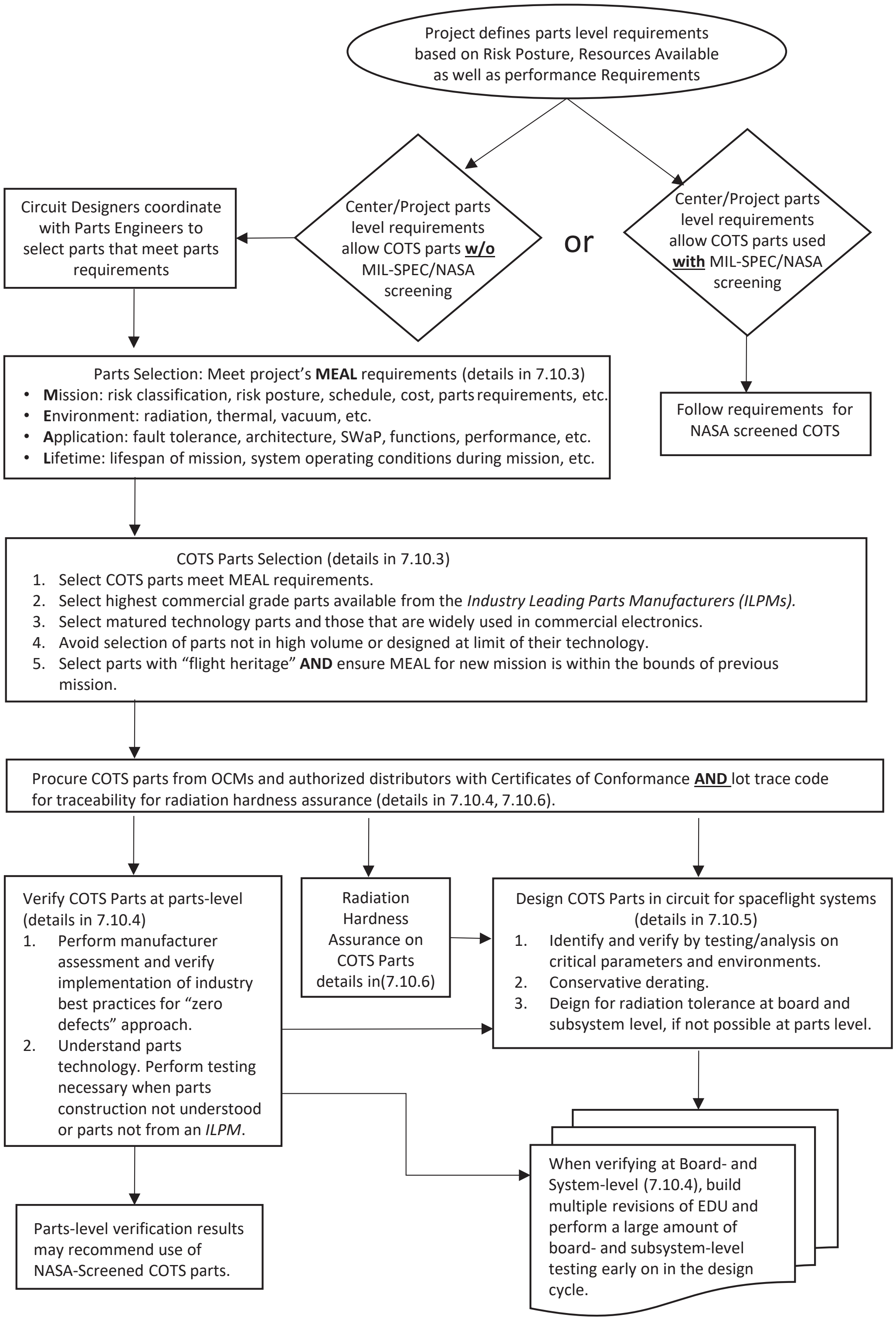



***Figure 4.0-1. NESC recommendations on COTS parts selection, procurement, circuit application, radiation hardness assurance and part-, board- and system-level verification. Recommendations in rectangles with section numbers for details.***

## 5.0 Assessment Plan

The NESC team performed the following tasks, which were the initial request. The CCP partners' related practices and their lessons learned are not included in the report, since the information cannot be made publicly available.

1. Discuss and summarize the different or various parts standards and approaches used by CCP partners, including parts selection, evaluation, screening, and qualification processes and criteria, and lessons learned from CCP parts leads/team and potentially from CCP partners.
2. Discuss, compile, and summarize the state of practices and/or best practices on use of COTS EEE parts for various programs/projects at NASA Centers. The practices and best practices should 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 EEE parts.
3. Based on 1 and 2, develop recommendations that could lead to future NASA Electronic Parts and Packaging (NEPP) Program and/or Agency guidance on COTS parts selection, evaluation, screening, qualification, and usage in space systems to perform as required over the life cycle for all types of space missions, by leveraging the lessons learned from CCP and the best practices currently being used across the Agency.

## 6.0 Problem Description, Proposed Solutions, and Risk Assessment

An increasing number of programs/projects are driving widespread use of COTS EEE parts to meet challenging size, weight, and power (SWaP) requirements.

NASA must capture best practices and lessons learned, and document the current practice as it evolves to promote uniform knowledge sharing and skill development across the Agency. Various NASA projects at Centers across the Agency and Commercial Crew Program (CCP) partners have utilized various guidance standards, techniques, and philosophies to select, evaluate, screen, and qualify different COTS EEE parts types. This increasing utilization of COTS hardware requires a multi-discipline mindset along with feedback from a diverse set of current users to ensure Mission, Environment, Applications and Lifetime (MEAL)[1] requirements are being met for the wide range of Agency needs with differing risk postures.

This task addresses part of the first short-term strategic vector for the parts community (i.e., "develop appropriate guidance for test, screening, qualification, and reliable usage of COTS and new EEE parts technologies, including hybrid parts and advanced packaging technologies, for all types of space missions"). The experience, knowledge, and lessons learned being gained by NASA Centers need to be recorded and organized so that the Agency benefits through information sharing.

[1] NASA/TM–2018-220074, "Guidelines for Verification Strategies to Minimize Risk Based on Mission, Environment, Application and Lifetime (MEAL)," June, 2018.

# 7.0 Center Practices on Use of COTS

Section 7.1.1 defined the scope of this assessment with key acronym and definitions of COTS, COTS assembly, COTS part, NASA-screened COTS part, and Industry Leading Parts Manufacturers (ILPMs). Section 7.1.2 includes NASA Centers' summaries and process flows on use of COTS practices at eight NASA Centers (i.e., ARC, GRC, GSFC, JPL, JSC, KSC, LaRC, and MSFC).

Sections 7.2 through 7.9 includes eight NASA Centers. Each report describes the Center's current practices, best practices, lessons learned (if any), and proposed recommendations on use of COTS in spaceflight systems (ARC, GRC, GSFC, JPL, JSC, LaRC and MSFC) or in critical GSE (KSC). For the purpose of easy comparison and consistency, each Center included the following topics in the Center reports in Sections 7.2 through 7.9:

- Center programs and projects and use of COTS
- Center strategy of use of COTS parts
- Center governing parts documents
- Current Practices on COTS parts selection, evaluation, screening and qualification for spaceflight missions/GSE
- Center best practices and lessons learned
- Center proposed recommendations

Section 7.10 summarized the current and/or best practices on use of COTS. It included the following seven sub-sections:

- Summary of current practices from the eight NASA Centers (Section 7.10.1)
- Risk context of use of COTS parts (Section 7.10.2)
- Best practices on COTS parts selection (Section 7.10.3)
- Current practices on COTS parts verifications (Section 7.10.4)
- Best practices on COTS applications (Section 7.10.5)
- COTS parts radiation hardness assurance (Section 7.10.6)
- Common concerns of use of COTS parts (Section 7.10.7)

Section 7.11 described Phase II of this assessment.

Note: The Phase II assessment was completed. The Phase II final report is available at https://ntrs.nasa.gov/citations/20220018183.

## 7.1 Scope of Assessment and Center Summaries on Use of COTS

There have been rapidly evolving parts technologies available in commercial industry. As demands for improved performance in spaceflight programs increase, and budget and schedules remain constrained, there is a continuously increasing desire to infuse large numbers of COTS parts in a wide range of spaceflight missions, ranging from Category 1-3, Class A-D, and sub-Class D (i.e., all risk postures and cost ranges for NASA space missions).

### 7.1.1 Scope of Assessment and Critical Definitions

The scope of the assessment was to:

1. Capture the NASA Centers' current practices, best practices, lessons learned and Center recommendations on use of COTS EEE parts in spaceflight systems from ARC, GRC, GSFC, JPL, JSC, LaRC and MSFC and COTS EEE parts, components and assemblies in GSE from KSC; and
2. Provide recommendations on use of COTS for spaceflight systems and GSE, including a set of best practices based on the Centers' current and best practices and the NESC team's discussions.

The following is key acronym and definitions in this report.

**COTS:** Commercial-Off-The-Shelf

**COTS Assembly**: A Commercial-Off-The-Shelf assembly designed for commercial applications for which the manufacturer establishes and controls the specifications for performance, configuration and reliability, including design, parts selection, software, firmware, materials, processes, and testing. Parts selection, screening, derating and qualification used in the assembly are at the discretion of the manufacturer.

**<u>Parts Types</u>**

**COTS Part:** A Commercial-Off-The-Shelf part designed for commercial applications for which the part manufacturer solely establishes and controls the specifications for performance, configuration and reliability, including design, materials, processes, and testing without additional requirements imposed by users and external organizations. It is typically available for sale through commercial distributors to the public with little or no lead time.

***Note:*** *By definition, COTS parts include any parts qualified and screened by commercial manufacturers or third party without government insight into the processes. COTS parts include consumer, industrial, commercial hi-rel, manufacturer hi-rel, industry hi-rel such as automotive electronics council (AEC) qualified or compliant automotive parts, space rated COTS, etc.*

**Space Rated COTS:** A COTS part that is produced on manufacturer-rated product lines with enhanced process controls and screening intended to provide parts that are suitable for space applications. Enhancements may include single wafer fab and assembly site with optimized material set, wafer lot RLAT, one-time TID characterization, and MIL-STD based screening flows. The qualification and screening are not subject to government oversight. Details will vary by manufacturer, so it is important to understand the specific part characteristics, manufacturing and screening flows when purchasing space rated COTS.

***Note:*** *The term "space-rated" is a term from the past that has carried over, for which some people assume it to mean parts that have been through many processes to prepare them for hostile environments in space, and others believe they are the parts that need to be used for reliability in space. The reality is that there is no consistent set of requirements that go into a part being "space-rated" to cover all part types. Make sure that this is not to be confused with MIL-SPEC parts with radiation designators, such as those per MIL-PRF-38535.*

**NASA-screened COTS Part**: A COTS part, after procurement, qualified and screened per NASA Agency, Center or Program parts requirements documents, such as EEE-INST-002 or equivalent documents, by NASA, NASA contractors, third-party or the part manufacturer.

***Note:*** *The parts levels in EEE-INST-002 or equivalent documents for EEE parts are imposed as screening levels, but not manufacturing grade levels. In addition, COTS parts are not designed for space radiation environments. The parts levels in EEE-INST-002 or equivalent documents do not indicate the level of radiation tolerance and, therefore, the selection of level 1, 2, or 3 parts per the documents does not imply or provide radiation hardness or mitigation of radiation effects at part-level.*

**<u>Parts Screening Types</u>**

MIL-SPEC/NASA screening – Nondestructive tests (electrical and environmental stress), applied to 100% of parts in a lot and intended to remove nonconforming parts (parts with random defects that are at increased risk of resulting in early failures, known as infant mortality) from an otherwise acceptable lot and thus increase confidence in the reliability of the parts selected for use. Specific tests and required thresholds are listed in applicable requirement documents (MIL-SPECS / NASA documents).

COTS manufacturer screening – Nondestructive tests defined and implemented by parts manufacturers, performed on 100% of parts and intended for functional verification of partial or full datasheet parametric specifications typically at room temperature or manufacturer-defined temperature range, or for removal of early failures, or identification of parametric outliers. It varies among different manufacturers.

***Note:*** *Both MIL-SPEC screening and NASA screening include burn-in, intended to remove infant mortality or early failures. COTS manufacturers define their own screening, which can be quite different among manufacturers, especially across different types of parts, e.g., semiconductors, passives, etc. COTS manufacturers may perform burn-in during qualification only and sample burn-in (burn-in on sample parts) to monitor production line.*

**<u>Parts Manufacturer</u>**

**Zero Defects Approach:** A strategy with a set of industry best practices including processes, methods and tools to drive to zero DPPM (defective part per million) or to a level of DPPB (defective part per billion) for semiconductor parts and any other parts types where applicable.

***Note:*** *Parts failure rate can be expressed as FIT (failure in time) or DPPM. FIT is a measure of fraction of parts failing per device-hour, while DPPM is a measure of the cumulative fraction of parts failing per part. For example, 1 FIT is equivalent to 4.38 DPPM in 6 months, or 8.76 DPPM in 1 year.*

**Industry Leading Parts Manufacturer (ILPM):** A parts manufacturer that has high volume automatic production facilities and can provide documented proof of the parts' technology, process and product qualification, and its implementation of industry best practices including processes, methods and tools towards "zero defects" approach for parts quality, reliability and workmanship for parts intended commercial applications.

***Note 1:*** *As it is defined, ILPMs may be closely related to high parts volume produced and market share for each part type.*

***Note 2****: Since most parts are not designed or manufactured for space radiation environments, a part from an ILPM may not meet project's radiation requirements.*

***Note 3:*** *The areas of the "zero defects" approach for part-level verification are described in section 7.10.3, roughly based on AEC-Q004[2], "Automotive Zero Defects Framework."*

***Note 4:*** *Burn-in as defined in MIL-SPEC for early failure removal is typically performed on COTS parts during qualification but not on parts for procurement. ILPMs are expected to perform 100% probe-testing at wafer level and/or at the final testing step for electrical compliance to the datasheet parameter specifications. These tests may be typically performed at room temperature and nominal conditions, the production test limits are expected to be established through multiple lots of characterization to ensure that they are sufficient to meet the datasheet specifications at the high and low end of the parameters over the entire specified set of conditions. It is expected that process and technology qualification, product qualification (typically including burn-in performed on multiple lots), and "zero defects" approach including production monitoring and statistical control, etc., are to ensure low DPPM, and sample burn-in performed on multiple lots regularly is to ensure health and consistency of the production lines.*

### 7.1.2 Center Summaries of Use of COTS

The section includes summaries of Center current practices on use of COTS parts in spaceflight systems at ARC, GRC, GSFC, JPL, JSC, LaRC, and MSFC, and KSC's current practices on use COTS parts and assemblies in critical GSE.

In general, COTS parts are typically selected by Circuit Designers based on parts datasheet performance specifications. Parts Engineers guide the selection to the highest available parts grade from well-known and reputable manufacturers, perform manufacturer assessment and evaluate the parts for target applications. Then the COTS parts will be acquired from original component manufacturers (OCMs) or authorized

[2]AEC-Q004, "Automotive Zero Defects Framework", February 26, 2020.

distributors. The criteria of selection, verification and acceptance of COTS parts into spaceflight systems varies among Centers and Program/Projects.

#### 7.1.2.1 ARC Summary on Use of COTS for Spaceflight Systems

ARC's strategic focus is in Class D/sub-D (NPR 7120.8) spaceflight projects and missions. The EEE parts management and control at ARC is governed by APR 8730.2: Ames EEE Parts Control Requirements, which was created in 2009 per NPD 8730.2C. The main goal of this document is to set quality control policy without undue burden on the numerous small and "low-budget" spaceflight projects at the Center. These projects are usually executed in collaboration with other NASA Centers, academia, or international partners. Typically, they are low-cost, quick-turn, short-duration, and high-risk/high-reward science projects with an LCC (life cycle-cost), excluding the launch cost, of $25M or less.

ARC's philosophy in EEE part selection emphasizes educated and calculated risks given the nature of these projects. The Chief Engineer's Office, S&MA, and project managers agree to take on risks that are perceived to be too great in traditional NASA sense; but, with the tiny budgets and huge potential scientific gains, it is what defines ARC's niche. These projects use nearly 100% COTS parts without any further MIL-SPEC/NASA screenings or qualifications being performed, other than visual inspections (i.e., used straight out of the catalogs of the manufacturers). However, parts are only procured from electronics industry leaders in the world, and either directly or strictly through their authorized distributors. These manufacturers have good quality control policies in place, and they stand behind their products. They are within the category of ILPMs as defined in this report. Most importantly, their products are very widely used with huge volumes in the commercial industry, which is the best proof of the quality for their products.

The use of COTS parts is necessary due to the SWaP, functions, and performance required for these ARC projects, which are mostly small-sats or nanosats. ARC chooses to maximize the flight hardware reliability at board and subsystem levels, instead of at the part level, because solid circuit design is much more effective for reliability than extensive attention to parts. COTS use allows large quantity of multi-revision engineering units to be built efficiently and affordably, which makes "test early and often" a viable flight hardware development strategy. This is especially important in getting the concurrent development of flight software, payload software, subsystem interface, form and fit, and system test procedures started early to reduce risks later in the assembly, integration, and test (AI&T) phase. It also shortens development cycle times while, at the same time, improving the thoroughness and robustness of the flight hardware designs.

Since these are usually short-duration projects (120 days or less) operating in either low Earth Orbit (LEO) or lunar orbits, TID radiation is not a huge challenge. However, SEE (Single Event Effects) type of radiation must still be addressed through mitigations implemented at board and subsystem levels rather than at part level. Circuit design mitigation is the main strategy used to deal with radiation, such as the use of redundancy (single-event burnout (SEB)), over current/voltage monitoring (single-event latchup (SEL)), single-event gate rupture (SEGR)), resetting circuits (H/W & S/W), and power cycling. Occasionally, space rated parts and/or redundancy are used to mitigate risk in mission critical single point failures. Modularization is a key approach implemented in the system architecture by utilizing separate power feeds for critical subsystems, so that damages can be quarantined and minimized, allowing partial mission successes. Single-event soft errors (single-event functional upsets (SEU), single-event functional interrupts (SEFI)) are dealt with using a watchdog timer, along with error detection and correction. Flash or magnetoresistive random-access memory (MRAM) memory are also used to prevent SEUs. Software protection methods, such as creating saved states of the system and software TMR (triple modular redundancies or registers) for critical data are also used. Shielding the parts from radiation with aluminum (66-100 mil) is also typically used.

Use of COTS parts is a proven strategy at ARC over the last 12 years based on mission data gathered over 30 successful spaceflight projects. Although the data were obtained from these Class D or sub-D projects that tend to have short durations with benign radiation environments, the same approaches can be implemented successfully in higher classes of missions if proper care, analysis, and judicious design choices are made.

**Center Process Flow on Use of COTS**

**<u>NOTIONAL ARC COTS PARTS SELECTION PROCESS</u>**

***Table 7.1.2-1. ARC Project Classifications***

| | | | |
|---|---|---|---|
| Project Category | 3 | | 3 |
| Mission Class | Class D/NPR 7120.5 | | Class Sub-D/NPR 7120.8 |
| Mission Type | Small Satellite, Science/Robotic | | Nanosat, Smaller Science |
| Part Level | Level 3 | COTS | COTS |
| Qualification Level | Low Military | Commercial | Commercial |

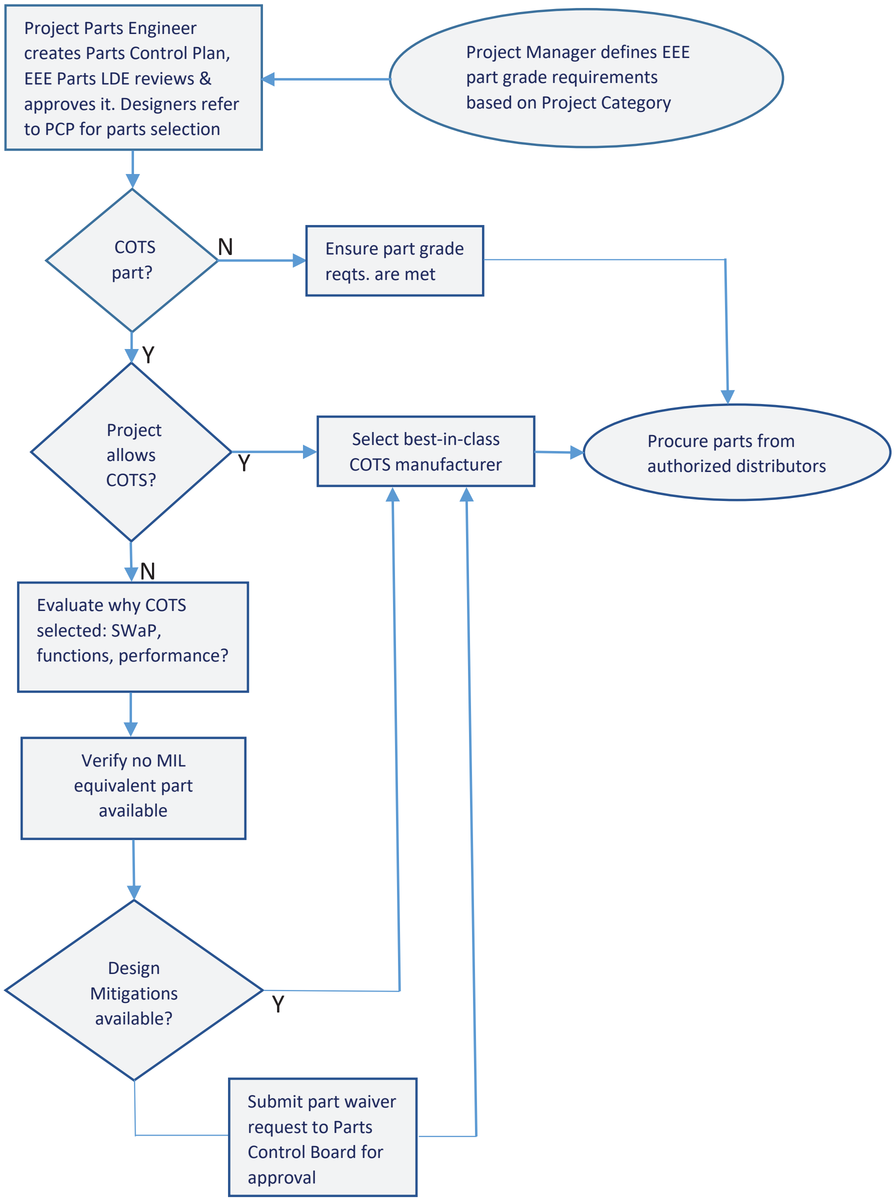



*Figure 7.1.2-1. Flowchart depicting ARC Center Process Flow on Use of COTS*

### 7.1.2.2 GRC Summary on Use of COTS for Spaceflight Systems

NASA GRC main areas of expertise are communications technology, propulsion, power, energy storage, and conversion, materials and structures, and physical sciences and biomedical technologies. GRC manages and/or partners on a variety of spaceflight programs and projects of all risk classifications A-D, as defined by NPR 8705.4 “Risk Classification for NASA Payloads,” although in-house design and build projects are typically Class D or lower. Mission costs for these projects are on the order of up to ~$100M, with mission lifetime goals of 1 to 3 years. These in-house Class D or sub-

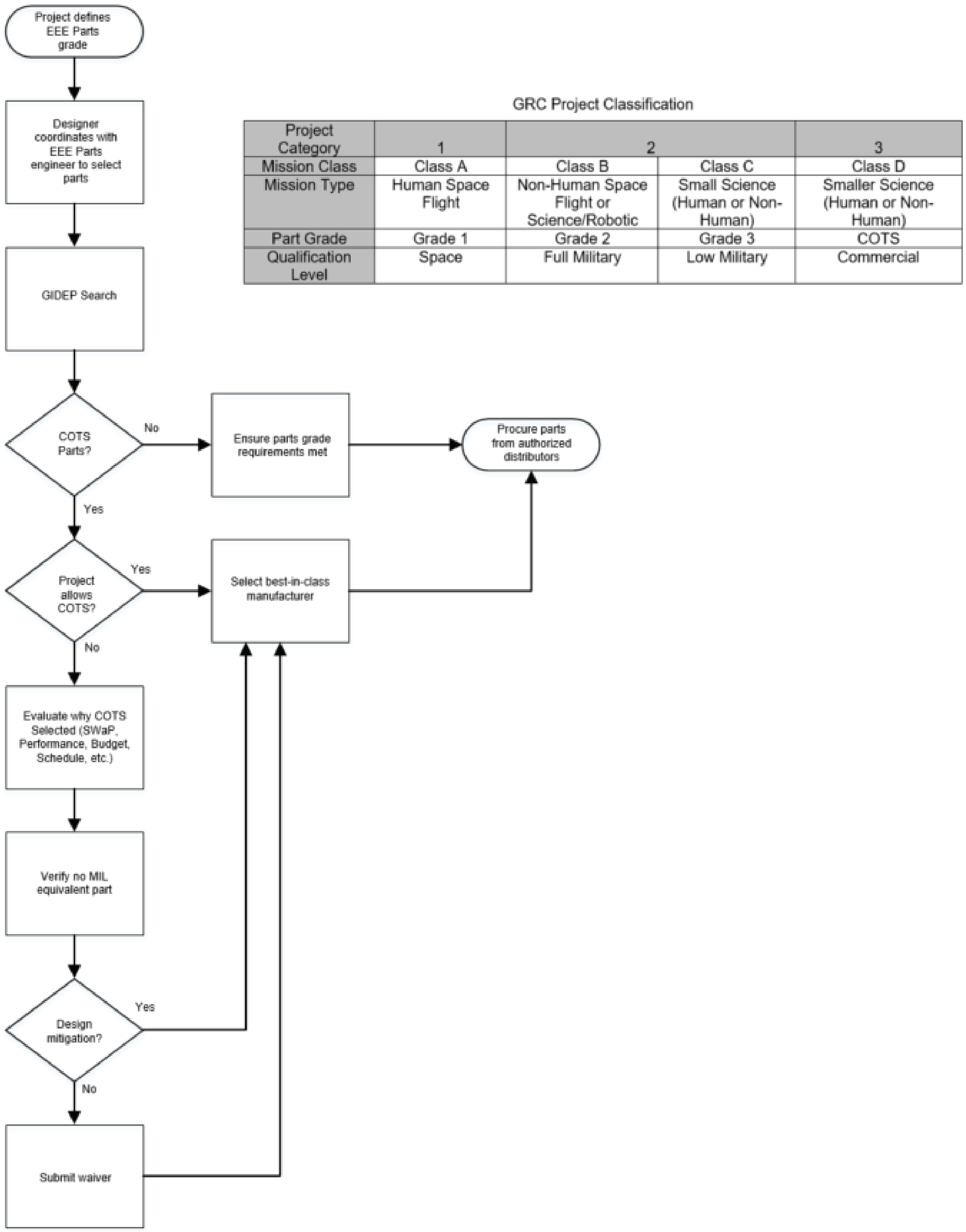
Class D projects include technology demonstration missions, International Space Station (ISS) payloads, and more recently, CubeSats.

Each project at GRC is required to develop a Parts Control Plan, which describes the project's part grade requirements, and its approach to using COTS. Historically, GRC has implemented traditional parts requirements on its projects; however, within the past decade, the use of COTS has become much more common due to declining availability of rad-hard parts, shrinking project budgets, and increased confidence in the reliability of COTS parts. On Class A-C projects, the use of COTS components follows a typical MIL-SPEC/NASA screening, qualification, and approval process. The Class D and sub-Class D projects have become more lenient in regards to use of COTS, due to budget and schedule reasons.

The missions that have used COTS parts have been largely successful. The keys for success involve a variety of design, test, and parts engineering considerations. From a design perspective, parts should be chosen that are known to be reliable and are suitable for the application. Throughout the project life cycle, breadboard and engineering units should be built with the intended parts to test out functionality and detect any problems with the design. Projects using COTS parts typically do environmental screening tests at a board or assembly level, consisting of thermal cycling, burn-in, and vibration testing. Parts should be procured directly from the manufacturers or authorized distributors and should be inspected for defects upon receipt. For COTS parts to be used in critical applications, approval of a screening and qualification plan is required.

Overall, COTS parts can be used successfully in projects by following good engineering practices and having a thorough understanding of part applications and risks. COTS will continue to become a larger share of the market. Especially for Class D and sub-Class D missions, NASA projects will be forced to adapt to more widespread use of COTS due to technology advancement goals, smaller project budgets, and more aggressive project schedules.

## Center Process Flow on Use of COTS




| Project Category | 1 | 2 | | 3 |
|---|---|---|---|---|
| Mission Class | Class A | Class B | Class C | Class D |
| Mission Type | Human Space Flight | Non-Human Space Flight or Science/Robotic | Small Science (Human or Non-Human) | Smaller Science (Human or Non-Human) |
| Part Grade | Grade 1 | Grade 2 | Grade 3 | COTS |
| Qualification Level | Space | Full Military | Low Military | Commercial |

*Figure 7.1.2-2. Flowchart depicting GRC Center Process Flow on Use of COTS*

### 7.1.2.3 GSFC Summary on Use of COTS for Spaceflight Systems

As the MIL-SPEC system continues to shrink relative to the overall market for global electronics, and COTS parts increase their dominance in the market, the need to establish an approach to define an appropriate context for reliable use of COTS parts in critical space applications grows. Recent efforts have exposed the fact that the MIL-SPEC testing system does not well apply to COTS parts, and given that the MIL-SPEC approach is not the only solution to assure parts are appropriate for reliable applications, a new approach is needed to define the boundaries for the use of COTS parts and the means to assure consistent reliable use. The first part of such an effort involves education of the parts engineering community, users of EEE parts, and systems engineers about the true meaning and implications of EEE parts requirements, how reliability is established for electronics, and what factors pertain to the reliable use of EEE parts, COTS or otherwise. GSFC has flown many variants of COTS parts for many years, but usage of such without MIL-SPEC/NASA screening per EEE-INST-002 has been confined to projects outside of those managed under NPR 7120.5 except in the few cases where resources were extremely limited to the extent that there was no question very early on that they would not be affordable, in cost or schedule. The new wave of very low-cost Class D missions will force a change on this practice, so some form of change is imminent. Experience in the several cases where pure (not NASA screened) COTS have been flown for extended periods of time on-orbit indicate no different propensity to failure than with MIL-SPEC parts at any level. It is noteworthy that discussions with systems engineers and electronics engineers across the Center indicate the misconception that current EEE parts requirements, which are based on screening and qualification levels, are based on levels of reliability, indicating that the current thoughts are that screening is equated to reliability.

**Historical Center Process Flow on Use of COTS (prior to NESC study)**

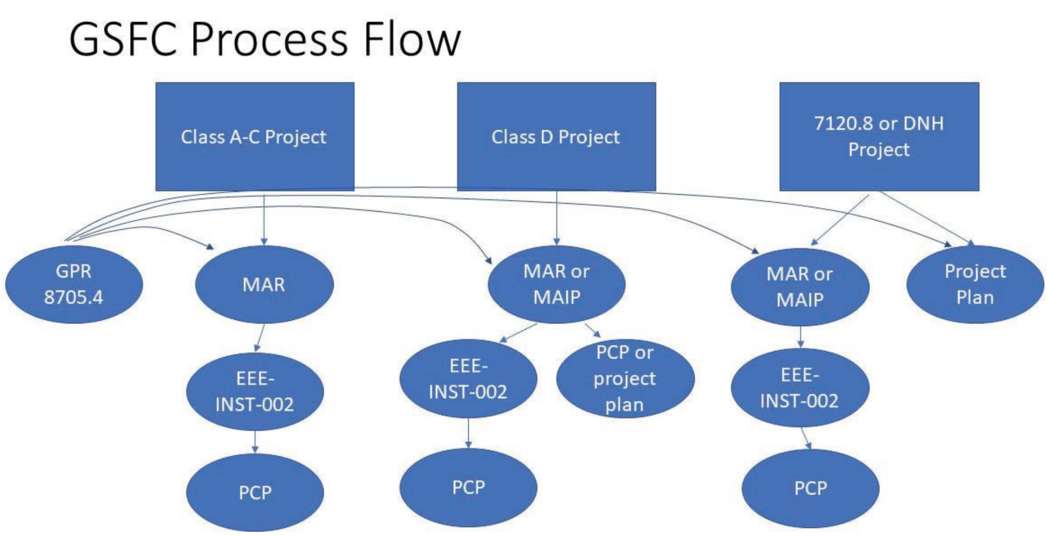



*Figure 7.1.2-3. Flowchart depicting GSFC Center Process Flow on Use of COTS*

#### 7.1.2.4 JPL Center Summary on Use of COTS for Spaceflight Systems

JPL strategy for use of COTS EEE parts is mission dependent, and based on minimizing risk. COTS use on Class A-C missions will require some level of MIL-SPEC/NASA qualification and screening that may be tailored to meet risk, schedule and cost constraints. COTS are avoided as much as possible for mission critical applications but, if necessary, a qualification and screening plan similar to MIL-SPEC parts will be applied. In these cases, it is important to understand the differences between COTS and MIL parts. Strict adherence to MIL-SPEC testing will not apply to all COTS. COTS may be used with documentation and minimal oversight for Class D missions and technical demonstrations. Project management will define the part grade requirements for the system, which will determine if COTS can be used. If COTS are allowed for use-as-is, the project assumes all associated risks.

COTS at JPL are typically selected by circuit designers based on datasheet performance specifications. Parts engineering will guide the selection to the highest available reliability grade, from well-known, reputable manufacturers that also produce military qualified product lines as much as possible. If a manufacturer has no space / military hardware experience, a Procurement Quality Assurance audit (audit criteria is Center specific) should be performed to assess manufacturing quality and reliability systems. The parts will be acquired from original component manufacturers (OCMs) or authorized distributors.

**Center Process Flow on Use of COTS**

**<u>JPL COTS PARTS SELECTION PROCESS</u>**

***Table 7.1.2-2. JPL Project Classifications***

| Project Category | 1 | | 2 | 3 | 3 |
|---|---|---|---|---|---|
| Mission Class | Class A | | Class B | Class C | Class D |
| Mission Type | High priority, high complexity, long duration | | High priority, medium duration | Low cost, short duration | CubeSat, Smaller Science |
| Part Grade | Grade 1 | Grade 2 | Grade 2 | Grade 3 / COTS | COTS |
| Qualification Level | Space | Military | Military | Military/Commercial | Commercial |

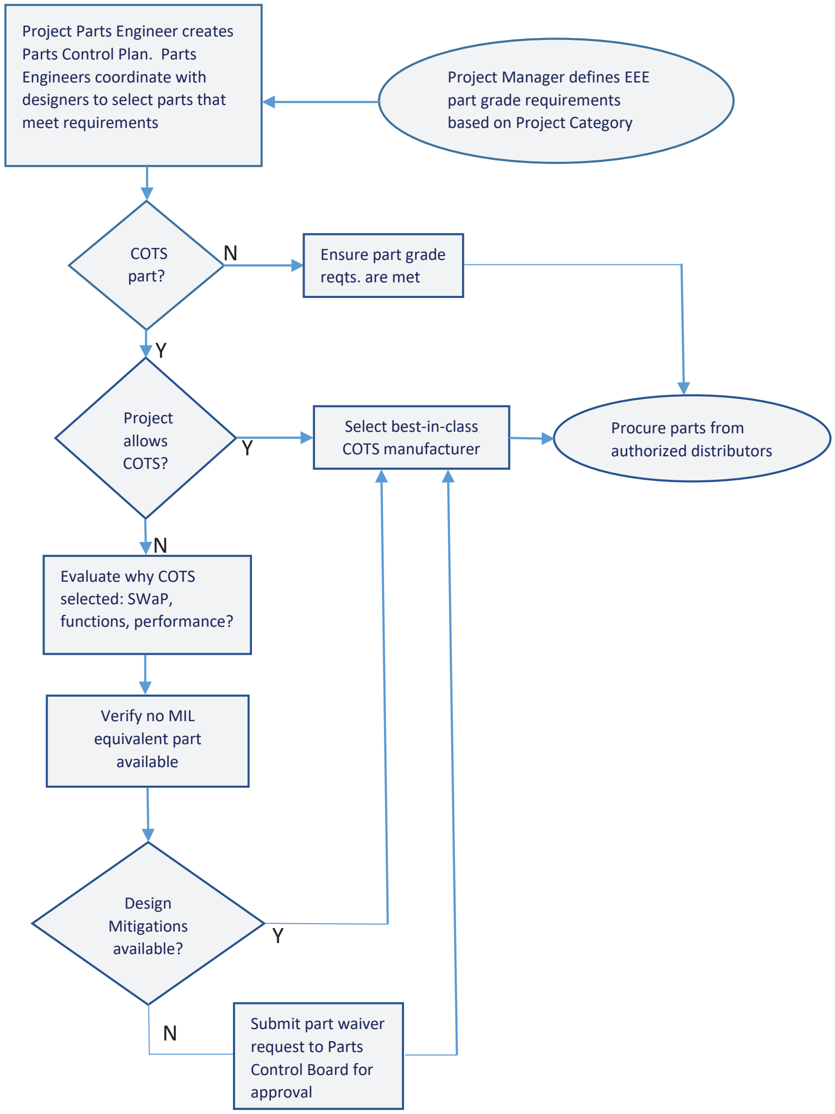



***Figure 7.1.2-4. Flowchart depicting JPL Center Process Flow on Use of COTS***

### 7.1.2.5 JSC Center Summary on Use of COTS for Spaceflight Systems

JSC implements two approaches to the use of COTS. For large programs such as ISS and Multi-Purpose Crew Vehicle (MPCV), life-critical and mission-critical hardware avoids the use of COTS in favor of traditional Grade 1 and Grade 2 parts. In such hardware COTS parts require full MIL-SPEC/NASA screening, part-level Qualification, and DPA. Because the cost and schedule impacts of this approach are large, COTS parts are selected only as a last resort.

For non-critical hardware COTS parts are widely utilized without part-level MIL-SPEC/NASA screening or qualification. The JSC Engineering EEE Parts group works with projects to select COTS parts from ILPMs and works to validate the practices of these manufacturers. JSC has successfully flown many flight hardware projects using COTS parts. Difficulties experienced in these projects have not been related to part quality. Workmanship, design, electrical overstress, ESD, and improper application have been the source of part failures. There are no known instances where parts from ILPMs have failed due to manufacturing defects.

Some commercial partners have recently begun to use COTS parts in life-critical and mission-critical multi-failure-tolerant applications without part-level screening and qualification. Their approach is to perform rigorous part-by-part and manufacturer-by-manufacturer validation of best practices. This approach has proven difficult and costly to implement.

The use of COTS should be encouraged. However, it cannot be assumed that every part made by a COTS manufacturer is defect-free and consistent with those parts used for qualification and failure rate calculation. Some level of verification must be performed for all but the least-critical projects. The inability of the EEE community to agree on suitable verifications, and the difficulty in obtaining verification-related information from COTS manufacturers, are the main roadblocks to the use of COTS parts in more critical applications.

**Center Process Flow on Use of COTS**

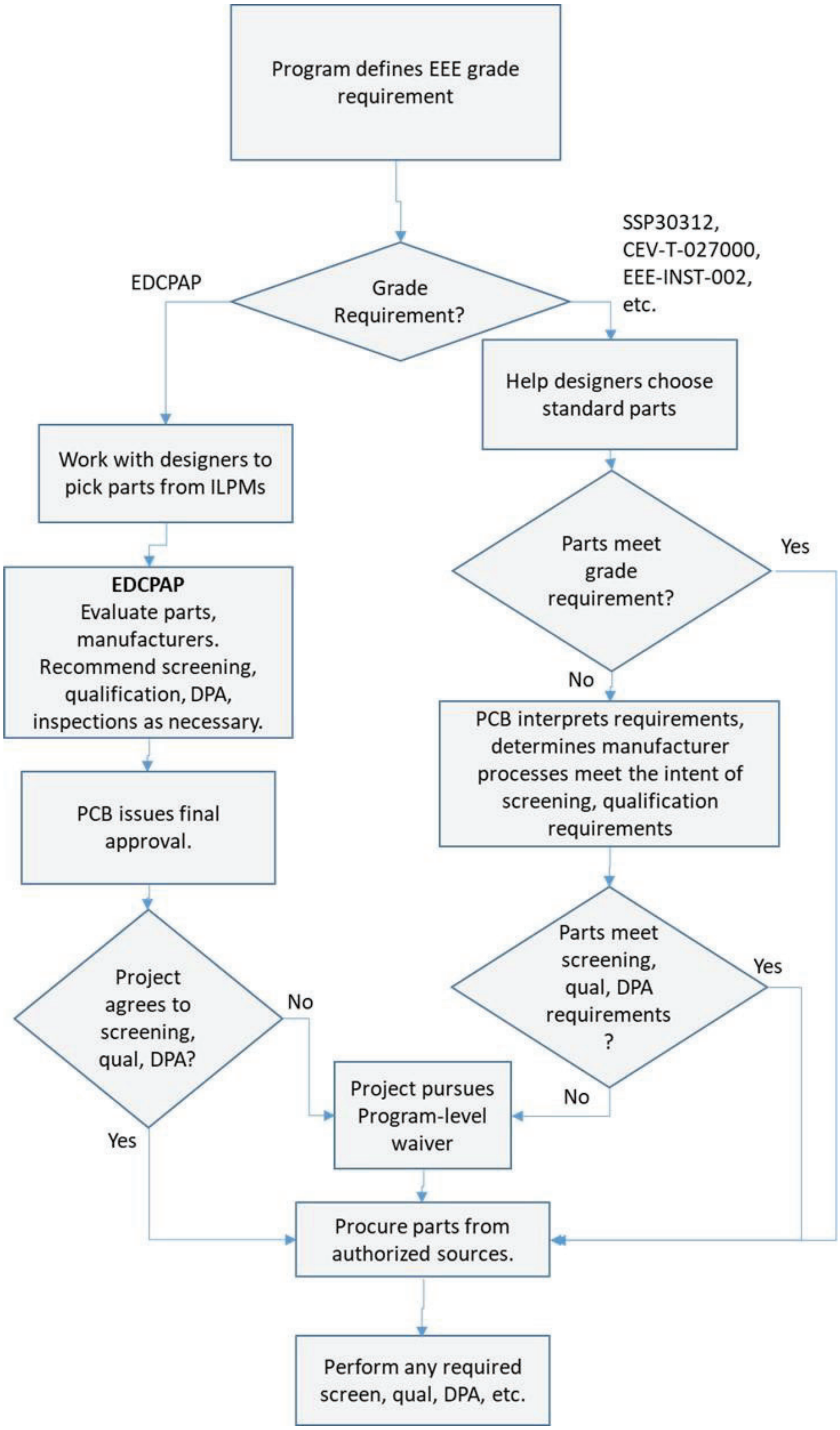



***Figure 7.1.2-5. Flowchart depicting JSC Center Process Flow on Use of COTS***

#### 7.1.2.6 KSC Center Summary on Use of COTS for Spaceflight Systems

The KSC supports multiple programs and projects including Exploration Ground Systems (EGS), Commercial Crew, Gateway and Exploration Research & Technology, which consists of small ground and flight projects. For this effort, KSC focused on the use of COTS in GSE for EGS that is the majority of the design and development efforts at KSC. EGS is responsible for MPCV and Space Launch System (SLS) vehicle and payload processing and launch. Main components of EGS include Command, Control & Communications: Launch Control System, Mobile Launcher Umbilical & Control Systems and GSE in the various processing facilities. These systems are safety critical or mission critical. They are designed for a 20-year life cycle and are Single Fault Tolerant: fail safe or fail operational.

**Selection:** EEE Parts are defined in the KSC-PLN-5406 EEE Parts Plan and includes higher level electronic assemblies. COTS electronic assemblies include line replacement units (LRUs) (e.g., power supplies and PLCs). High-level assembly racks and enclosures contain many LRUs and other COTS components. For this discussion, the term assemblies include LRUs, racks and enclosures Parts are selected based on functional operational and environmental requirements. Parts and assemblies are procured from the original equipment manufacturer (OEM) or their franchised (authorized) distributors. Parts and equipment are reviewed for applicable Government Industry Data Exchange Program (GIDEP) Alerts/Advisories and assessed for obsolescence. Certificates of Conformance along with lot/batch numbers may be requested for critical items. Grades 2-4 are used in GSE designs. Grade 3-4 parts undergo full qualification EMC, vibe, acoustic, and thermal. Grade Description per KSC-PLN-5406: Grade 2 - "Full Military" quality-class qualified parts, or equivalent. Grade 3 - "Low Military" quality-class parts, and Vendor High Reliability or equivalent, Industrial/High Reliability COTS, AEC EEE parts. Grade 4 - "Commercial" quality-class parts.

**Evaluation:** GSE undergo a rigorous technical review process as defined in the Kennedy Documented Procedure KDP-P-2713 including verification & validation testing leading to Design Certification or System Acceptance.

Screening: Screening is performed on GSE Critical Items as defined in KSC-PLN-5406. Critical Items are identified in the system Reliability and Safety Assessment Report (RSAR) or System Assurance Analysis (SAA) Critical Item List (CIL). Screening is performed per KSC-PLN-5406, which leveraged GSFC-EEE-INST-002.

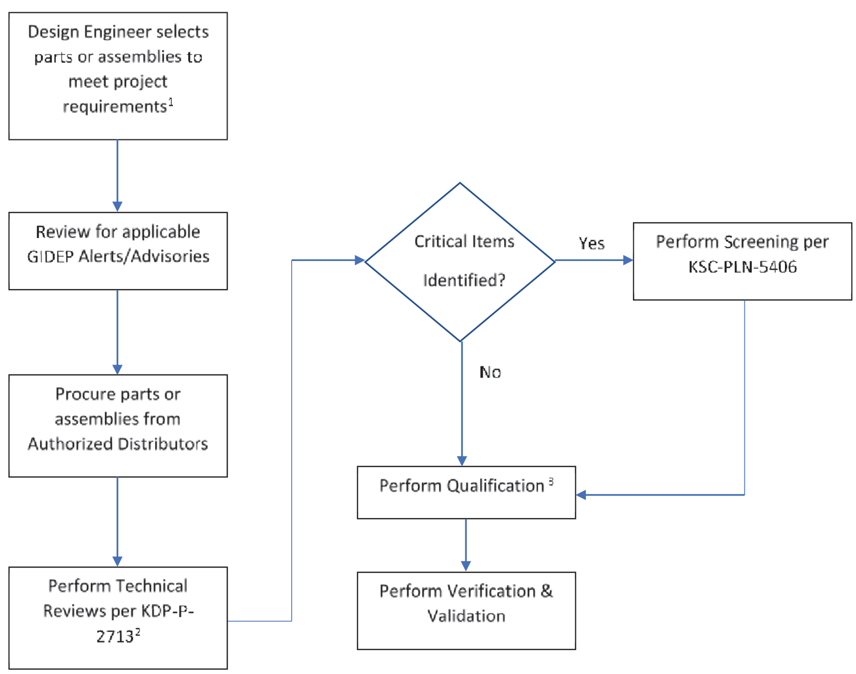
**Derating:** Derating is performed per KSC-PLN-5406, which leveraged GSFC-EEE-INST-002. Added GSE derating requirements per NFPA 70E – National Electric Code. Derating calculations and analysis are documented in system Design Analysis Reports.

**Qualification:** All GSE systems go through some level of qualification. Qualification may be performed at the component level, LRU assembly level or high-level rack or enclosure assembly. This includes Functional/Performance, Electromagnetic Compatibility, Vibration, Acoustic and Thermal testing. A qualified parts list is maintained.

**Recommendation:** The use of COTS parts and equipment can be very beneficial, saving design & development costs and schedule and for GSE, COTS products should be used to the fullest extent possible when they meet the project requirements. COTS should be qualified for their operational and environmental requirements. Pedigree requirements should be identified and understood, request CoCs for critical items, An obsolescence analysis should be performed when selecting a part to ensure part availability or alternative meets or exceeds production milestones and mission duration. Obsolescence should be tracked throughout the project life cycle. Maintain warranties and vendor support (H/W & S/W) for COTS assemblies. Stay away from sole sources if possible. Depending on the application and criticality, implement redundancy. Maintain a qualified parts list.

### Center Process Flow on Use of COTS

KSC Parts & Assemblies Selection and Utilization Flow (Notional)




Notes:

1. Selection of parts, assemblies and grades are based upon functional, environmental and operational requirements as well as criticality.
2. KDP-P-2173 defines the technical review process and associated products. This includes 30%,60%,90% design reviews or PDR, CDRs. An obsolescence assessment is performed and documented in the Logistic Support Analysis. Risks and Critical Items are documented in the Reliability and Safety Assessment Report and the System Assurance Analysis. Derating is documented in the System Design Analysis Report.
3. Qualification may be performed at the component level, LRU assembly level or high-level rack or enclosure assembly. This includes Functional/Performance, Electromagnetic Compatibility, Vibration, Acoustic and Thermal testing

***Figure 7.1.2-6. Flowchart depicting KSC Center Process Flow on Use of COTS***

#### 7.1.2.7 LaRC Center Summary on Use of COTS for Spaceflight Systems

Almost all LaRC projects have anywhere from a few COTS parts and or components to several for its NASA class C & D missions. The risk levels associated with these types of projects make COTS usage applications more attractive from a cost and schedule perspective. The use of COTS for these programs – while effective – does create some additional work that is not desirable with standardized space and military parts usage. This is the hidden total cost of these commercial unique part implementation efforts.

The typical selection criteria address hardware or instrument functions not requiring high reliability but most certainly needing unique functionality not found in other MIL-aerospace standardized products readily available. When the primary performance factor for the mission is not operation critical, or there is space mission and/or vehicle/instrument redundancy the comfort level for usage becomes more tolerable.

**Selection:**

At LaRC, while there is no standard procedure for evaluating/selecting/screening COTS parts per se, each EEE Parts program is customized to the project and driven by Agency and Center policy directives. Those requirements ultimately flow to the tailored project EEE parts plan that has some guidance for dealing with COTS when they are foreseen for the project application. Every effort is made to ensure that parts/components are procured from heritage, well-understood, reputable manufacturers that possess credentials satisfying at least ISO9000 and AS91000 to produce their qualified product lines. If a manufacturer has no certifications or spaceflight/military hardware experience, then supplier development activities are performed to evaluate the product design, manufacturing process, quality and reliability systems of the vendor. To increase confidence in part quality, LaRC typically performs all environmental testing on Center on all COTS parts/components for in-house projects.

**Evaluation:**

Initial EEE parts reviews for part/components can involve a rigorous technical review process, that leverages off the application of guidelines such as EEE-INST-002 or MIL-PRF-38534 for workmanship and qualification efforts associated at the vendor control level and post procurement efforts needed at LaRC. These efforts of analysis, test or both - including verification & validation testing are intended to lead to Product Certification or System Acceptance level for the items in question.

**Screening:**

Testing is performed at the System Level for components and sub-assemblies – while screening is performed for piece-part EEE parts – leveraging off EEE-INST-002 as the part guideline. All parts are derated per manufacturer's recommendations and additional safety margin is added when early risk of failure is a mission concern.

**Recommendation:**

Early identification and vendor partnering when possible is key to COTS implementation success. When needed, vendor oversight and customer presence enhance and reduce concerns for hidden quality/reliability issues. Testing is a must to ensure products meet all datasheet claims. The cost of selection and use most also capture the research/analysis and post procurement testing – whether at the piece part, sub-system or box level assembly. The ultimate cost, however, is when there are COTS anomalies at the system level that need remediation before final delivery. These are typically thought to be system checkout cost – but should be linked to the parts selection and typically are overlooked.

At LaRC, the EEE Parts Office tries to discourage the use of COTS, but allow implementation when no other function or vendor offering is available. In most cases, when usage is unavoidable, the items are captured using the non-standard part documentation process and the project signs off the risk of using the part to complete the approval process.

## Center Process Flow on Use of COTS

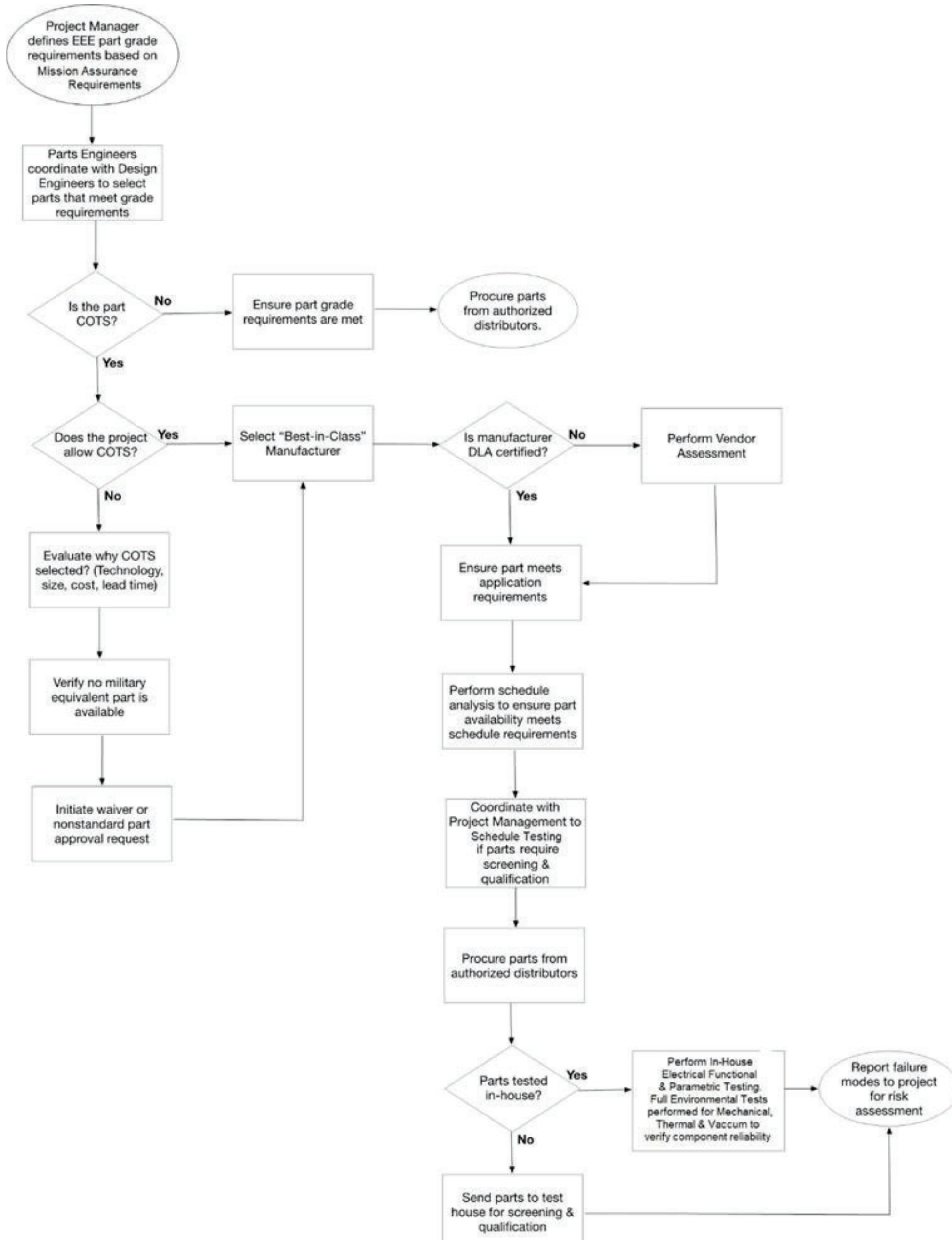



***Figure 7.1.2-7. Flowchart depicting LaRC Center Process Flow on Use of COTS***

#### 7.1.2.8 MSFC Center Summary on Use of COTS for Spaceflight Systems

MSFC-STD-3012 Grade 4 COTS EEE parts typically meet vendor standards for high reliability or commercial marketplace reliability, but have not been independently verified. Grade 4 parts should be selected for equipment where high reliability is not a primary factor, the mission is not critical, or a repeat mission is not scheduled. In addition, the duration of the mission should be short (<6 months) and the ability to repair flight hardware should be practical. Flight experiments and GSE are typical examples where Grade 4 parts may be considered for use. These projects are typically classified as Class D and are small, low-cost, short duration missions. It is the responsibility of project management to define the part grade requirements for the system, which will determine if COTS parts are allowed for use. If COTS parts are allowed, then the project assumes all associated risks.

At MSFC, the standard procedure for selecting COTS parts begins with choosing automotive qualified products, if available. Parts should also be procured from well-known, reputable manufacturers that possess certifications for other military qualified product lines. If a manufacturer has no certifications or spaceflight/military hardware experience, then an audit should be performed to evaluate the manufacturing quality and reliability systems. To increase confidence in part quality, MSFC performs PIND and x-ray on COTS parts for in-house projects.

## Center Process Flow on Use of COTS

### MSFC COTS Parts Selection & Usage Process

**Table 1. Project Classification**

| Project Category | 1 | | 2 | | 3 | |
|---|---|---|---|---|---|---|
| Mission Class | Class A | | Class B | Class C | Class D | |
| Mission Type | Human Space Flight | | Non-Human Space Flight or Science/Robotic | Small Science (Human or Non-Human) | Smaller Science (Human or Non-Human) | |
| Part Grade | Grade 1 | Grade 2 | Grade 2 | Grade 3 | Grade 3 | Grade 4 |
| Qualification Level | Space | Full military | | Low military | | Commercial |

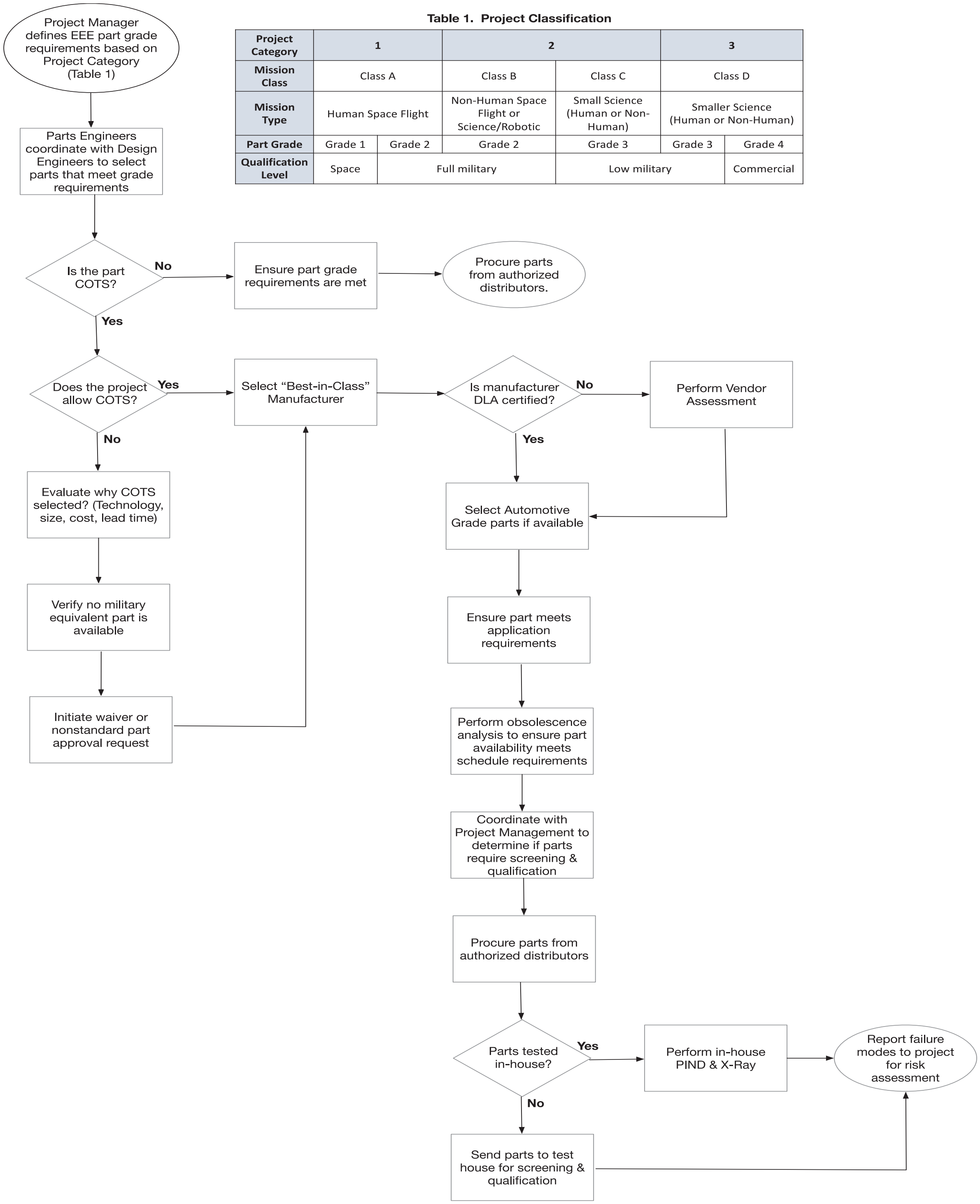



*Figure 7.1.2-8. Flowchart depicting MSFC Center Process Flow on Use of COTS*

## 7.2 ARC's Current Practices on Use of COTS Parts for Spaceflight Systems

### 7.2.1 Center Programs and Projects and Use of COTS

The NASA ARC's focus is in low-cost Class D and sub-D (NPR 7120.8) spaceflight missions, which consist of small spacecraft, nanosatellites, and science payloads. ARC develops most of the spaceflight hardware internally except the radios, which are strictly bought from outside vendors and they usually have flight heritage. There is an Engineering Evaluation Lab (EEL) that supports the hardware qualification and environmental testing, such as thermal, vacuum, shock and vibration, electromagnetic interference/electromagnetic capability (EMI/EMC), etc. There are also machine shops on site that manufacture the mechanical structures for the projects from prototyping, form-and-fit check, engineering development unit (EDU) to qualification unit and flight build. ARC has a multi-mission operation center (MMOC) that handles the mission operations for these spaceflight projects. In addition, ARC also collaborates with Santa Clara University and Stanford University for mission operations on some of the nano-satellite projects.

Many of the nano-satellite projects at ARC are developed in collaboration with academia (Stanford, SCU, Michigan, Purdue, Colorado, Arizona State, Florida, MIT, etc.) and international partners (German DLR, Saudi KACST, Swedish Space Agency, etc.), along with other NASA Centers and the military (Air Force and Navy). Hence, there is a broad spectrum of spaceflight projects being developed at ARC, involving mostly space biology and physics experiments. There are numerous science payloads for the ISS being also developed at ARC.

The Class D small satellite projects that were developed and operated by ARC over the last 12 years (LCROSS, Kepler, LADEE, IRIS) were between \$100M and \$250M in life cycle cost (LCC). However, these projects did not utilize many truly COTS parts and they were usually only used in non-critical functions and the payloads. On the other hand, the Class Sub-D nano-satellite projects being developed over the same period at ARC were using almost completely COTS parts. All of these nano-sat projects had an LCC of under \$25M, development cycle of about 2 years, and operated in the LEO with a target mission duration of mostly 30 days or less for full success criteria; however, most of them operated in orbit for at least 1 to 3 years.

### 7.2.2 Center Strategy of Use of COTS

ARC's EEE parts selection philosophy emphasizes educated and calculated risks to enable the realization of rapid-development, low-cost, high-risk with high-reward sub-D class nano-sat projects. Many of them are technology demonstration and proof-of-concept type of projects with short required durations, typically 30 days or less, on a shoestring budget. The key to successfully executing this type of projects is to get the buy-ins from all the stakeholders (funding directorate, chief engineer's office, safety and mission assurance, principal investigator, project manager, etc.) upfront to using nearly completely COTS parts. Listing and putting all the risks in front of the stakeholders and being transparent in the approach and execution are keys to the success. Some of the risk factors may not be quantified accurately; but, as long as everyone agrees to sign off on them while the development team tries their best to minimize the risks within the cost and schedule constraints, the projects are usually allowed to proceed. Sometimes, the state-of-the-art (SOTA) COTS parts are not able to perform the function necessary (e.g., the ultraviolet light emitting diode (UV- LED)) device for the UV-LED project, so the only option is to use experimental parts after testing and qualification. These types of unique parts are usually only used in the payloads, which tend to demand more challenging capabilities in function, performance, size, weight, and power. It should be noted that the challenges and risks associated with using such parts are based on the need to advance a capability by using a brand new and unproven part lacking other options, not because of the fact that the parts are COTS. ARC has the opportunity to fly such missions, keeping the door open to innovation and advancement.

#### 7.2.3 Center Governing Parts Documents

The ARC EEE parts control policy document is APR 8730.2: Ames EEE Parts Control Requirements, which was created in 2009 per requirements in NPD 8730.2C.

#### 7.2.4 Current Practices on COTS Selection, Evaluation, Screening and Qualification

Since ARC's focus is in Class D missions, where single-point failures are common, heavy use of COTS makes a lot of sense especially given the difficult SWaP, performance, cost and schedule challenges. Most of the missions are short-duration (120 days or less) for the LEO or lunar orbits, where TID is not a huge challenge, and SEE are addressed through mitigations implemented at board and subsystem levels when using COTS parts. Furthermore, the short durations of the missions justify the use of COTS, which tend to be made with newer semiconductor technologies with smaller feature sizes and much thinner gate oxide that lead to better inherent TID performance. In addition, strategic use of aluminum shielding in critical spots can further improve radiation tolerance in the flight hardware.

##### 7.2.4.1 COTS Parts Selection, Evaluation, Screening and Qualification

Typical ARC EEE parts for spaceflight projects are plastic (Plastic Encapsulated Microcircuits (PEM)) COTS parts that are readily available through major electronics vendors, who are authorized distributors of leading manufacturers. Certificates of Conformance (CoCs) for the parts can usually be obtained at an additional cost, although they may not be available sometimes, when ordering parts for flight hardware builds. As for prototype and engineering development builds, the CoCs are not required per APR 8730.2; hence, they are usually forgone, which lead to lower cost and shorter lead time in obtaining parts. Parts are sometimes obtained as free samples directly from the OCMs when that helps to improve the lead time in getting the parts. This approach is possible because COTS parts tend to be low cost and widely used in commercial applications; hence, the OCMs regularly offer free samples to attract new customers/applications for their parts. This also minimizes the risk of counterfeited parts entering the part inventory. Another approach ARC uses to avoid counterfeit parts is by strictly purchasing from the OCMs or their authorized distributors only.

COTS parts are usually selected based on the performance specified on the datasheets, and whenever available, higher grade versions (typically, with tighter parametric specifications and/or wider operational temperature ranges) of the parts are purchased. Furthermore, these selected parts are usually made by major electronics manufacturers that have good quality control policies in place, and who stand behind their products. Most importantly, their products are very widely used with huge volumes in the commercial industry, which is the best proof of the quality for their products.

Another key selection criterion is the circuit designer's familiarity with the parts or similar parts from the same OCM, from past positive experiences. In addition, circuits and parts that have performed successfully in prior spaceflight projects are heavily reused because flight heritage is a strongly preferred part selection criterion at ARC.

There has not been MIL-SPEC/NASA screening or qualification of COTS parts performed at part-level at ARC historically; however, it is not ruled out for future missions if the need arises, for instance, in long duration and/or deep space missions in which a mission partner requires it. Parts are usually evaluated in a circuit, then on a PCB, followed by a sub-assembly. The qualification of parts is only performed indirectly via the qualification of a subsystem or system. However, by the time a part gets through the qualification process, hundreds of hours of operational life would usually have been completed on it, which helps to weed out infant mortality parts and uncover workmanship issues.

Baseline EEE part level requirements are defined based on project category, budget, performance, and schedule. If the baseline parts are not available due to SWaP, cost or schedule constraints, COTS parts are selected and used with hardware and/or software mitigations implemented to ensure risk level consistent with the project's risk profile. Typically, the traditional NASA 5x5 risk matrix is used. Part related risk factors are usually minimized through circuit design and/or software mitigations, and they are usually driven down to an acceptable level at the board or sub-system level. Circuit analysis and simulation results are used in the design phase, followed by verification and validation through testing in the lab, to minimize the risk factors. The most serious part related risk factors are usually related to radiation effect due to some uncertainties associated with the mission environment. Mitigation approaches include shielding, purchasing some radiation-hardened parts, using redundancy, sensing overcurrent/overvoltage events and resetting the affected circuits are often implemented. Another common risk factor is the variability in the responses from the biological samples in the payloads, which may require extra margins to be added in the electronic sensing and monitoring circuits. There may not be any good ways to quantify certain risk factors accurately; hence, they will only be qualitatively analyzed and will require key stakeholders' agreement prior to finalizing the flight hardware build. These risk factors will be properly documented, with any dissenting voices, and officially kept on record.

#### 7.2.4.2 Radiation Effects Evaluation on COTS

Certainly, the biggest barrier to widespread use of COTS parts in spaceflight projects is the radiation effects they must tolerate and survive during the duration of the missions. If only widely-used COTS parts are selected for spaceflight projects, the quality of the parts is certainly not a concern since the large variety of applications and high volume uses of the parts in the commercial industry are the best proof of quality for the parts. However, since radiation performance of COTS parts is not a concern in the commercial industry, it is not an optimized or monitored capability during design or manufacturing of the parts. In addition, the radiation performance can vary widely from lot-to-lot, and even wafer-to-wafer, so it is quite different to deal with than the other performance parameters, which tend to be extremely consistent regardless of where parts are fabricated. If the radiation performance of a COTS part needs to be tested and quantified, it will be necessary to limit the die to those from the same lot, or even the same wafer, in order for sample testing to yield meaningful and relevant radiation performance data.

Since most of the ARC spaceflight projects are of the Class D (and lower) variety, and the mission duration is typically 30 days or less, the radiation challenges are usually not too severe. Hence, most of the ARC projects use either 100% COTS or nearly all COTS parts, along with a few non-COTS parts. The most widely used method at ARC to combat radiation issues is implemented via circuit design, along with some software mitigations in concert. In some instances, radiation tolerant or hardened parts are used as a last resort, especially when the stakeholders cannot agree on taking the risk with COTS parts.

Below are some of the typical ways that ARC utilizes, mostly at system or board level, to deal with the various types of radiation concerns in the Class D projects.

**Total Ionizing Dose (TID)**

Total ionizing dose causes parametric shifts in transistors that can lead to measurement errors or eventually part malfunction. Since TID is a cumulative effect, the dose is summed across all mission segments. Some COTS parts may not accumulate TID damage when powered off; hence, one of the ways ARC uses to minimize radiation effect is to only turn on functions as needed, which requires proper architectural choices to be made upfront to enable this capability via software control.

TID performance is an area where a COTS part made in a more advanced silicon process technology, (complementary metal–oxide–semiconductor (CMOS) or bipolar complementary metal–oxide–semiconductor (BiCMOS)), has an advantage over one made in an older technology node. This is because the transistor gate area and oxide thickness are lower in a newer technology, so there are less total number of trap sites for charges generated during a radiation event to get trapped. Hence, it is highly advisable to choose a functionally similar part from a newer technology node to carry out a circuit function, which is a key strategy used on ARC's spaceflight projects.

Typical TID for an ARC Class D nanosat mission is only about 5-10krad, which most newer COTS parts can inherently tolerate. In addition, Aluminum shielding can be effectively used over critical sections of a subsystem, and it is usually an available option though not used often.

**Enhanced Low Dose Rate Sensitivity (ELDRS)**

Silicon bipolar devices' radiation susceptibility can be dependent on radiation dose rate. Experiments have shown bipolar and BiCMOS parts can have higher parametric shifts due to very low dose rates seen in mission environment that are not captured by accelerated ground testing normally conducted for TID. The effect of ELDRS is cumulative throughout the entire mission. If a system is shown to have no bipolar or Bi-CMOS parts, there is no ELDRS radiation requirement.

Most bipolar devices fabricated using the newer semiconductor technologies do not have the ELDRS issue due to improvements in the wafer processing technologies; hence, they are preferentially selected by ARC projects over the older ones. In addition, the durations for most ARC Class D projects are not long enough to develop ELDRS issues.

**Displacement Damage Dose (DDD)**

Neutrons, protons, alpha particles, heavy ions, and very high-energy photons cause lattice displacement, or displacement damage. The damage associated with the collision between energetic particles and atoms within the crystal lattice is in the form of defects that can trap electrons and holes, which in turn causes parametric shifts, especially in the analog properties of transistors. This type of problem is particularly significant in bipolar transistors because they are dependent on minority carriers in the base regions, which leads to reduction in the transistor gain - the most critical analog circuit design parameter. Displacement damage is a cumulative effect, the dose is summed across all mission segments. Counterintuitively, higher doses over short time cause partial annealing of the damaged lattice, leading to a lower degree of damage than with the same total doses delivered in low intensity over a long time.

Bipolar transistors are inherently more radiation tolerant than CMOS because of the lack of $SiO_2$ (silicon dioxide) to silicon interface junction. If bipolar transistors are only used in digital circuits, the displacement damage is a much lesser concern. Again, due to the orbits and short duration of most ARC's Class D missions, this type of radiation damage is not a great concern; however, the use of bipolar transistors in critical analog circuits is carefully scrutinized while using them in digital circuits are more readily adopted.

**Single-Event Effects (SEE)**

There are two types of SEE induced failures and damages: soft errors (SEU, SEFI) and hard/permanent part damages (SEL, SEB, SEGR). Below are the ways regularly implemented for spaceflight projects at ARC to deal with the two categories of SEEs.

Soft errors (SEU, SEFI):

- The use of a watchdog timer circuit to monitor the performance of the microcontroller or on-board-computer. A reset will be triggered by the watchdog timer and executed when malfunctions have been detected to clear the soft errors and bring them back to the normal state of operation. Flash or MRAM memory are also options to prevent SEUs.
- Software protection methods can also be used, such as creating saved states of the system (implemented on the O/OREOS project) and software TMR (triple modular redundant registers) for critical data.
- EDAC and ECC SDRAM (error detection and correction): this type of function is usually implemented to detect and correct errors in the data storage on board or transmission down to Earth.

Hard errors (SEL, SEB, SEGR):

- SEL: Over-current/voltage monitoring circuits are used to sense the currents and voltages going into subsystems. If a SEE happens and the current and/or voltage limits in a subsystem are exceeded, it will get powered down via a hardware control mechanism for a short period of time (e.g., 20) and then powered back up. In addition, an interrupt signal is sent to the onboard computer or microcontroller each time. This power cycling is to prevent the subsystem from being latched up in a high current state and get permanently damaged. If the over current/voltage situation exists on repowering up, the process will be repeated for a few more times before the software control takes over and turns it off completely. When this happens, a malfunction message will be telemetered down to the ground station for further decisions, which may include turning the subsystem back on, perhaps with some changes in the operation via a software modification, to see if it can be salvaged. This has proven to be a very effective way to safeguard the hardware from permanent radiation damages in ARC's Class D missions.
- SEGR: Power MOSFET transistors are vulnerable to SEGR, which can lead to permanent damage of the parts. Due to the random nature of a SEGR occurrence, it is not a cumulative dose effect. A device must be powered on and operating for a SEGR to occur; thus, it is only a concern during mission segments when a subsystem is powered on. The strategy in implementing the SEL safeguard, by partitioning circuit functions into groups that can be individually power cycled, lends itself very useful by providing the ability to selectively turn them off when not needed to minimize chances of SEGR happening. Redundant transistors can also be used to ruggedize a COTS power MOSFET, assuming board

space is not a limitation. If it is mission critical, there is always the option of using a radiation tolerant or hardened power MOSFET instead. A bipolar power transistor may be a viable substitute in some cases if its own limitations (higher power consumption due to base drive current, ELDRS, thermal run-away) can be overcome.

- SEB: Power transistor and power diodes are vulnerable to SEB damage that can lead to permanent failure of the parts. Due to the random nature of a SEB occurrence, it is not a cumulative dose effect. A device must be powered on and operating for a SEB to occur; thus, it is only a concern during mission segments when a subsystem is powered on. Hence, selectively turning subsystems off when not in use, not only saves power, it also minimizes the chances of a SEB happening. Similarly, dealing with SEGR, redundancy can be used to ruggedize a COTS circuit. In addition, the same technique to deal with SEL can be used to prevent SEB problems.

#### 7.2.5 Center Best Practices

A list of Lessons Learned is included in Section 11. A list of best practices is outlined as follows:

**Best practices on parts level**

1. Strictly adhere to the Center policy to only purchase/acquire EEE parts from OCMs or their authorized distributors, and never go through any other third parties.
2. Visually inspect parts to look for signs of counterfeiting or defects (best effort only, without using any tools such as an x-ray machine) before putting them to use. There has not been a single confirmed case of counterfeited parts at ARC over the last 12 years, which is likely due to near-100% use of COTS parts that have very low rate of counterfeiting.
3. Whenever possible, always obtain CoC for EEE parts used in flight hardware, so that parts can be traceable to a specific manufacturer, part number, and lot number or lot trace code.
4. Select widely used COTS parts manufactured by major semiconductor OCMs, and always select the highest grade available.
5. For TID consideration, COTS parts fabricated in the newer CMOS/BiCMOS technology nodes are preferred over those from older technologies.
6. Reuse COTS parts that have established successful flight heritage.
7. Thoroughly review part datasheets to ensure the performance specifications meet project requirements under all mission environmental and operational conditions.
8. When derating parts, do not use a fixed factor for supply voltage, current or temperature. Always ensure that derating does not push the parts outside of the operational condition limits specified in the datasheets.

9. Look for COTS version of radiation tolerant parts since they offer some level of radiation assurance, which is better than none. The lead time and cost are also more reasonable than that of rad-hard MIL-SPEC parts.

**Best practices on circuit board level**

1. Obtain circuit models from manufacturers, and then thoroughly simulate the circuit design using a SPICE simulator tool, such as the one preferred by the Agency, Altium.
2. Diligently prototype key circuits before PCB-level integration with other circuits, which makes debugging and verification simpler and easier.
3. Peer review circuit design informally often and share lessons learned.
4. Make it a habit to reuse circuits after successful missions because flight heritage should be a strong consideration.
5. Strategically use rad-hard (where applicable) parts and/or redundancy to mitigate risks in items for single-point failures critical to mission success.
6. Take full advantage of the abundant availability and low-cost nature of COTS parts to build a large quantity of engineering development units (EDU) for each revision, so that concurrent engineering development effort for flight software, payload software, subsystem interface, form and fit, and system test procedures can get started early in the process. Furthermore, building several revisions of EDUs is efficient and affordable. This not only reduces risks in the system integration and qualification phases, it also shortens hardware development cycle times while, at the same time, improving the thoroughness and robustness of the flight hardware designs.

**Best practices on assembly level**

1. Modularize subsystems such that damages can be quarantined and minimized so partial mission success can be achieved. This will require separate power feeds and controllability for each modular block of circuits.
2. Utilize current sensing circuit to monitor current consumption in subsystems, so that over-current conditions due to radiation events can be shut down quickly (20-40ms) to prevent part damage. The technique can also be used to protect individual parts if so necessary.
3. Resetting or power cycling of subsystems can also be carried out via software, in conjunction with the monitoring hardware, to deal with soft errors caused by SEE radiation.
4. The use of COTS parts allows multiple revision of EDUs to be built efficiently and affordably. Hence, environmental testing and qualification can be started sooner, which is very helpful in discovering major issues early on, so that they can be dealt with sooner without causing significant impact to the schedule.

### 7.2.6 Center Proposed Recommendations

1. To reap the benefits of using COTS parts, the traditional way and philosophy of developing spaceflight hardware in NASA must change. A new set of reliability assurance steps appropriate for COTS parts that are complementary, rather than duplicative to those already performed by the manufacturers, needs to be developed so that they can also be used by missions higher than Class D. This can be a joint effort with some of the leaders in the semiconductor industry who are interested in developing hi-rel parts for space applications.
2. Not all COTS parts are created equally, so choosing parts made by electronics industry leaders makes good sense. These manufacturers have good quality control policies in place, and they stand behind their products. Most importantly, their products are very widely used with huge volumes in the commercial industry, which is the best testament for the quality of their products. Furthermore, they usually have very well established low DPPM (defective parts per million) numbers for their catalog parts.
3. For Class D and below projects, use COTS parts without additional MIL-SPEC/NASA screening or qualification, other than visual inspections (i.e., used straight out of the catalogs of the manufacturers). Build in robustness and reliability at the board and subsystem levels instead through solid design approaches, along with both hardware and software (H/W and S/W) mitigation techniques.
4. Design for radiation tolerance at board and subsystem level, not part level, by using strategic redundancy, over-current/voltage monitoring circuits, and other mitigations (H/W and S/W) through circuit designs.
5. Strategically using rad-hard (where applicable) parts in critical applications and/or using redundancy where it is resource-effective (e.g., cost, schedule, or space on the board/box).
6. Use commercial grade of rad-hard parts, if available, to allow savings in cost and lead-time as compared to using MIL-SPEC rad-hard parts. These parts do offer some level of radiation assurance, which is better than none.

## 7.3 NASA GRC's Current Practices on Use of COTS Parts for Spaceflight Systems

### 7.3.1 Center Programs and Projects and Use of COTS

The NASA GRC's main areas of expertise are in communications technology, propulsion, power, energy storage, and conversion, materials and structures, and physical sciences and biomedical technologies. GRC manages and/or partners on a variety of spaceflight programs and projects of all risk classifications A-D, as defined by NPR 8705.4 "Risk Classification for NASA Payloads," although in-house design and build projects are typically Class D or lower. Mission costs for these projects are on the order of up to ~$100M, with mission lifetime goals of 1 to 3 years. These in-house Class D or sub-Class D projects include technology demonstration missions, ISS payloads, and more recently, CubeSats.

### 7.3.2 Center Strategy of Use of COTS

Historically, GRC has implemented fairly traditional parts requirements on its projects; however, within the past decade, the use of COTS has become much more common due to declining availability of space-grade parts, shrinking project budgets, and increased confidence in the reliability of COTS parts. The standard approach at NASA GRC has been to set the EEE Parts grade level based on the project mission risk classification as defined by NPR 8705.4. Recent missions that GRC has been involved in that are classified as higher than Class D have been contractor insight/oversight, and higher-grade parts requirements are flowed down to the contractor and implemented as standard on these missions. However, with many of GRC's Class D and below missions, COTS parts have become, if not standard, at least accepted, and successfully flown.

Each project at GRC is required to develop a Parts Control Plan. This document can be standalone, but it is more commonly incorporated as a section in the Safety & Mission Assurance Plan (SMAP). S&MA, and therefore EEE Parts requirements, are tailorable based on the project's risk classification. GRC recognizes that it may not be practicable or necessary for Class D or CubeSat missions to require a complete set of EEE Parts Assurance Requirements.

### 7.3.3 Center Governing Parts Documents

GRC's overarching parts requirements are contained within GLPR 7120.5.30, "Space Assurance Requirements (SAR)." The SAR defines Safety and Mission Assurance (S&MA) requirements, including EEE Parts requirements, for projects that are classified under NPR 7120.5E, "NASA Space Flight Program and Project Management Requirements." The SAR EEE Parts requirements are derived from guidance in NPD 8730.2C NASA Parts Policy.

The SAR also flows down to several lower-level GRC documents. These documents include GLP-QER-8730.4, "EEE Parts Assurance," a process document for developing and implementing a EEE Parts control program; GLHB-QER-8730.1, "EEE and Mechanical Parts Management," a handbook that provides covering requirements, processes, testing, and procedures for the specification, selection, application, qualification, screening, and traceability of parts and assemblies used in flight hardware; and GLWI-QER-8730.6, "Design for Radiation," a work instruction detailing the process for defining radiation requirements and selecting parts to meet that mission environment.

Additionally, the document EEE-INST-002, "Instructions for EEE Parts Selection, Screening, Qualification, and Derating" is used extensively on GRC projects to determine project parts requirements.

Figure 7.3-1 shows the GRC flow down of EEE Parts documents.

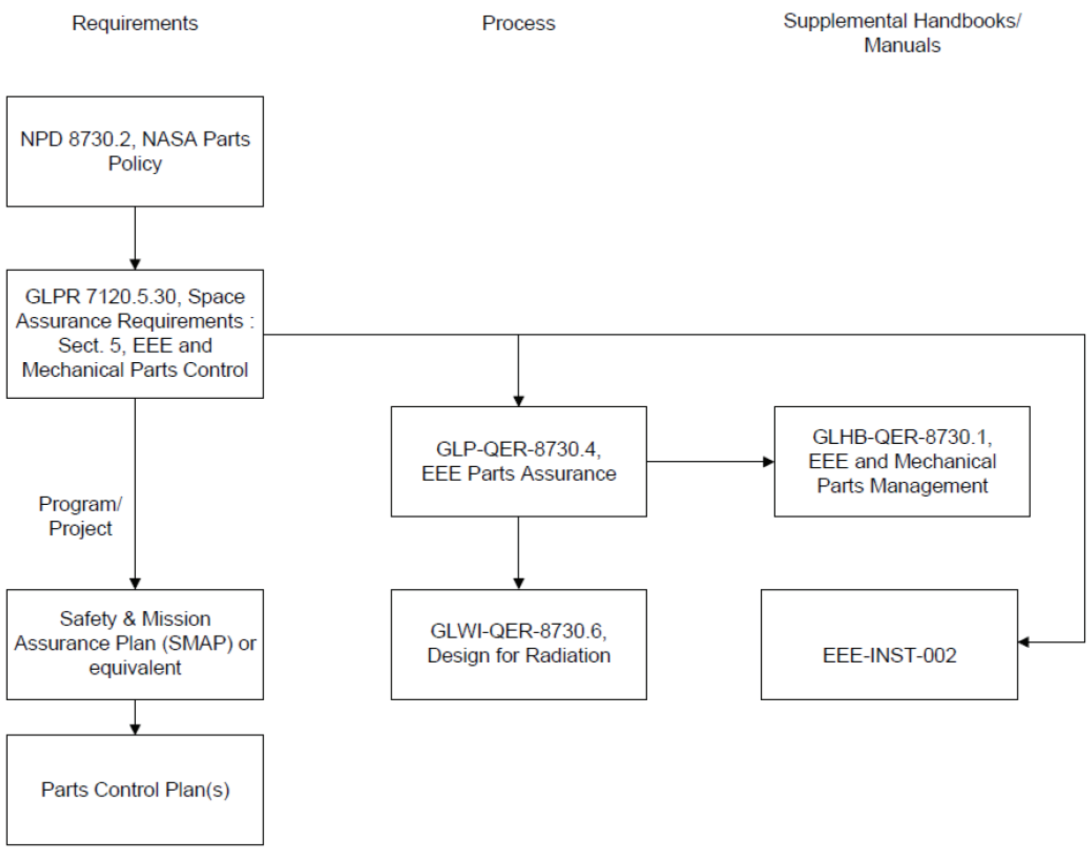



***Figure 7.3-1. GRC EEE Parts Documents***

### 7.3.4 Current Practices on COTS Selection, Evaluation, Screening and Qualification

<u>Parts Selection</u>

The project's Parts Control Plan, which is often a part of the SMAP, defines the part grade level requirements for the project. The SMAP often defines higher-grade parts as the project's standard, even in Class D missions; however, for Class D, COTS are often deemed acceptable for budget and/or schedule reasons, and the project may grant a deviation or waiver. It is recognized that COTS parts often have "unknown" risk.

Projects should use good engineering and design practices from the outset of the project. When selecting COTS parts, it is imperative to understand their applications and limitations so they can be used with maximum chance of success.

When possible, projects should choose COTS parts that have successful spaceflight heritage. When selecting parts, GRC requires procurement from the manufacturer or manufacturer's authorized distributors to minimize the chance of purchasing counterfeit parts. If neither of those options is available, a process requiring GRC approval may be used, after taking steps to investigate the independent distributor's compliance verification process, obtain certificates of conformance and supply chain traceability, and verify parts compliance through visual inspection, electrical testing, and destructive and nondestructive physical analysis.

Projects are required to maintain a parts list. For COTS parts, the information required to be tracked on the parts lists includes manufacturer's part number, part name or brief description, manufacturer name, quantity used, and drawing number and name of the assembly, subassembly, or printed circuit board (PCB) where the part is used. Since COTS assemblies often do not contain detailed parts lists, the assembly may be listed as a single line item on the project parts list. GIDEP and NASA Advisory searches are run against the parts lists on a recurring basis to identify any issues that have been discovered with parts that have been used in the project design.

COTS parts may become obsolete more rapidly than traditional parts used in spaceflight projects. Projects need to consider parts availability throughout the project life cycle when selecting parts. For projects building an engineering unit and a flight unit, parts should be procured at the same time to the maximum extent possible to ensure spares and reduce the chance of lot-to-lot variation.

Parts Evaluation

Parts risks are evaluated at the project level through the NASA 5x5 risk matrix process. The risks of using COTS parts is usually mitigated through testing or analysis. For some lower budget projects, the risk may be accepted.

Upon receipt, parts are required to undergo a receiving visual inspection to examine for any obvious external defects, verify any required certifications are provided, and to ensure that the correct number of parts has been received and parts markings do not look suspect. For unfamiliar parts, functional or parametric testing should be performed by the engineering team as early as possible to ensure parts meet design needs.

Parts are required to be derated to reduce the risk of failures, per either the derating requirements of EEE-INST-002 or another project-approved derating plan. Additionally, common practice is for a derating analysis to be performed during design activities, ensuring that parts meet derating margins under worst-case conditions. Some projects also require a reliability analysis, and for COTS parts this often must rely on data acquired from the manufacturer.

Parts should also be visually inspected prior to assembly into flight systems or subsystems to ensure they are free of debris, defects, or manufacturing faults that would interfere with their form, fit, and function. Testing should also occur at the board or sub-assembly level prior to integration into the full system to ensure performance is as expected.

Parts Screening and Qualification

GRC allows for COTS parts to be used for higher-reliability applications if they are subjected to upgrade screening at the piece part level. EEE-INST-002 is used to determine screening requirements, or other requirements can be used with project approval. Limited upgrade screening can be useful; however, if this process is widely used, upgrade screening may significantly increase project costs. Particle impact noise detection (PIND) is only required for COTS parts if used in critical applications.

For projects with less-stringent parts requirements, COTS are subjected to environmental screening, including thermal cycling, burn-in, and vibration testing at the board or assembly level. Thermal cycling is performed for a minimum of ten cycles, with the extreme temperatures within ± 10 ºC of the worst-case temperature expected during the mission. Burn-in is required for a minimum of 100 hours before flight with no failures. If any failures are experienced, the burn-in time is restarted from zero. Random vibration testing is performed in three axes to the worst cast test levels and durations specified in NASA-STD-7001, “Payload Vibroacoustic Test Criteria.”

Typically, it is standard to require Level 1 parts in safety critical applications, no matter the risk classification level of the project. COTS parts may be used in these applications with proper design, a screening and qualification plan, and Engineering Review Board (ERB) approval.

Radiation Effects Evaluation on COTS

At the start of a project, the mission radiation environment and radiation hardness requirements are defined. To the extent it is possible, the preference is to select parts with appropriate radiation hardness or radiation tolerance levels in the design. Where COTS parts are used; however, the next step is to try to mitigate the risk through design and analysis.

As GRC does not have a large expertise in radiation effects, historical data or other NASA Centers may be consulted during development. For TID, shielding may be used to reduce the expected total dose. Safety-critical circuits must be designed such that they will not fail in the event of SEE or are capable of recovery if SEE occurs. SEE soft errors may be mitigated through design practices such as watchdog timers, TMR, and error detection and correction (EDAC). De-rating practices are used to try to mitigate destructive events such as SEB and SEGR. Another option is to power on circuits only when necessary to minimize their susceptibility. Displacement damage is rarely of concern in GRC missions.

Generally, GRC projects do not have a sufficient budget to perform radiation testing on parts. Occasionally, parts used in critical applications may be radiation tested, but this testing is performed on a select few parts and usually in conjunction with another NASA program to share resources.

### 7.3.5 Center Best Practices

A list of best practices is outlined as follows:

**Best practices on parts level**

1. Procure parts only from manufacturer or manufacturer's authorized distributors. When possible, also try to procure parts whose manufacturers have known flight heritage and/or reliable processes.
2. Know the application rated operating environments of parts planned for usage within the circuits and thoroughly understand the datasheets to ensure maximum chance of successful usage. Poor engineering design cannot be overcome, no matter how reliable the parts.
3. De-rate parts per manufacturers' recommendations and/or NASA standards, such as EEE-INST-002.
4. Run GIDEP searches on parts that have been procured, both prior to purchasing parts and throughout the project life cycle.

**Best practices on circuit board level**

1. Use good workmanship practices when assembling boards. Conformal coat boards after assembly.
2. Whenever possible, build and test breadboard/prototype and engineering units before building the final design. This practice allows issues to be discovered earlier in the process, when it is less costly to correct them.

**Good/best practices on assembly level**

1. Perform environmental testing to mitigate risk, including thermal cycling, burn-in, and vibration testing.
2. Ruggedize assemblies where possible. Examples of measures to ruggedize may include staking parts, securing wire harnessing, and securing connectors with epoxy.
3. Although COTS missions are often lower budget and need to have tailored requirements to ensure costs do not rise, some level of configuration control should be maintained. Maintain detailed records. Store parts and assemblies in a controlled humidity environment and use proper ESD handling practices to minimize the chance of damage.

**Lessons learned**

No specific lessons learned; have been incorporated into the best practices section.

### 7.3.6 Center Proposed Recommendations

1. Thoroughly understand the application and environment that parts are being used in, and select and de-rate parts appropriately in designs.
2. For Class D missions, follow proven development and testing steps, such as creating breadboard and engineering-level hardware to prove out functionality, and subjecting hardware to an environmental test campaign.
3. Identify and document COTS parts that have been used successfully in past projects to provide proven data and confidence for future projects.

## 7.4 NASA GSFC's Current Practices on Use of COTS Parts for Spaceflight Systems

### 7.4.1 Center Programs and Projects

The NASA GSFC A, B, C, and D missions that are required to follow NPR 7120.5 *"NASA Space Flight Program and Project Management Requirements",* and sub class D missions: 7120.8-class and "do no harm" space missions, follow guidance per Goddard Procedural Requirements (GPR) 8705.4, "Risk Classification Guidelines and Risk-Based SMA Practices for GSFC Payloads and Systems". Sounding rocket payloads, and balloon payloads that are most often governed by NPR 7120.8 *"NASA Research and Technology Program and Project Management Requirements* generally use COTS parts without additional MIL-SPEC/NASA screening.

GSFC hosts both in-house developed and built instruments and spacecraft, and awards and manages contracts for out-of-house developed and built instruments and hardware. As such, it is important to have a well-defined set of EEE parts requirements that both in house and out of house flight hardware developers can reference and follow. While these requirements are in theory flowed down from guidance in Agency and GSFC level documents NPR 8705.4, NASA-STD-8739.10, and GPR 8705.4, in practice, minimum parts screening level has been typically set at Level 2 based on tradition and fear that lower screening levels will result in mission failure, and the misinterpretation that screening level is a major contributor to mission reliability. Only in a few more recent cases have the screening levels been set to Level 3 or COTS with limited specialized screening based on absolutely prohibitive resource constraints. The screening levels are set in the Safety and Mission Assurance planning process and are established for a project as requirements in the project Mission Assurance Requirements (MAR) document. The requirement then is flowed down into project-specific Parts Control Plan documents, and the specific requirements at the part level are taken from the GSFC Parts Branch document EEE-INST-002: "*Instructions for EEE Parts Selection, Screening, Qualification, and Derating."*

COTS Parts are allowed for use on all mission classes; however, the perception that parts screening is a primary reliability driver ultimately steers most projects towards Level 2, with many drawn to use Level 1 parts extensively, depending on the preferences of the project design engineers, parts engineers, and systems engineers. The more severe mission environments and lifetimes tends to necessitate higher radiation tolerance/performance, which is often unavailable, or unknown with COTS parts (including NASA-screened COTS parts that fully meet Agency and Center requirements), as with many MIL-SPEC parts. The increased screening and qualification requirements in place to align with Center and Agency requirements significantly increase the costs associated with using COTS parts. The lower tolerance for risk tends to avoid "unknown" EEE parts, and the programmatic and schedule risks that come with screening and qualifying a COTS part for flight. As a result, the higher class missions tend to favor electronics designs based more heavily on standard "MIL-SPEC" parts. COTS parts are allowed, but tend only to be used when necessary to meet an electrical performance need or prohibitive delivery schedule. With the addition of screening and qualification testing, and often a customized source control drawing and even part number, these parts are manufactured as "commercial" but are far from pure COTS as defined in this study, and are NASA-screened COTS as defined earlier.

### 7.4.2 Center Strategy of Use of COTS

The GSFC strategy towards using COTS varies with the mission classification and defining project documents. In general, Class A, B, and C missions tend to favor heavier use of standard "MIL-SPEC" parts. There are some commonly recurring COTS parts used in these designs, typically for a desired electrical performance, and which have typically successfully passed thorough screening, qualification, and radiation performance testing campaigns on prior missions. New procurements of these parts typically require at least screening tests such as burn-in, and often qualification tests, unless recent lot qualification data are available. As electrical performance requirements grow on newer missions, these projects may also look to use newer COTS parts, which would typically require a more extensive screening, qualification, and radiation testing campaign, to meet the requirements selected by the project. These testing campaign costs are significant, so the candidate parts tend to be ones with a unique performance, or successful flight history on a lower class mission.

Class D missions tend to be more of a mixed bag between MIL-SPEC and COTS parts, depending on the individual subsystem. Typical spaceflight subsystems such as power, housekeeping, communication, may be derived from "heritage" spaceflight designs that use traditional MIL-SPEC parts. These subsystems also tend to be single string, or limited fault tolerance, so designs often favor "higher grade" MIL-SPEC parts. However, the science and data processing subsystems of class D missions tend to have more cutting edge performance requirements, which necessitates a higher focus towards COTS parts and innovation. The Class D risk posture tends to allow for relaxed screening and qualification testing requirements at the piece part level when accepted by some projects, so use of COTS parts in these subsystems is often closer to a true "COTS" application. Note that per NASA-STD-8739.10, Class D projects may use COTS parts with no additional screening, so the current practice is to greatly exceed the recommended level of screening.

Sub Class D missions (at GSFC, denoted 7120.8 and "do no harm", as applicable) tend to heavily use COTS, even for their more standard subsystems like power, housekeeping, and communication. The manufacturer lead times, parts costs, and physical part sizes of traditional "MIL-SPEC" parts tends to preclude them from meeting sub class D mission needs. Sub-D missions are generally shorter in life and have a higher acceptance of technical risk, although even with extensive use of COTS, GSFC is not experiencing any significant difference in reliability or lifetime between systems built with screened parts (including MIL-SPEC parts) and systems built with unscreened parts (or more precisely, commercially-screened) COTS parts. Note that fault-tolerance and proper derating play strongly into these results and they do not necessarily imply that the COTS parts performed on their own equivalently to MIL-SPEC counterparts. Smart use of COTS parts in these mission types provides a balance in overall risk posture. Lifetime of parts is generally a function of derating, robust system-level testing, and good design practices, as opposed to part-level screening and qualification.

### 7.4.3 Center Governing Parts Documents

In addition to the NPR and GPR documents, Projects will establish a unique Mission Assurance Requirements Document, which will define the required screening level of parts for the mission, or potentially identify different screening requirements by subsystem. The MAR will typically also call for a detailed Parts control Plan Document, which will describe how the EEE parts are selected, reviewed, and approved to meet the required screening requirements. The documents used, as described in early sections, are NPR 8705.4, NASA-STD-8739.10, GPR 8705.4, and the branch document, EEE-INST-002. For the most part, sub-D missions follow only GPR 8705.4.

### 7.4.4 Current Practices on COTS Selection, Evaluation, Screening and Qualification

#### 7.4.4.1 COTS Parts Selection, Evaluation, Screening and Qualification

The EEE-INST-002 describes the requirements for screening, and qualification tests, and derated operating condition requirements. INST defines three separate screening levels of EEE parts Level 1 being the highest, then Level 2, then Level 3. Although terms such as "grade", "reliability level", and "quality level" are used, none of those terms are accurate, since the requirements have nothing to do with reliability, different manufacturing processes or equipment, or different levels of quality -they are all about screening and qualification. Per NPR 8705.4 and NASA-STD-8739.10, the screening levels generally align with mission Class A tying to Level 1, B to Level 2, etc. EEE-INST-002 does not currently include Level 4 (pure COTS) as specified in 8739.10, but highly constrained projects may use a "Level 4" approach.

Level 1 requirements tend to align closest with the highest classes of MIL-SPEC parts available- class V, K, JANS, etc. In general, for each part type, Level 1 requirements include both screening and sample based lot qualification tests for COTS/non-MIL-SPEC parts. There is an increased emphasis on developing Source Control Drawings, and documented testing flows for Level 1.

Level 2 requirements tend to align closest with the second highest classes of MIL-SPEC parts available (Class Q, Class H, JANTXV). In general, for each part type, Level 2 requirements include both screening and sample based lot qualification tests for COTS/non mil parts, although sample sizes and burn in duration are slightly reduced from Level 1.

Level 3 requirements also tend to align with MIL specification, allowing lower grades like Class M, or /883 parts. These parts and classes tend to be associated with older parts/specs, which are occasionally used in new designs, but not widespread. In general, Level 3 defines screening requirements, but does not include qualification requirements. This provides a perception that Level 3 applies better to short duration missions, like many Class D, where infant mortality is important, but long-term end of life/wear out mechanisms are less of a concern. However, process controls have improved greatly in many commercial product lines with complete automation, and variability is far less common than in the past. As a result, there has been a drastic reduction in infant mortality failures compared to decades ago. Hence, there has been no noted reduction in reliability as a function of screening level, qualification, or MIL-SPEC vs COTS in general, when in typical applications (not necessarily at the piece part level). The notable exception to the lack of qualification for Level 3 is in the PEM section, which requires sample-based lot qualification tests even for Level 3. COTS encompasses more than PEMS, but typically, COTS PEMS offer the most performance advantages over MIL-SPEC and are typically what is meant when discussing COTS. This way, the existing requirements of EEE-INST-002 are not well-suited for COTS adoption into Class D missions, and additional language and evaluation criteria are being added to project MARs, and Parts Control Board discussions to effectively evaluate COTS parts for Class D applications.

#### 7.4.4.2 Radiation Effects Evaluation on COTS

Class A, B, and C missions tend to take a very complete approach to evaluating radiation effects on COTS, which includes total dose testing, ELDRs, and SEEs testing. Test data would be required to verify radiation tolerance, and specific SET may be required to calculate upset rates to verify that science data requirements could be met. At GSFC, radiation tolerant design of circuits is often supplanted by piece-parts focus on radiation hardness because it tends to be easier, if affordable, to mitigate radiation at the part level.

Class D missions also evaluate radiation effects on their COTS parts; however, they have a limited budget to conduct additional testing. EEE parts and electronics designs are reviewed to identify the most susceptible candidates, and then either find suitable replacement parts (often a different COTS, with known better radiation performance), conduct radiation testing, or take a deeper look at the overall system architecture to see if overall requirements can be met. For example, if a part is susceptible to latchups, can watchdog circuits be added to reset a latched part? If a severe worst-case rate of latchups and resets occurred, would mission science objectives be attainable? A latchup current limiter may be added to any part with a known or suspected high-current event.

Sub-D missions are generally shorter in length, therefore TID testing is not a significant concern. Sub-D missions typically do not have the funds to do SEE tests. Parts are selected based on in-family SEE performance, past history, and design mitigation features may be added to protect parts that have unknown radiation tolerance.

### 7.4.5 Center Best Practices

A list of Lessons Learned is included in Section 11. A list of best practices is outlined as follows:

**Best practices on parts level**

1. The most perceptive approach at catching infant mortality is burn-in screening, although caution should be used that undue risk is not taken for the board as a whole. There have been recent experiences where burn-in was performed on a COTS board to an arbitrarily-defined temperature level, damaging the board because of a lack of understanding of the allowable stress level for the COTS board and lack of clarity in the documentation.
2. COTS electrical performance occasionally falls out of specification at high and low temperatures. Verify critical parameters are met for all operating temperatures. COTS parts in general have tighter temperature ranges and less inherent derating than MIL-SPEC parts. Unfortunately, the misunderstanding of this has been cause of misuse of COTS. Likewise, it may result in the selection of a COTS part over a MIL-SPEC part under the misperception that the COTS part has a much higher rating (when it actually does not).
3. Ensure that proper parts stress and derating is performed on any parts used, but understand that for any extended, reliable use with stringent performance requirements, COTS parts in general may need even more derating than guidelines recommend.
4. This is where accelerated testing can be done. It is used it to identify manufacturing weaknesses and defects, not to justify a part will survive a specific application. Accelerated testing is an “over test” by design/intention to be perceptive. Reducing acceleration factor reduces perceptibility. Failing an accelerated test does not indicate that a part would fail in normal operation.
5. It should be noted that most forms of accelerated testing do not predict reliability well for appropriately derated parts, because these parts will not generally reach the stress level required to activate the degradation or failure mechanism.

**Best practices on circuit board level**

1. At board level testing it is critically important to achieve a significant number of powered run time hours. At the board level, you have less ability to do accelerated testing, but test under flight like conditions as much as possible. If you are skipping piece part testing and burn-in, this is where you want to find your failures and replace them, not at later assembly levels.

2. Ambient thermal testing on an EDU/ETU, or the flight unit in highly constrained missions. Ambient thermal testing is more economical to implement than thermal vacuum testing, and can provide immediate first-order feedback to the project regarding interface timing (i.e., verifies part timing over temperature) and can uncover major design deficiencies.
3. In designs that support a military/space equivalent part in place of a COTS part, consider the use of a dual-footprint on the circuit board in case the board will be used in multiple applications, subject to different parts requirements.
4. Thorough thermal and structural engineering, ample margins, and a test campaign that verifies the design models and margin. This practice provides a safe operational environment for all parts.
5. Designing for manufacturability is a good practice for circuit board design. Special considerations may be needed for COTS parts (including NASA-screened COTS parts that meet current Agency requirements), which may have different features or require different assembly process than standard military/space parts.
6. If using a COTS part that includes a high speed interface (i.e., > 200Mbps), it may be advised to conduct a signal integrity analysis to insure significant margin exists, as internal timing of a COTS part is sometimes not trusted unless verified through a specialized screening process.
7. If using a COTS part that has a power input that is very sensitive to fluctuations (e.g., $\pm$3%), it may be advised to perform a power integrity analysis to ensure significant margin exists, as the functional sensitivity may vary from part-to-part.

**Best practices on assembly level**

1. Ideally, assembly level testing verification should be performed as part of a combined effort with lower level testing verification practices.
2. Be prepared to respond to part failures that may occur when testing at the assembly level. Having spare assemblies or boards on hand can mitigate schedule impacts from part failures, and help with troubleshooting.
3. Do not over-test at this stage. Test as you fly.
4. Plan a test campaign that will validate all assembly functionality, and will verify all design margins predicted from analyses and models.
5. Accumulate at least 1,000 hours of powered test time, with the last 200 hours being failure free.
6. Conducting tests at realistic full load, especially focused on any use of unscreened COTS parts.

### 7.4.6 Center Proposed Recommendations

1. Education is required for engineers and project teams concerning the current meaning of parts requirements. Avoid use of the term “grade’, “reliability level”, or

"quality level", unless you are within a particular manufacturer's own line, in which there are differences in manufacturing processes or equipment, or different established and measured failure rates.

2. Avoid using the term "failure" to represent a nonconformance in a part, an out-of-spec condition, or a failure or anomaly in an accelerated test. The part may function at normal application stress levels, and last for years, even if nonconforming or failing a life test. Additionally, when capturing failure data of any class of part, be sure to delineate between parts that failed on their own merits, and parts that were damaged by the circuits or radiation, and be sure to capture derating information.
    a. Use the term failure to represent a condition in which the part no longer performs its function in the given application within the part's rating. (open, short, cannot write to SRAM, etc.)
    b. Use the term nonconformance or "out-of-spec" condition to represent parts that perform the function, but otherwise do not meet the ancillary part specifications.
    c. Note: Parts that fail at or near maximum rated values but above appropriate derated conditions may be denoted as failures. However, caution should be considered about the interpretation of such failures as they pertain to part reliability.
3. Use more conservative derating for a typical COTS part in comparison to its MIL-SPEC counterpart to achieve comparable reliability, notwithstanding other pertinent attributes of either type of part. Note that the primary drivers for part reliability in a circuit application are derating and radiation tolerance in the circuit and that MIL-SPEC parts have an inherent derating that does not occur in COTS parts.
4. Radiation-tolerant circuit design should supersede individual part radiation hardness efforts, whether using COTS or MIL-SPEC parts. For COTS parts, plan on more extensive radiation mitigations than with MIL-SPEC counterparts, as there should be a greater level of expectation that radiation will cause a problem. Note that even rad hard MIL-SPEC parts have failed due to radiation hits in poor designs, so avoid assumptions that the use of MIL-SPEC parts allows for inattention to radiation.
5. Do not expect existing approaches for inferring reliability of EEE parts to apply directly to most COTS parts or that appropriate approaches for establishing reliability at the piece part level exist today. Use circuit level fault-tolerant design and testing (with proper derating practices and attention to the radiation environment) to assure reliability of a part in an application (this applies to the use of COTS or MIL-SPEC parts as part reliability does little to assure system reliability). Note that reliability is not "built-in" to parts, whether MIL-SPEC or COTS, or parts grades in between, and in particular, reliability at the part level for MIL-SPEC parts is a highly-conservative, qualitative by-product of known

historical performance, strict controls on variability, and verification of failure rates at high stress levels after the fact.

6. When using large quantities of COTS parts in critical applications, it is good practice, when affordable, to (1) procure parts from several lot date codes to make a determination of variability for key parameters through part-level testing if the most important attribute of the parts is that they are similar to previous versions of the parts, or (2) procure all parts from the same lot date code if the only important attribute is that all parts in the application are minimally variable among those in the same application.
7. Avoid any expectation that COTS parts in general can tolerate the environmental ranges that equivalent MIL-SPEC parts can handle. Always plan on extensive testing when using COTS parts in applications involving extreme temperature conditions.

## 7.5 NASA JPL's Current Practices on Use of COTS Parts for Spaceflight Systems

### 7.5.1 Center Programs and Projects and Use of COTS

The NASA JPL missions range from flagship to technical demonstrations.

Typical flagship missions are Mars2020 and Europa Clipper. Category 1, Risk classification A, high cost (>$1B), long duration. Use of COTS in this type of mission is limited to parts that are not available in Space or Mil grades. The COTS parts will be up-screened for reliability and radiation in this type of mission.

MAIA is an example of a Category 3, risk class C mission. Low cost, short duration. COTS parts are used with screening for critical parts.

EMIT and DSOC are Category 3 risk class C and D missions. COTS are used for cost and availability reasons.

MarCO is a CubeSat mission that flew in 2018. COTS were used extensively; selected and documented but without screening or qualification. The CubeSats performed well with minor glitches that were recoverable with work-arounds.

### 7.5.2 Center Strategy of Use of COTS

JPL strategy for use of COTS is mission dependent, and based on minimizing risk. COTS use on flagship missions (Category 1, Risk Class A) is limited and any COTS used will be subjected to qualification if possible, DPA, and targeted screening.

### 7.5.3 Center Governing Parts Documents

When COTS are required, it is important to get as much information as possible from manufacturer's reliability and radiation data. Qualification and screening are desirable, but may be tailored to maximize value, and may be waived for missions with high-risk tolerance.

EEE-INST-002, JPL Parts Engineering Technical Standard (DocID 78157) and PEMs guideline (DocID 62212) are the governing documents.

### 7.5.4 Current Practices on COTS Selection, Evaluation, Screening and Qualification

#### 7.5.4.1 COTS Parts Selection, Evaluation, Screening and Qualification

COTS are typically selected by designers based on performance specified on datasheets. This often includes guidance from Parts Engineering. Higher reliability grade versions are selected when available. Most typical COTS are plastic (PEMS), acquired from OCMs or authorized distributors. Certificate of Conformance is typically required for flight parts. Evaluation, screening and qualification varies by mission. Project risk evaluation is performed at part, circuit and assembly level depending on mission risk tolerance.

#### 7.5.4.2 Radiation Effects Evaluation on COTS

When COTS are selected for project use, radiation effects are evaluated according to mission requirements. Analysis alone may be sufficient for intrinsically rad-tolerant parts in low radiation (5-10 krad) missions. Critical parts will be tested, which may include TID high and low dose rate, MIL-STD-883 Method 1019 testing, RLAT, and ELDRS testing. SEE testing includes SEE Picosecond Laser, Heavy Ion and Proton testing per ASTM F1192 and EIA/JESD 57, and Cf-252 screening.

### 7.5.5 Center Best Practices

A list of Lessons Learned is included in Section 11. A list of best practices is outlined as follows:

**Best practices on parts level**

1. Datasheet and manufacturer's reliability data review.
2. DPA, single lot buy (when possible), up-screen by x-ray, burn-in, life test.
3. Qualification is recommended for mission critical COTS.
4. Purchase from OCMs or authorized distributors.
5. Obtain CoC for flight parts.
6. Select widely used parts from major manufacturers, at highest available reliability grade.
7. Parts should be inspected and accepted by quality assurance.
8. Follow derating requirements.

**Best practices on circuit board level**

1. Identify critical components and use space grade parts if possible.
2. COTS in critical applications require additional attention including qualification and screening.

### 7.5.6 Center Proposed Recommendations

1. Buy parts from OCMs and authorized distributers.
2. Circuit design margins need to account for greater parametric variation in COTS compared to space grade parts.
3. Lot specific screening and life test is recommended for high reliability applications.
4. For critical application parts, perform screening and life test with interim measurements and initial and end-point, to quantify parametric drift.
5. Storage, soldering profile and cleaning must be reviewed against manufacturer recommendations to avoid degradation.
6. Use circuit mitigation (watchdog circuits) and power cycling to limit functional disruption during nondestructive radiation upsets, and reduce or eliminate the effects of potentially destructive upsets such as micro-latchup.

## 7.6 NASA JSC's Current Practices on Use of COTS Parts for Spaceflight Systems

### 7.6.1 Center Programs and Projects and Center Strategy of Use of COTS

The NASA JSC is home to most of NASA's contracted manned spaceflight programs. It is the lead Center for the ISS, MPCV, and Gateway Programs, and was the lead Center for the Space Shuttle Program (SSP). These programs involve multi-billion dollar contracts over many years. They involve prime and sub-contractors who perform most of the design, with NASA engineering performing both insight and oversight roles. In each of these programs, the prime contractor creates an EEE Parts plan as a Type 1 deliverable, meaning that NASA approval is required. Usually these plans are created with NASA EEE Parts involvement. These programs are "traditional" in the sense that they identify Grades of parts and associate the required Grade with the criticality of the application. Though the plans are unique to each program and vary in their details, the part grades generally follow the familiar Grade 1, 2, 3 that are common to GSFC, MSFC, and others. Grade 1 parts, military "Class S," are required for those applications where failure or failures would result in loss of life or loss of the vehicle. Grade 2 parts, military "Class B," are required for those applications where failure would result in human injury or significant loss of mission objectives.

JSC is also home to the Commercial Orbital Transportation Services Program (usually termed COTS, but referred to in this report as "Commercial Cargo" to avoid confusion with COTS parts) and is co-lead of the CCP. These programs are implemented as service contracts. Whereas the government eventually takes ownership of ISS, MPCV, SSP, and Gateway vehicles, it buys a service using contractor-owned vehicles in the Commercial Cargo Program and CCP. As such, NASA's role is limited to that of ensuring the safety of the crew, the ISS, and the cargo being transported. In the case of the Commercial Cargo Program, there are essentially no EEE requirements placed on the contracts, except for those parts that directly interface with the ISS Program. The ISS Program deliberately chose not to require the use of traditional EEE parts. This approach has paid off, as the Commercial Cargo Program has been very successful.

There have been no significant failures of avionics in any mission. The CCP required partners to "meet the intent of" a traditional parts program. The approaches taken by the two contractors were very different, with one taking a "traditional" approach, and the other baselining the use of COTS parts. NASA chose to accept both approaches, though the COTS approach identified as involving an elevated level of risk.

In addition to these major projects, JSC has produced a significant amount of government-furnished equipment (GFE) that operates in or on ISS, SSP, MPCV, and Gateway, and is transported to ISS via Commercial Cargo or Commercial Crew. This hardware is designed and built by JSC civil servant and contractor personnel without involvement by the program prime contractor. GFE is almost never necessary to the functioning of the vehicle. It may be exercise equipment, video inspection, crew support, contingency, or other supporting functions.

### 7.6.2 Center Strategy of Use of COTS

There is no JSC-wide strategy for the use of COTS. As mentioned above, each program sets its own COTS requirements. Those requirements are binding on the applicable prime contractor and its sub-contractors. They are not applicable to GFE projects.

It is in the GFE projects where the programs are usually receptive to the use of unscreened COTS. For GFE projects, JSC follows a range of strategies. Some projects, such as the Laser Air Monitor (LAM) on MPCV, EVA Battery Operations Terminal (EBOT) on ISS, and the Exploration Extra-Vehicular Mobility Unit (xEMU) require the use of traditional parts. Any COTS parts are required to undergo full MIL-SPEC/NASA screening and qualification. However, most GFE projects follow the EDCPAP, which is described in Section 7.6.4.1. This process allows for and the use of COTS parts without additional MIL-SPEC/NASA screening or qualification. In their place are verification that the part manufacturers follow best practices that ensure defect-free parts.

### 7.6.3 Center Governing Parts Documents

JPD5320.6, "Implementation of NASA's EEE Parts Policy" is the JSC document that governs EEE Parts. It assigns responsibilities to EEE groups in the Safety and Mission Assurance Directorate and the Engineering Directorate. Among those is the responsibility to, "Provide primary support to projects during the requirements definition phase to ensure the parts requirements are commensurate with the mission objectives." This gives projects, working with SMA and Engineering EEE personnel, wide range in setting requirements. No strict traditional Criticality/Part Grade association is made.

### 7.6.4 Current Practices on COTS Selection, Evaluation, Screening and Qualification

#### 7.6.4.1 COTS Parts Selection, Evaluation, Screening and Qualification

**Traditional COTS Processes**

Contractor-based programs such as ISS and MPCV allow the use of COTS parts. The ISS EEE Plan, SSP-30312, and the MPCV EEE Plan, CEV-T-027000, both include screening and qualification requirements for COTS, i.e. NASA-screened COTS. Though the details of those requirements vary program-to-program, they are similar to, and often based on, EEE-INST-002. There has been relatively little usage of COTS parts in such programs. The MPCV flight computer and network interface card, discussed in A.5 are notable examples of the use of COTS parts.

**EDCPAP**

JSC has an alternative parts plan that it follows for most GFE projects. This is the Engineering Directorate Certified Parts Approval Process, or EDCPAP. This process starts with the requirement that every part making up flight hardware should be defect-free and should be qualified to the limits of its datasheet. EDCPAP seeks to meet these requirements by gaining insight into the manufacturer's processes. If evidence that the manufacturer is following best practices for process control, screening, defect elimination, periodic testing for reliability monitoring, qualification, process change re-qualification, etc., then the part requirements are met. If such information cannot be obtained, then the "traditional" approach of part-level MIL-SPEC/NASA screening and qualification may be employed.

Another variable is assembly-level testing. All GFE flight hardware undergoes acceptance testing at the box-level, which includes thermal cycling and random vibration testing. It often also includes burn-in and may include thermal vac. Some projects are content to let these tests take the place of part-level MIL-SPEC/NASA screening for those parts where manufacturer data is not available. The hot and cold soak temperatures during thermal cycle testing bound the temperature extremes predicted for the hardware during the mission, usually with a 10 °C margin at both hot and cold.

A weak point of EDCPAP is that it does not place strict requirements on what data is sufficient to satisfy the part requirements. While it is common for a manufacturer to state in their publicly published quality materials that they follow best practices including those listed above, it is not clear whether such uncorroborated evidence is adequate. It seems reasonable that the verification requirements for a COTS part used in a life-critical system should be more stringent than for a part used in a non-critical flight experiment. It is for this reason that stakeholders from all relevant organizations (Program office, Crew office, Mission Operations, SMA, Engineering, etc.) agree to EEE requirements.

Several thousand parts have received EDCPAP evaluation since the process's creation in 2000. There have been no confirmed part failures in flight hardware attributed to manufacturing defects.

#### 7.6.4.2 Radiation Effects Evaluation on COTS

As with part selection requirements, radiation effects requirements are specific to each project. In addition, no distinction is made based on the pedigree or grade of part. All parts for a given project must meet the radiation requirements for that project. If the part has existing test data that meets project requirements, then no testing is required. If no test data or insufficient test data exists then part-level or board-level radiation testing will be performed.

### 7.6.5 Center Best Practices

A list of best practices is outlined as follows:

**Best practices on parts level**

As described above, EDCPAP seeks to verify that part manufacturers follow best practices that result in parts that are free of defects and exhibit high part-to-part and lot-to-lot homogeneity. What follows is a list of some of those best practices. This is not a comprehensive list. AEC-Q004, "Zero Defects Guideline" goes into much more detail and contains many more points.

1. The OCM designs parts with an eye toward manufacturability, testability and field reliability, and operating life. Tools that facilitate this are the Design FMEA and Process FMEA.
2. Parts are manufactured on automated, high-volume production lines with minimal human operation. Parts not built on such lines should not benefit from assumptions about sameness part-to-part or lot-to-lot and are candidates for part-level screening and qualification.
3. The OCM understands and documents the entire manufacturing process and the impact and sensitivity of each step on product characteristics and quality. A robust manufacturing plan allows for step-by-step verification and assurance that the in-process work meets standards and is acceptable to move to the next manufacturing step. This is done through the use of Process FMEA, establishment of a robust control plan, process characterization (reference JEP132), SPC (reference EIA-557), and standards for allowable deviations in key process characteristics (i.e., automotive manufacturers commonly require CpK > 1.67 for key processes).
4. The OCM's end-product testing includes 100% electrical verification of datasheet parameters, multi-lot qualification (JESD47, AEC-Q100), shift-based, lot-based, daily, weekly, quarterly samples pulled for process monitor testing and ongoing reliability testing, generation of statistically relevant Early Life Failure Rates (JESD74), outgoing Defect Parts Per Million (JESD16), and useful life Failure In Time (JESD85).

5. The OCM implements rules for the removal of outlying parts (i.e., AEC-Q001), removal of abnormal lots (i.e., AEC-Q002). These rules may apply at either the finished part level or in-process.
6. The OCM implements a robust change system that assures all major changes are properly qualified (JEDEC and AEC and others provide requirements for requalification) and that customers are notified of major changes (JESD46).
7. The OCM implements a robust Quality Management System that is acceptable for spaceflight. AS9100 and IATF16949 are examples of certifications that indicate good quality management.

**Best practices on circuit board level**

1. With regard to best practices at the circuit board level, JSC concurs with and has nothing to add to those practices that have been listed by other Centers.

**Best Practices on assembly level**

1. With regard to best practices at the assembly level, JSC concurs with and has nothing to add to those practices that have been listed by other Centers.

#### 7.6.6 Center Proposed Recommendations

1. Contracts that implement part-level DPA, Screening, and Qualification should include requirements that summary results be delivered to NASA. Currently no such requirements are in place. All that is known is that the parts that were used in flight hardware passed. Nothing is learned about failures, yield, risks associated with handling and logistics.
2. A follow-on task should be created to investigate the universality of "manufacturer best practices." A series of telecons where team members query the practices of COTS manufacturers to determine a) to what extent do they follow the "manufacturer best practices" that have been identified, and b) additional best practices that should be included in the list.

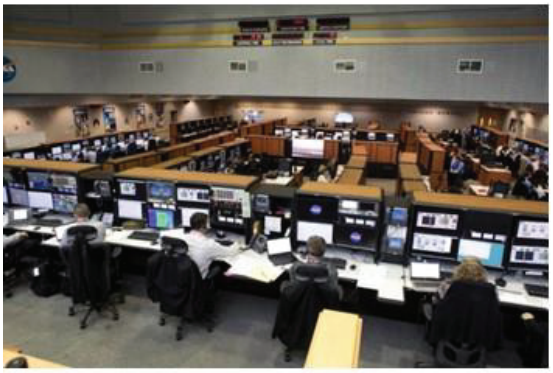
## 7.7 NASA KSC's Current Practices on Use of COTS Parts and Assemblies for Critical Ground Equipment

### 7.7.1 Center Programs and Projects and Center Strategy of Use of COTS

The NASA KSC supports multiple programs and projects including EGS, Commercial Crew, Gateway and Exploration Research & Technology, which consists of small ground and flight projects. For this effort, KSC focused on the use of COTS in EGS GSE, which is the majority of the design and development efforts at KSC. Use of COTS for CCP and Research & Technology are covered by other Center's best practices.

EGS is responsible for MPCV and SLS vehicle and payload processing and launch. Main components of EGS include Command, Control & Communications: Launch Control System, Mobile Launcher Umbilical & Control Systems and GSE in the various processing facilities and on the Mobile Launcher.

Launch Control System



Launch Control Center &
Vehicle Assembly Building


Mobile Launcher in the VAB

EGS is defined as a Category 1 project as defined in NPR-7120.5. The systems are safety critical or mission critical. They are designed for a 20-year life cycle. The systems are single fault tolerant, they either fail operational or fail safe. Systems are certified to function in their intended operational environment. This requires extensive evaluation, analysis, qualification and testing.

### 7.7.2 Center Strategy of Use of COTS

GSE is certified to function in their intended operational environment. This requires extensive evaluation, analysis, qualification and testing. COTS equipment is used to the maximum extent possible when (1) it satisfies the intended function, (2) it will not degrade the safety or reliability of the flight or ground system, and (3) it provides a cost savings that exceeds possible cost increases that may result from unique maintenance or logistics requirements, modifications, or an increase in the complexity of the interfacing equipment. Vendor or contractor documentation and supporting test data is incorporated into system control documents.

When a program/project approves the use of COTS equipment in GSE, the following design requirements apply:

1. COTS equipment shall be evaluated for acceptability from a materials and processes (M&P) standpoint and in its intended environmental conditions (temperature, humidity, vibration, acoustic, EMC, etc.).
2. Qualification tests and inspections are performed as required.
3. Vendor documentation shall be provided as evidence that requirements have been met.
4. Modifications to COTS shall be performed in accordance with KSC-DE-512 SM.
5. COTS incorporated into GSE shall be selected for use within the limits of the manufacturer's specified ratings (e.g., environmental, mechanical, electrical, EMC, etc.). If the environment (e.g., vibration & EMI) are beyond manufacturer specifications, design mitigations are implemented.

KSC has a qualification panel and team that is responsible identifying and performing qualification tasks and tests. KSC has a several labs that support qualification including the Electromagnetics Lab, Cryogenics Lab, Vibration & Acoustic Test Facility, Sensors & Transducers Lab, Engineering Development Lab, Thermal Chamber and the Launch Equipment Test Facility.

### 7.7.3 Center Governing Parts Documents

KSC-DE-512 Ground Systems Development Standard is the overarching document specifies the documents listed below. NASA-STD-5005 is the Agency Standard for the Design and Fabrication of Ground Support Equipment. KSC-DE-512 meets or exceeds requirements of NASA-STD-5005.

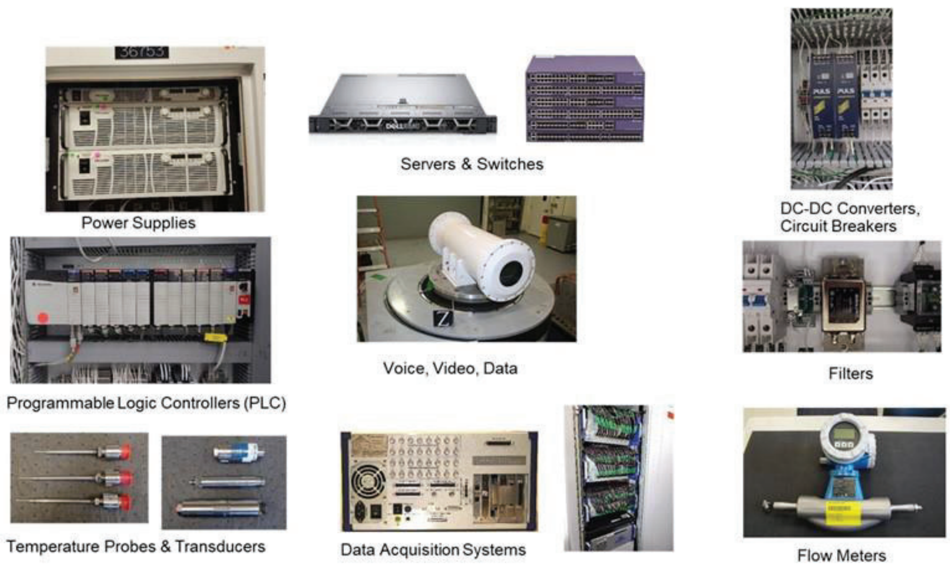
- KSC-PLN-5406: Design and Development Electrical, Electronic, Electromechanical (EEE) Parts Plan. This plan addresses parts selection, evaluation, screening.
- KSC-NE-9187: Sensors, Transducers and Signal Conditioning Systems Selection Guidelines.
- KSC-STD-164: Standard for Environmental Test Methods for GSE.
- KSC-STD-G-0003: Standard for Qualification of Launch Support and Facility Components.
- KSC-STD-E-0022: Bonding, Grounding, Shielding, Electromagnetic Interference, Lightning and Transient Protection, Design Requirements for Ground Systems.
- Other qualification plans, and standards include:
- KSC-NE-10074: Electrical Ground Support Equipment Qualification Plan.
- K0000283895-SPC: Standard for Mobile Launcher Ground Support Equipment Vibration Qualification.

### 7.7.4 COTS Parts Selection, Evaluation, Screening and Qualification

#### 7.7.4.1 COTS Parts Selection & Evaluation

KSC EEE Parts are defined in KSC-PLN-5406 and includes electronic assemblies. COTS electronic assemblies include LRUs such as power supplies and PLCs. High-level assembly racks and enclosures contain many LRUs and other COTS components. For this discussion, the term assemblies include LRUs, racks, and enclosures. Sensors, transducers, data acquisition and instrumentation are included.

Sample COTS Components and Assemblies



Rack Level Assemblies


COTS components & assemblies are selected according to operational & functional requirements, operational environment (natural & induced), pedigree, quality, reliability and maintainability.

**EEE Parts Grade Description per KSC-PLN-5406**

| Grade | Summary | Reliability | MTBF* | Cost | Typical |
|---|---|---|---|---|---|
| 1 | "Space" quality-class qualified parts, or equivalent. | Highest | Longest | Very High | Spaceflight |
| 2 | "Full Military" quality-class qualified parts, or equivalent. | Very High | Very Long | High | Spaceflight or critical ground support equipment |
| 3 | "Low Military" quality-class parts, and Vendor High Reliability or equivalent.<br><br>Industrial/High Reliability COTS<br><br>AEC EEE parts | Medium | Variable | Moderate | Spaceflight experiments, aeronautical flight experiments, critical ground support equipment, test demonstrations. Screening and qualification performed as required. |
| 4 | "Commercial" quality-class parts. Qualification data at manufacturer's discretion. No government process monitors incorporated during manufacturing. | Variable | Variable | Lowest | Aeronautical flight experiments, test demonstrations, and prototypes. Critical ground support equipment with appropriate qualification and screening. |

*: Mean Time Between Failures

Selection & Procurement:

Once a potential component or assembly is identified, understanding and knowing its pedigree is important. This is done during the selection and procurement process.

- Parts and assemblies are procured from the OCM, OEM or their franchised (authorized) distributors. This assists with counterfeit avoidance.
- When specified, CoCs are requested.

- Parts and equipment are reviewed for applicable GIDEP Alerts, GIDEP Safe-Alerts, GIDEP Problem Advisories, and GIDEP Agency Action Notices, and NASA Advisories during part selection and procurement phases.
- Once received, parts are visually inspected for defects before they are put into logistics.
- Once a part or assembly is purchased it may be traced or tracked for a number of reasons:
- To readily identify location and usage of parts (serialized, lot/batch, etc.).
- To trace components to the assembly and the next higher-level assembly.
- In case of obsolescence, NASA advisory alerts, and GIDEP alerts, to readily identify the affected parts and application aiding in the implementation of resolution.
- To assure genuine authentic parts and materials by requesting supplier or manufacturer lot/batch codes, date codes, or serial numbers in conjunction with CoCs.
- To provide an unbroken supply chain history and part pedigree.
- To monitor and control critical items.
- To track limited-life items and monitor maintenance requirements and cycles.
- For GSE, traceability and track is available for the following: Limited-life items (batteries)/limited shelf-life items, critical components or assemblies, configuration controlled items and components or assemblies subject to periodic checkout, test, calibration, servicing, maintenance, or inspection, or items under warranty.

Obsolescence Management:

Projects with extended product life cycles, such as GSE (20+ years), and those that utilize heritage hardware are exposed to a higher risk of being affected by parts obsolescence. COTS parts and equipment have much shorter life due to technology advancements, vendor support and constant upgrades.

Parts are assessed prior to selection to ensure part availability meets or exceeds production milestones and mission duration. Parts are monitored throughout the system life cycle to identify and mitigate obsolescence issues before they occur. Obsolescence monitoring provides notification of part discontinuance to allow projects with enough time to procure spares. Lifetime buys may be necessary.

A Logistic Support Analysis (LSA) is developed for every GSE subsystem:

- Identifies obsolete parts and provides alternative parts & vendors

- Identifies lifetime buys when necessary
- Plan Refreshes

Maintain warranties and support (H/W & S/W) and stay away from sole sources if possible.

Reliability and Maintainability:

EGS GSE subsystems must meet reliability, maintainability and availability requirements. To meet these numbers, high reliability and industrial COTS components and assemblies are selected. GSE systems are single fault tolerant, they either fail operational or fail safe. Redundancy is usually implemented increasing the reliability. An analysis is performed at the higher assembly and system level.

Example EGS RMA Requirements.

| Configuration | Reliability (@ 24 hours) | Maintainability (hrs) | Availability ($A_{inh}$ @ 24 hrs) |
|---|---|---|---|
| REQUIREMENT | 0.999760 | 15.00 | 0.999880 |

Design and Development Review Process:

GSE undergo a rigorous technical review process as defined in the KDP-P-2713. This KDP defines required reviews such as System Requirements Review (SRR), 30%-60%-90% Design Reviews, Preliminary Design Reviews (PDR), Critical Design Reviews (CDR) and Test Readiness Reviews (TRR) for verification and validation tests. The KDP also defines the associated products required for each review and milestone. This eventually leads to system Design Certification or System Acceptance. Example required products include:

- System Requirements
- Design Verification Matrix
- Configuration Management Plan (CMP)
- Quality Assurance Plan (QAP)
- Acquisition Plan
- Logistics Support Analysis Development Plan
- Software Assurance Classification Assessment (SACA)
- Software Management Plan and NPR 7150.2 Compliance Matrix
- Risk Matrix
- Reliability and Safety Assessment Report (RSAR)
- IT/OT Security Assessment
- System Assurance Analysis (SAA)
- Software Safety Analysis (SSA)
- Engineering Drawings and/or Models
- Software Maintenance Plan
- Design Analysis Reports
- Engineering Math Models4

- Procurement Specification
- Reliability, Maintainability, and Availability (RMA) Analysis
- Operations & Maintenance Requirements Specification Document (OMRSD)
- Design Data Manual
- Logistics Support Analysis (LSA)
- IT/OT System Security Plan
- EMC Management Plan
- Component Qualification Plan
- Verification & Validation Reports

**COTS Parts Screening and Derating**

Screening:

Screening is performed on GSE critical items as defined in KSC-PLN-5406. Critical Items are identified in the system RSAR or System Assurance Analysis (SAA) Critical Item List (CIL). Screening is performed per KSC-PLN-5406, which leveraged GSFC-EEE-INST-002. Screening requirements are documented on engineering drawings. 100% functional tests are performed at the higher assembly level.

Derating:

Derating is performed per KSC-PLN-5406, which leveraged GSFC-EEE-INST-002. Added GSE derating requirements (NFPA 70E – National Electric Code). Derating calculations and analysis are documented in system Design Analysis Reports.

**COTS Parts Qualification**

All GSE systems go through some level of qualification. Qualification may be performed at the component level, LRU assembly level or high-level rack or enclosure assembly.

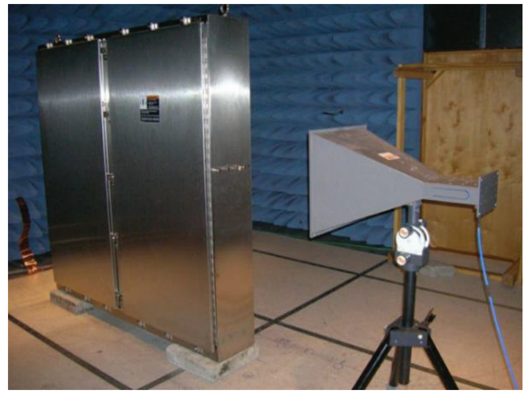
Qualification includes the following:

- Functional/Performance – Verify functionality and vendor performance specifications.
- EMC – Verify functional performance in the specified electromagnetic environment.
- Vibration - Verify functional performance in the specified launch induced environment.
- Acoustic - Verify functional performance in the specified launch induced environment.
- Thermal - Verify functional performance in the natural environment.

KSC has a qualification panel and team that is responsible for identifying and performing qualification tasks and tests. KSC has a several labs that support qualification including the Electromagnetics Lab, Cryogenics Lab, Vibration &

Acoustic Test Facility, Sensors & Transducers Lab, Engineering Development Lab, Thermal Chamber and the Launch Equipment Test Facility.

Electromagnetic Compatibility Testing:



Electromagnetic Compatibility Testing requirements are specified in KSC-E-STD-E-0022.

Tests include Conducted Emissions & Susceptibility, Radiated Emissions & Susceptibility. Testing is in accordance with MIL-STD-461. Testing may be performed at the component level, assembly (LRU) level or rack level.

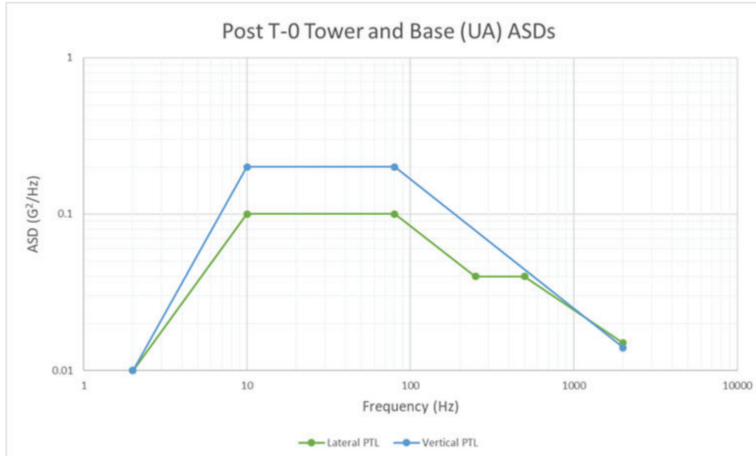
Requirements:

- GSE shall be electromagnetically compatible within themselves such that system operational performance requirements are met.
- GSE shall be capable of providing full performance in conjunction with other subsystems and equipment that are required to operate concurrently.
- GSE shall not create EMI that cause neighboring systems to malfunction.
- Electrical and electronic GSC shall be designed to perform when exposed to a minimum level of 20 volts per meter (V/m) in the frequency range from 30 Hz to 18 GHz. Equipment in the Launch Control Center have a 50 V/m requirement.

Most COTS systems comply with commercial FCC regulations or European standards and usually do not meet requirements for GSE. Mitigations include the following:

- EMI Shielded Enclosures (min 26 dB attenuation) and shielded cable with $360^0$ termination
- EMI Filters
- Operational RF Clear Zones

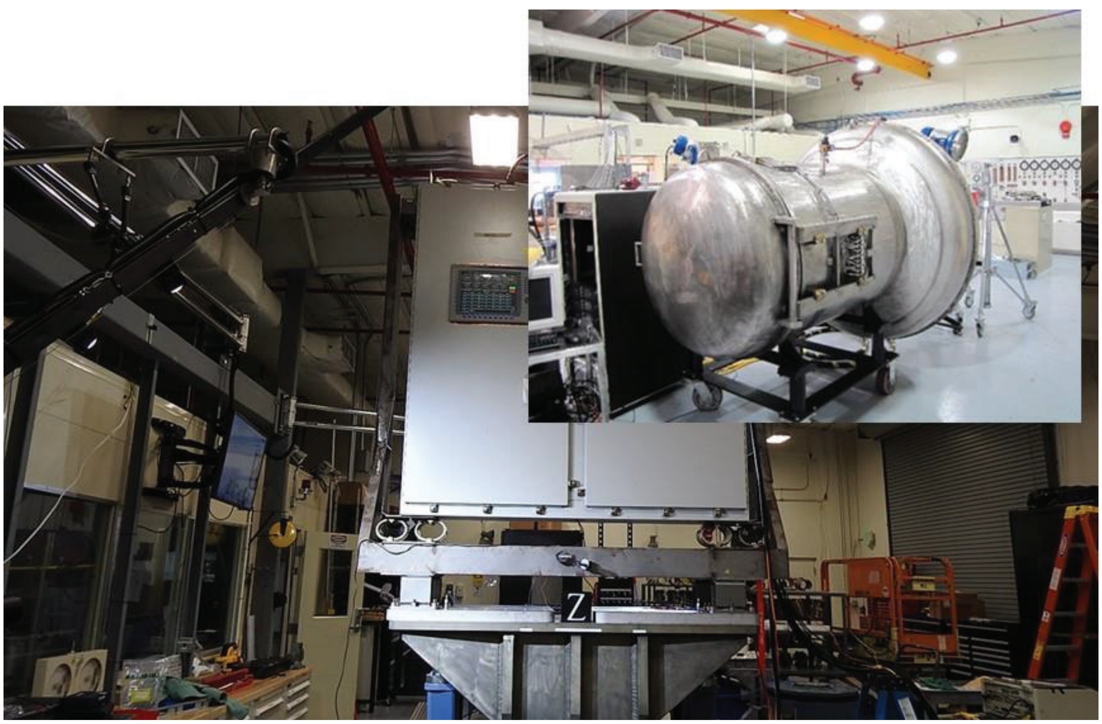
Vibration Testing:



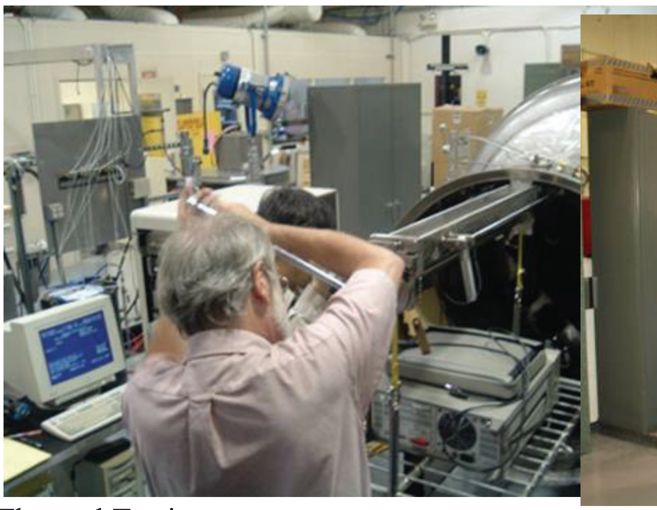

GSE located on the Mobile Launcher required to function during and after exposure to the launch induced environment are subjected to vibration testing. The induced environments are specified in K0000132092-ANA, Space Launch Systems (SLS) Mobile Launcher Rocket Exhaust Plume Induced Environment, Volume I & II: Acoustic and Vibration, Thermal and Pressure. Vibration qualification is performed in accordance with K0000283895-SPC. Levels vary according to location of equipment and use of isolators. Tests represent 10 launches, 30 seconds each axis. Testing may be performed at the component level, assembly (LRU) level or rack level.

| FREQ(Hz) | ASD(G2/Hz) | dB | OCT | dB/OCT | AREA | Grms |
|---|---|---|---|---|---|---|
| 2 | 0.0100 | | | | | |
| 10 | 0.2000 | 13.01 | 2.32 | 5.60 | 0.69 | 0.83 |
| 80 | 0.2000 | 0.00 | 3.00 | 0.00 | 14.69 | 3.83 |
| 2000 | 0.0140 | -11.55 | 4.64 | -2.49 | 83.72 | 9.15 |

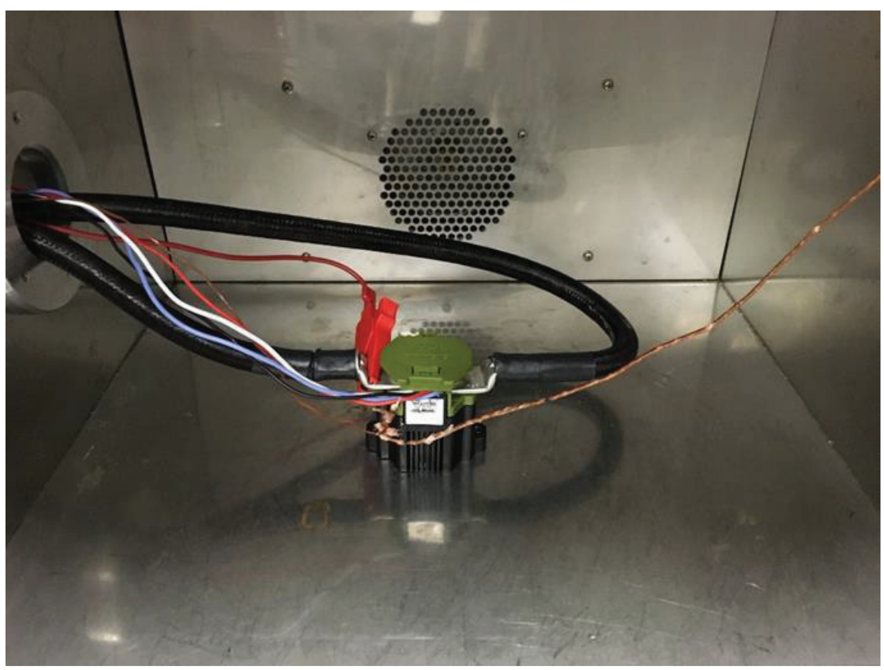
Acoustic Testing:



GSE located outside on the ML tower required to function during and after exposure to the launch induced environment are subjected to acoustic testing. The induced environments are specified in K0000132092-ANA, Space Launch Systems (SLS) Mobile Launcher Rocket Exhaust Plume Induced Environment, Volume I & II: Acoustic and Vibration, Thermal and Pressure. Tests are performed on equipment located outside the electrical rooms along the tower of the mobile launcher. Electrical rooms provide 11.63 dB attenuation. Tests are conducted at the component or LRU assembly level.




Thermal Testing:



GSE used or stored in an exterior environment shall be designed to function after exposure to the natural environment at its respective geographical location as specified in NASA/TM-2008-215633.

GSE designed to function within a controlled interior environment shall be designed to the following temperature and humidity requirements:
Temperature: +15 °C to +27 °C and within the extremes of +11 °C to +40 °C for a maximum of 1 hour.

Humidity: nominal 55%, within a range of 30% to 70%.

Testing is performed at the component or LRU assembly level. Analysis may be performed in-lieu of formal testing. This is usually at the box or enclosure level.

**COTS Parts – Embedded Software**

Nearly all COTS assemblies contain embedded software. These assemblies may be used in critical GSE applications. Software incorporated into the design of GSE must meet the requirements of NPR 7150.2. This includes firmware and embedded software in COTS assemblies (e.g., the software in PLCs and motor controllers). NPR 7150.2 contains provisions applicable to COTS software in NASA-developed systems. A SACA is performed at the subsystem level. All GSE systems fall under an Information Technology (IT) System Security Plan. IT security assessments are performed at the assembly and system levels. There have been instances where COTS assemblies had to be removed from GSE because of IT vulnerabilities. IT security requirements specified in NPR 2810.1 and NPR 7150.2. A Software Safety Analysis is also performed. All subsystems have software management/maintenance plans that includes embedded software and firmware upgrades and configuration management.

**Radiation Effects Evaluation on COTS**

Radiation testing is not performed on GSE.

### 7.7.5 Center Best Practices

A list of best practices is outlined as follows:

1. Understand your operational environment. Select parts that fit functional, operational, and environmental requirements.
2. Qualify parts and assemblies. Do it early in the project. Qualification should be done early in design & development process. Delaying qualification until after equipment is fabricated and installed can result in huge cost and schedule hits if equipment fails qualification. Qualification could result in a redesign and other costly mitigations.
3. Procure from the OCM, OEM or their franchised (authorized) distributors. Request CoCs.
4. Perform Obsolescence analysis when considering a part and track obsolescence throughout the project life cycle. Stay away from sole sources if possible. Identify alternative parts & vendors and lifetime buys when necessary. Plan refreshes to avoid obsolescence issues later. Technology is ever changing, and COTS products have a short life cycle. Components and equipment may become obsolete before the system becomes operational. Plan for obsolescence. GSE usually have a 20 year + life cycle requirement.
5. Maintain warranties and vendor support (H/W & S/W).
6. Implement redundancy. This increases system reliability and availability.
7. Maintain a qualified parts list database. KSC has a qualification team responsible for the qualification of GSE components and assemblies and they maintain a

qualified parts list. KSC's qualified parts list has been uploaded to EPARTS Agency database.

### 7.7.6 Center Proposed Recommendations

The use of COTS parts and equipment can be very beneficial, saving design & development costs and schedule and for GSE, COTS products should be used to the fullest extent possible when they meet the project requirements. COTS should be qualified for their operational and environmental requirements. Pedigree requirements should be identified and understood, request CoCs for critical items. An obsolescence analysis should be performed when selecting a part and track obsolescence throughout the project life cycle. Maintain warranties and vendor support (H/W & S/W) for COTS assemblies. Stay away from sole sources if possible. Depending on the application and criticality, implement redundancy. Maintain a qualified parts list.

## 7.8 NASA LaRC's Current Practices on Use of COTS Parts for Spaceflight Systems

### 7.8.1 Center Programs and Projects and Use of COTS

The NASA LaRC typically services a variety of Spaceflight missions. These missions can span from Class A and manned-Spaceflight to Class C&D type instrument hardware builds. Typically, work is either contracted out-of-house with government oversight or performed on Center. There are some projects that require a combination of both resource approaches. Most of LaRC's electronics hardware design efforts are for low cost Class C & D type missions with a few being "Do No Harm" Demonstration Technology Objective (DTO) projects. Regardless, Cost and Schedule are typical factors that decide the best methods to service these projects and occasionally the use of COTS parts and components is required to satisfy special functional needs. The typical LaRC project workload is comprised of only a few Class C/D missions (ISS, atmospheric science & interplanetary payloads) per year and several other smaller high-risk missions. Thus, there is only a small EEE Parts Group to service these projects, and this warrants the use of as much standard product as possible. When COTS parts/components are required, typically they are evaluated at the upper assembly or even system level via burn-in and environmental testing. The LaRC EEE Parts Group performs both EEE Parts Engineering function and Mission Assurance oversight when required to ensure contractual efforts meet mission requirements. This report documents examples from several projects and both types of engineering support functions to depict a wide variety of COTS usage examples, approach philosophies, and application challenges.

LaRC has all of the typical facilities (similar to other Centers) for design, fabrication and test of its in-house and contractor built (or combination built) hardware. While the EEE Parts Lab provides primarily FMEA and intermediate disposition for parts analysis – it is part of the larger hardware verification capability on Center that supports the hardware qualification, environmental testing & diagnostics. LaRC also has a complete portfolio of environmental and nondestructive test capabilities in the areas of thermal, vacuum, shock and vibration, EMI/EMC, x-ray, CT-x-ray, XRF, etc… for the purpose of testing/screening components to mitigate reliability concerns. The on-center machine shop manufactures mechanical structures when necessary for testing & prototyping, the EDUs and flight build hardware units.

Many of the externally contracted class D projects at LaRC are managed in collaboration with academia such as (MIT, Oklahoma University, Michigan, Colorado, etc.). There are some class C&D projects that incorporate the support of notable Aerospace contractors such as (South-West Research Institute, Orbital-ATK, Ball Aerospace, Harris, Northrop-Grumman Aerospace Systems, Lockheed-Martin, etc.), along with other NASA Centers. Hence, there is a broad spectrum of spaceflight projects that have been developed at LaRC, involving mostly atmospheric science, some SSP orbiter and ISS science payload missions and a few small satellite and CubeSat missions.

While a few of the LaRC Missions have cost between $200 and $300M, most projects are in the $100 and $200M range. Recent Class D small projects have been proposed and cost-capped at $100M. The small and CubeSat projects typically are run at $50M and less depending on the mission duration requirements and fidelity of the science data required. Several LaRC DTO mission durations were defined only for on orbit periods ranging from days to weeks. Most class D missions have minimum on-orbit operational requirements of one year with three-year goals. Interplanetary (Mars) mission durations are for 9 months and a few hours of orbital insertion and descent. However, the class C missions have had 5- to 7-year duration requirements and the project costs reflected their more stringent approaches to mitigate hardware reliability concerns.

### 7.8.2 Center Strategy of Use of COTS

The LaRC EEE Parts Office selection philosophy emphasizes the use of the Mil-system for selection and application of EEE Parts for its project requirements. The main goal is to cost manage supply chain risk by leveraging on the DoD supplier development quality assurance efforts. Utilizing the efforts of the Defense Logistics Agency (DLA) Land & Maritime activity for electronic parts commodity specification, qualification and verification for most of the LaRC project electronic needs. However, it is important to clarify that for upper level electronic assemblies and some system level components – LaRC does use COTS components, which are comprised of electronic parts. There is a preference for these components to have parts that are compliant to GSFC EEE-INST-002 requirements guideline, but that is not always possible. Under those circumstances, additional mitigation is necessary and that typically requires component level testing. These additional steps are considered modification to the baseline off the shelf item. This is referred to as modified COTS. If at all possible – the LaRC approach is to use standard parts, or have as much testing or pedigree purchased from the OEM. Under unique circumstances when the vendor does not have the test capability, LaRC then, takes conditional delivery of the item and performs its own in-house (typically environmental) testing.

LaRC does not have the resources for its internal projects to design, fabricate and build – flight computers, inertial navigation/management units, power management/sourcing assemblies, large solid state data recorders, cryo-coolers, etc., hence, for certain customer requirement specific applications, COTS component solutions are the most cost effective project solution. These types of solutions have been successfully implemented on all short duration DTO and class D missions.

The success can be attributed to a combination of the following: Good communication/networking within the Agency on heritage and new technology. This involves utilization of the NEPP program and experiences of the other NASA Centers for specific part commodities and system level components. Ensuring when possible COTS reverse engineering if necessary and low level EEE parts review/analysis to find suspect or problem areas of reliability risk. When heritage or pedigree information is not available – specifying appropriate test strategies as early as possible to aid in reliability/survivability risk mitigation for timely costing and project preparation. It is critical to ensure that the project's engineering/design, management and mission assurance staff be made aware of the risks associated with the COTS selection and that a timely plan is discussed as early as pre-phase A in the project management life cycle. However, the COTS success criteria relies heavily on ensuring the project reliability criteria is understood and matches up with the perceived risk of component anomaly or failure. From this understanding, the appropriate action can be taken to assess the true cost of usage. There have been no true COTS implementations on LaRC projects. All parts have had some testing to ensure they meet datasheet requirements, and possess no latent defects from their respective OEMs. Some of the typical COTS parts historically used are laser diodes, power supply hybrids, and various physical property detectors (or sensors). Sensor Transducers ranging from "niche" Optical Detector Assemblies (in hybrid packaging) or pressure sensor transducers to Quartz Contamination Modules have been used with success, but had their implementation and testing costs to accommodate their integration and test anomaly issues. System level components such as flight computers and IMU components have also had similar issues, however, the benefit to cost ratio is attractive when viewing the alternative costs associated with a ground up equipment build. At LaRC, the EEE parts function supports the systems level testing, for input, review and approval of all testing associated with COTS implementation.

### 7.8.3 Center Governing Parts Documents

The LaRC EEE parts process control policy document is LMS-OP-5515. This requirement is parented by several LaRC policy requirements including LPR7120.5, LPR 5300.1 and LMS-OP-5502. In addition, Agency EEE Parts Management directives such as NPD 8730.2C, NASA-STD-8739.10 and NPR 8705.4 mission risk classification requirements that drive the formulation of customer/project specific EEE Parts project management plans. This approach allows agile approaches for innovative projects that need specific and tailored approaches for engineering and mission assurance cost effective solutions.

### 7.8.4 Current Practices on COTS Selection, Evaluation, Screening and Qualification

Since LaRC's projects are a wide variety of Class D missions and some Class C, where single-point failures are allowed or system redundancy mitigates some failure mechanisms, some COTS usage is implemented when function, performance, cost and schedule challenges need to be championed. In addition, most of the missions are for short LEO orbits or interplanetary missions, where radiation is performance can be understood either through analysis or minor testing approaches. Using COTS with good design approaches further reduces application anomaly risks and short duration missions justify COTS usage.

Typically, for part-level electronic components, EEE-INST-002 guidelines are used and the COTS part lot qualification and part screening guidelines are used. This circumstance is not exercised very often due to the LaRC EEE Parts Office philosophy for cost effective piece part selection and reliability concerns. Exceptions to this rule are items where unique functions are needed and the aerospace market does not have clear competitive choices. Such examples are opto-electronic devices such as laser diodes and optical detectors. These devices would have source control drawings generated to document all qualification and verification aspects and lot procurement sizes and the test methods required (per EEE-INST-002) to specify the screening requirements.

For board level and system component level reliability assurance - a variety of methods are used to evaluate the selected items for acceptability. Research for heritage usage research within the Agency and previous LaRC projects is conducted, and analysis of any lower level EEE parts lists/(Bill of Materials lists) to evaluate initial part selection reliability risks. In addition, any technology experience that the NASA Electronics Parts & Packaging Program might have is also leveraged to decide if the item is a good candidate for testing if no substantive information is available. Test plans are discussed with the system test and verification team to implement the best possible approach to qualify and verify item performance, burn-in and remove any unwanted infant mortality issues at the system level.

Radiation effects efforts for COTS components are typically dependent on the mission risk classification and weighing the cost/benefit ratio for risks and performance. Costly testing usually prohibits some component selections, while other parts can be approved with analysis and similarity only. For typical class D short duration missions, and depending on the wafer-level technology, proton testing and latchup mitigation are used as quick and cost effective solutions for quick time to market type applications. For Class C/D missions, radiation testing budgets do not exceed about 100K$ or the part/component is considered for de-scope.

Thus, when the initial COTS section is considered the total cost to benefit ratio is considered and an estimate for total cost implementation is used for justification/approval. However, there are limited experiences where other unforeseen vendor/workmanship related issues do tend to increase the cost for implementation with added risk mitigation related project costs.

#### 7.8.4.1 COTS Parts Selection, Evaluation, Screening and Qualification

Typical LaRC EEE parts for spaceflight projects are military and space reliability grade parts. When COTS components are used, military off the shelf or high reliability components are preferred. The baseline approach focuses on the traceability aspect of the supply chain and part qualification. Procurements are from authorized distributors, or customer evaluated vendors – where certificate of conformance is required as normal business practice. When available, additional test data is procured with the COTS items. When additional assurance/vendor confidence levels are required, government inspection points are included in the purchase contract to allow oversight on the workmanship aspect of the item. By definition, these initial efforts make the COTS items modified and any further testing also means the items are modified COTS components. By definition, these initial efforts make the COTS items modified and any further testing means the items are modified COTS components. When possible, LaRC takes whatever steps make sense for cost-effective risk reduction – especially for the low volume production COTS vendors.

COTS components are selected based on system functional needs/datasheet performances and are verified thru environmental testing. Whenever available, modified OCM versions (with tighter/custom specifications) of the parts are purchased. Furthermore, these selected components are usually made by unique OCM's such as sensing and physical transducer manufacturers at (TRL level 6). While past positive experiences from the same OCM are important – it is not always possible – which drives the vendor assessment activity prior to item purchase/contract award. To reduce these costs, flight heritage part selection is a strongly recommended by the LaRC EEE Parts Office.

Historically, LaRC has avoided in-house part-level screening or qualification of COTS parts for cost/resource reasons; however, it is not ruled out for external contracted work when the functional need arises and the contractor submits NSPARs documenting the actions need for acceptable risk and application usage. Parts are usually evaluated by analysis/similarity to others previously used; while components at the PCB or sub-assembly level are evaluated by system testing. The qualification of components is performed indirectly via the qualification of a subsystem or system. However, by the time the electronics item gets through the qualification process, hundreds of hours of operational life would usually have been completed on it, which helps to weed out infant mortality parts and uncover workmanship issues.

Project risk evaluation is done at the project level based on the technical/reliability risk analysis performed at the EEE part (and sub-assembly) level. In some cases, various mitigation approaches are recommended to reduce the reliability risks down. Typical component selections have a variety of low level risk concerns, and the efforts required to buy down risk are cost effective, and somewhat improve the desire to use the part. Extremely risky COTS parts are typically not selected for perceived low benefit/cost ratios or possible unknown latent defect issues causing unnecessary project schedule risks.

Radiation effects are also considered when using COTS parts/components. For EEE Part Level microcircuits, latchup concerns are always a foremost concern with 21st century technology features and wafer size/designs. If testing is thought to be out of scope depending on the project classification, then the part is discouraged for selection or design mitigation approaches are advisable, which may require electronic sensing and monitoring circuits. However, this is not preferred for longer term missions, and redundancy or de-scope (alternate selection) would be encouraged.

#### 7.8.4.2 Radiation Effects Evaluation on COTS

LaRC's Spaceflight projects are a variety of the class C & D variety, and the class D mission duration are grouped – some are 14 days or less, and the rest are 1 year or less with 3-year goals. This makes the radiation performance challenge success criteria a little easier to technically plan for and mitigate. Whereas, for LEO missions, analysis and as little testing as possible are used for the less than 1-year missions. In general, previous environmental mission heritage, analysis, and some testing with design mitigation are used for success. Whenever possible, COTS components are reviewed for heritage or low-level parts selection that would indicate some radiation tolerance for the mission in question. For greater than 1-year missions, a more rigorous review and testing approach would be required – depending on the complexity of the COTs part being considered.

The below list of radiation effects are dealt with by a varied of methods:

**Total Ionizing Dose (TID)**

Depending on the technology (Bipolar or CMOS) analysis or testing depending on the orbit and mission duration. LaRC depend heavily on part list analysis and heritage radiation testing results and approval by similarity.

**Enhanced Low Dose Rate Sensitivity (ELDRS)**

Depending on the technology, (Bipolar or CMOS) analysis or testing depending on the orbit and mission duration – due to short mission duration or long-term circuit deactivation – not considered a major risk for COTS.

**Displacement Damage Dose (DDD)**

Depending on the technology (Bipolar or CMOS) analysis or testing depending on the orbit and mission duration – all power switching circuits are reviewed for derating, operation and possible consideration for replacement – if not possible, then testing is considered for better longevity reliability understanding.

**Single-Event Effects (SEE)**

Depending on the technology (Bipolar or CMOS) analysis or testing depending on the orbit and mission duration – typically when the heritage COTs circuit/application analysis indicates that there is a lack of functional or parametric performance data – the final design must be considered with proposed current limiting and verification testing to address circuit intermittent operation and latchup concerns.

#### 7.8.5 Center Best Practices

A list of Lessons Learned is included in Section 11. A list of best practices is outlined as follows:

**Best practices on parts level**

1. Strictly adhere to the Agency/Center policy to only purchase/acquire EEE parts from OCMs or their authorized distributors, and never go through any other third parties.
2. Visually inspect "problem" parts to look for various issues (counterfeiting or defects) before final acceptance. "Problem" parts are typically those with higher than normal technical risk associated with them or known GIDEP alert/advisory type components or vendor related.
3. Always require/obtain CoC for EEE parts used in flight hardware, so that parts can be traceable to a specific manufacturer, part number, and lot number or lot trace code.
4. When absolutely necessary, look for COTS parts that may have a related technical similarity to a radiation tolerant parts version, which may offer some level of radiation assurance.
5. For TID consideration, COTS parts fabricated in the newer CMOS/BiCMOS technology nodes are preferred over those from older technologies.
6. Select COTS parts that have established successful (Center or multi-Center) flight heritage usage.
7. Review lower level part bill of materials for components to ensure the performance specifications meet project requirements under all mission environmental and operational conditions.
8. For Radiation latchup concerns rely on system design redundancy/over current protection and possible testing for performance verification.
9. Purchase early and plan for significant lot performance issues schedule and cost-wise.

**Best practices on circuit board level**

1. Workmanship is a must. Most electronics failures are due to connectivity. Solder joint integrity and moisture/ionic contamination concerns must be addressed.
2. Diligently prototype and engineering circuits add to circuit experience and design fabrication process vetting before PCB-level integration with other circuits, which makes qualification/verification somewhat more reliable.
3. Peer review circuit design informally via enhanced design/EEE parts communication and share lessons learned.
4. Make it a habit to reuse circuits after successful missions because flight heritage should be a strong consideration.
5. Strategically using space rated parts and/or redundancy for single-point failures.

6. Look for typical application fail points such as high voltage/current parts, and NEPP application note applicable lessons learned – selectively replace problem parts.

**Best practices on assembly level**

1. Modularize system design such that redundancy be implemented mission success can be achieved if even thru limited strategy mode of operation. This will requires knowledge of cold sparring and cross strapping power feeds and controllability for each modular system component.
2. Utilize current sensing circuit to monitor current consumption in subsystems, so that over-current conditions due to radiation events can monitored and addressed to prevent loss of system. Resetting or power cycling of the subsystem can also be carried out via software in conjunction with the monitoring hardware. Need to emphasize here, over-current mitigation does not prevent part/component damage – Latchup will take life out of the items, and without extensive (cost prohibitive testing) the amount of degradation over the life of the part is unknown.
3. The use of COTS components allows for unique system functions to be realized more cost effectively and within a reasonable project schedule. Hence, environmental testing and qualification are used as early as possible in the system design cycle. When implemented - this beneficial approach can discover major issues early for proper schedule impact triage.

### 7.8.6 Center Proposed Recommendations

1. Depending on the mission classification – COTS can be highly desirable, (for higher risk missions) and or COTS can be highly discouraged (for very low risk missions). The Benefit to Cost ratio has be to be fairly well-understood and contrasted with the project budget and schedule considerations.
2. To reap the benefits of using COTS parts, the traditional way and philosophy of developing spaceflight hardware in NASA has to change. If every COTS part has to go through extra screening and qualification before it can be used, then the huge advantages in lead time, availability, performance and cost are mostly lost. In fact, the costs involved in space-qualifying a COTS part may be more costly than choosing a MIL-SPEC-space environment part, which is especially true with passive components.
3. Robust circuit designs can allow the use of more risky parts typical of some COTS parts. Large quantity usage allows for a broader experience and possible reduction in testing needs. Of course, if there is an issue – the large scale of implementation increases reliability risks that robustness throughout the flight hardware design might not address.
4. Higher Reliability Part/Component performance cannot be tested into an item. Building small numbers of final working units for hardware delivery – hurts/hinders the true understanding of COTS performance from a statistical perspective. Aggressive project schedules are a detriment to the need for time to properly vet certain COTS items that are not representative of good manufacturing process

controlled fabrication and quality assurance. These constraints lead to disastrous and unforeseen project cost and schedule overruns.

5. Make sure to be using GIDEP– even for COTS where the vendor may not be a member or participate. The NASA advisory and Urgent Data requests can reveal information that may be of use in steering clear from vendor related bad customer experiences.

## 7.9 NASA MSFC's Current Practices on Use of COTS Parts for Spaceflight Systems

### 7.9.1 Center Programs and Projects and Use of COTS

The majority of projects at NASA MSFC are project Category 1 human spaceflight missions. On these missions traditional military EEE parts are used for the baseline design and construction. Historically on the SSP Propulsion elements the EEE parts program was essentially a strict Grade 1 program due to the fact that a catastrophic failure could potentially occur, jeopardizing the Crew, vehicle and/or the mission. For the current SLS Program the EEE parts requirements are directly linked to mission criticality. SLS-RQMT-019, Space Launch System Program Electrical, Electronic and Electromechanical Parts Management and Control Requirements Document requires the use of Grade 1 parts for Criticality 1 applications and allows the use of Grade 2 parts for Criticality 1R redundant applications. Therefore, Grade 2 EEE parts are the baseline for SLS Elements. The Grades of EEE parts are defined in MSFC-STD-3012. COTS components used in Criticality 1R boxes are required to be qualified by Appendix B for PEMs or other commodities to a similar constructed Military Specification including selection, screening and derating. Whereas in a Criticality 3 applications or development flight instrumentation and do no harm hardware is allowed to use Grade 3 and Grade 4 (COTS) EEE parts within their designs without any additional screens or tests.

Small low-cost Project Class D missions have recently come under MSFC managed missions. For these Class D missions the selection process has generally been to specify and use at least AEC parts where available, and using well-known and highly reputable manufacturers' products. However, true COTS EEE parts are allowed to be used for select projects.

- Projects are Category 1, 2, or 3 and shall be assigned to a category based initially on: (1) the project life cycle cost (LCC) estimate, the inclusion of significant radioactive material 2, and whether or not the system being developed is for human spaceflight.
    - Category 1 - All Human Space Flight or LCC > $1B
    - Category 2 - $250M <LCC <$1B, High priority <$250M
    - Category 3 – LCC < $250M Medium and Low priority
- Payload Risk Classification

### 7.9.2 Center Strategy of Use of COTS

Grade 4 (COTS) EEE parts typically meet vendor standards for high reliability or commercial marketplace reliability, but have not been independently verified. Grade 4 should be selected for equipment where high reliability is not a primary factor, the mission is not critical, or a repeat mission is possible. The duration of a mission would typically not be lengthy. Repair may be very practical. This is a typical choice for flight experiments and GSE.

COTS parts are primarily designed for benign environments and are considered as high-risk parts when used in space applications without additional screening. For this reason, no COTS parts are considered acceptable in high-reliability applications "as is." Additional testing, screening, and analysis to assure parts reliably operate in their intended space environment.

Developers proposing to use COTS parts shall address the following items in their Parts Control Program Plan: source selection (manufacturers and distributors), storage conditions for all stages of use, packing, shipping and handling, electrostatic discharge (ESD), screening and qualification testing, derating, radiation hardness assurance, test house selection and control, and data collection and retention.

### 7.9.3 Center Governing Parts Documents

MSFC-STD-3012 is the governing document where Grade 4 is classified as COTS EEE parts. Within this MSFC standard, COTS parts are not subjected or required to be subjected to any additional screens or tests.

### 7.9.4 Current Practices on COTS Selection, Evaluation, Screening and Qualification

On most of COTS EEE parts, MSFC inquire with the project on their risk posture if they are acceptable to use the parts without any additional MIL-SPEC/NASA screening; it is at the projects risk to accept. However, the EEE parts team has chosen to suggest to MSFC projects to perform particle impact noise detections (PIND) and x-ray inspections detection screening based on in-house capability and ease of eliminating obvious defective parts. MSFC has limited in-house electrical testing capability and believe the risk of removing parts from reels, packaging would likely cause more damage than value added. Most Projects are willing to receptive to accepting these two screens for their COTS assemblies.

COTS designed and assembled hardware are subjected to breadboard evaluation followed by box level acceptance and Qualification testing.

Traditional MIL-SPEC/NASA screening and qualification on COTS is required for Category 1 critical applications. For Class D Projects traditional MIL-SPEC/NASA screening and qualification is not performed due to high cost.

#### 7.9.4.1 COTS Parts Selection, Evaluation, Screening and Qualification

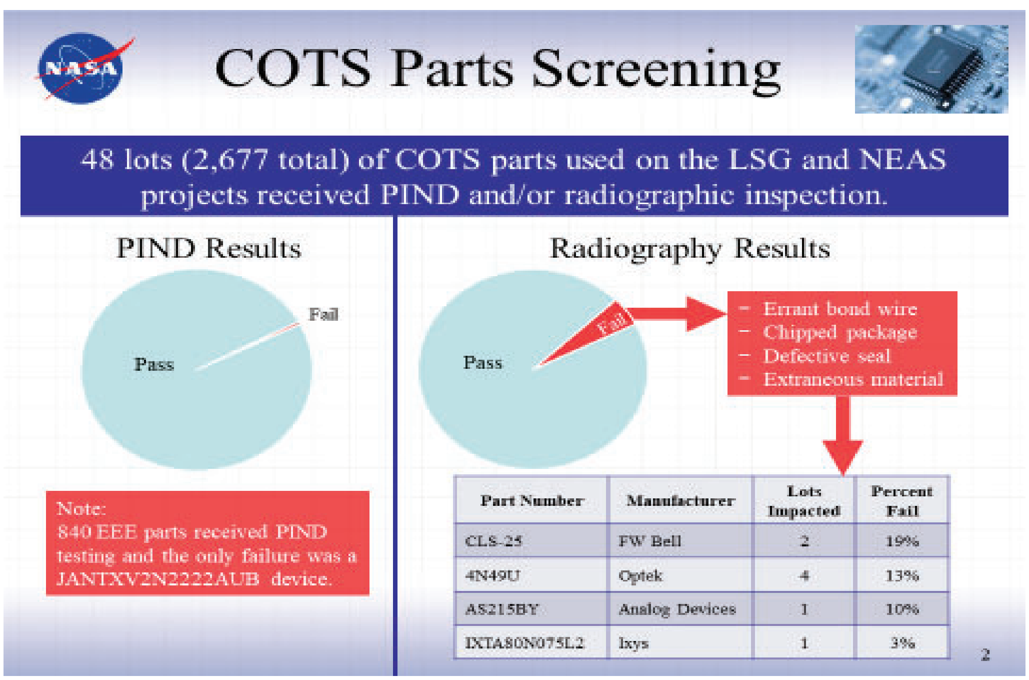
MSFC first strategy of using COTS for project is to use the follow guidelines:

1. Select automotive qualified parts first, if available.
2. Procure parts only from Authorized distributors.
3. Perform PIND and x-ray.

MSFC second priority is to select the Best-In-Class COTS EEE Parts Manufacturers and fully understanding the following design criteria.

1. Definition of the application environment
   - Determine the EEE Part application environment
   - Understand design feature requirements
2. Part identification and selection
   - Close interaction between Design and Parts Engineering
   - Determine the best technology type available for the application
3. Identification and Qualification of manufacturers
   - General assessment and specific family/line assessment
   - Vendors overall commitment to quality and reliability
4. Validation of line and part capability to meet environmental requirements
   - Qualification results, NASA's GIDEP Alerts

MSFC third checkpoint for using COTS EEE Parts is to perform PIND and x-ray inspections. These two screens are effective in screening out manufacturing defects with wire bonds, internal foreign object debris (FOD), package seal and any obvious defects. See screening summary charts.



| Project | Part Grade Requirements | Tests Performed | Total Parts | Grade 4 Parts |
|---|---|---|---|---|
| LSG | Grade 2 or 3 if available, otherwise Grade 4. | PIND & X-Ray | 428 | 351 |
| NEAS | Grade 2 or 3 if available, otherwise Grade 4. | PIND & X-Ray | 44 | 12 |
| FILMRS | Grade 4 | None Required | 212 | 212 |
| 4BCO2 | Grade 4 | None Required | 238 | 238 |
| H2ST | Grade 4 | None Required | 40 | 40 |
| | | ***Total Parts** | 962 | 853 |

#### 7.9.4.2 Radiation Effects Evaluation on COTS

For Grade 4 parts, used in spaceflight applications, the effects of the projected ionizing radiation on each part shall be determined by analysis and/or test. Radiation evaluation shall address all threats appropriate for the technology, application, and environment, including TID, ELDRS, SEE, and displacement damage as defined in the project ionizing radiation control document and shall be assessed on a lot-specific basis according to the project requirements. Failure mitigation or a design margin shall be established by the project to assure acceptable performance in the projected radiation environment.

### 7.9.5 Center Best Practices

A list of best practices is outlined as follows:

**Best practices on parts level**

1. Establish and maintain an ongoing relationship with qualified manufacturers, prefer well-known manufacturers.
2. Procure from OEM or franchised authorized distributors
3. Procure from as few lots as possible with sufficient quantity to limit lot variances, help with Homogeneity and Obsolescence.
4. Discuss project part requirements early on so COTS testing and risk assessments are clearly identified. If additional testing beyond in-house PIND and x-ray is required, then factor in schedule and cost of sending parts to test house.
5. X-ray screening inspection is a quick, valuable tool for COTS parts to weed out suspect parts. PIND screening is recommended for cavity devices.
6. Use “Best of Class” manufacturers.

7. Establish relationship with design engineers to ensure best COTS parts are selected and procured.
8. Incorporate obsolescence analysis into COTS selection process.
9. Ensure manufacturer assessment is performed beyond only a datasheet review. Some vendors use misleading language of spaceflight history for parts and assemblies.

**Best practices on circuit board level**

1. Perform bread board testing sufficiently enough to prove that selected piece parts meet the performance required to achieve mission goals.

**Best practices on assembly level**

1. Performing Acceptance Test Procedure (ATP) and Qualification Test Procedure (QTP) at the assembly level achieves some confidence that intended parts should likely survive in its intended operating environment. However, this does not necessarily indicate there will be no COTS EEE parts failures and is only suitable for low-criticality missions.at the assembly level achieves some confidence that intended parts should likely survive in its intended operating environment, however this does not necessarily indicate there will be no COTS EEE parts failures and is only suitable for low-criticality missions.
2. To reduce the likelihood that parts failures result in unacceptable mission risk, standard practice dictates designers to: develop and implement a systems engineering-oriented mission assurance program to address EEE parts derating, qualification, traceability, and counterfeit control, and demonstrate how it mitigates the risks associated with EEE parts applications, and provide data supporting the effectiveness of the proposed screening approach, ensuring part failure rates are adequately bounded.

### 7.9.6 Center Proposed Recommendations

- Ensure part grade requirements are clearly defined by project management and if COTS parts (MSFC Grade 4) are permitted, then project assumes risk.
- Coordinate with management to determine if project requires additional screening and qualification for COTS parts. (In-house PIND and/or x-ray or send parts to test house for additional screening).
    - Factor time for additional testing into project schedule.
- Establish interaction between parts engineers and design engineers to ensure best COTS parts are selected.
- Select AEC-Q parts first, if available.
- Choose (if possible) manufacturers that possess DLA certifications for other qualified product lines.
    - Ask if AEC-Q or commercial equivalents for qualified parts are available.
- Perform audit for manufacturers with no certifications or known spaceflight history.
    - Identify manufacturer's policy on quality and reliability.
- Ensure parts meet application requirements.

    - Determine the EEE Part application environment.
    - Understand design feature requirements.
    - Evaluate radiation effects.
- Perform obsolescence analysis to ensure projected part availability exceeds mission requirements.
    - Evaluate part life cycle to ensure availability from hardware design & part selection to procurement and installation.
    - Review manufacturer's life cycle management policy.
        - Is advanced notification for product end-of-life provided?
        - Are discontinued parts submitted to GIDEP for (Diminishing Manufacturing Source) announcements?
    - Coordinate with project to determine if design is a single or multiple build to ensure sufficient part quantities are procured.
- Procure parts from manufacturer's authorized distributors.

## 7.10 Use of COTS - Current Practices and Best Practices

Section 7.10.1 summarizes current practices on use of COTS through projects managed by the eight Centers, ranging from Category 1-3, Class A-D, sub-Class D and critical GSE. All projects used COTS parts, components and assemblies based on each Center's current and best practices.

Section 7.10.2 discusses the risk context in use of COTS parts. Best or current practices and considerations on COTS parts selection, COTS parts verifications, COTS parts applications and COTS parts radiation hardness assurance (RHA) are described in Sections 7.10.3, 7.10.4, 7.10.5 and 7.10.6, respectively. Section 7.10.7 provides the team's responses to a list of common concerns of use of COTS parts.

### 7.10.1 Summary of Current Practices on Use of COTS

A list of projects managed by the eight NASA Centers ranging from all mission risk classification and cost range (i.e., Category 1-3, Class A-D, sub-Class D (i.e., to critical GSE, and with different mission environments, mission lifetime, fault tolerance requirements, mission cost, mission outcome, etc.) were reviewed.

Critical GSE is equipment that is operated in conjunction with a vehicle or instrument, the failure of which can cause mission failure or loss of life.

All projects are listed in the team's COTS parts, components and assemblies based on each Center's current and best practices.

- <u>For safety and mission critical systems for missions with Category 1-3 and Class A-D, and sub-Class D</u>, NASA has a history of using NASA-screened COTS parts (defined in Section 7.1.1) ( i.e., performing additional and full part-level screening and space qualification on the COTS parts per GSFC EEE-INST-002 or equivalent documents before incorporating them into the spaceflight systems).

- For safety and mission critical systems for Category 1-3 and Class A-C missions, NASA Center current practices typically use NASA-screened COTS parts when MIL-SPEC parts are not available or appropriate for the application.
- For mission critical systems Class D and sub-Class D missions, there is a wide range of differences in current Center's practices on selection and verification of COTS across the Agency, resulting in different levels of COTS verification at part-level, board-level and system-level.
- For non-safety or non-mission critical systems, current Center use of COTS practices range from using NASA-screened COTS parts to the best effort on part-level verification or use of a waiver process, or using COTS parts without any further MIL-SPEC/NASA screening and qualification at part-level, depending on mission classification level and risk posture of the mission
- For critical GSE, current practice on use of COTS is full qualification per KSC-DE-512 and KSC-NE-10074. GSE subsystems undergo a rigorous technical review process as defined in the KDP-P-2713 including verification & validation testing leading to Design Certification or System Acceptance. All GSE systems go through some level of qualification. This includes Functional/Performance, Electromagnetic Compatibility, Vibration, Acoustic and Thermal testing. Derating is performed per KSC-PLN-5406. Screening is performed on GSE Critical Items as defined in KSC-PLN-5406.

### 7.10.2 Risk Context in Use of COTS

#### 7.10.2.1 Understanding Risk

Per GSFC-HDBK-8005[3], "In performing any activity that has uncertainty in achieving an outcome, it is natural to have concerns that represent the things that can go wrong or the things that may not be well-understood. These concerns may have a range of plausibility and uncertainty (e.g., occurrence of the event may be impossible, improbable, possible, probable, etc.) based on analysis, prior experience, observation, brainstorming, or even speculation".

At the core of risk is a concern, defined as "a logical determination that an undesired event may occur or that the protections against such an event may not be sufficiently well-understood based on available data".

- Safety - spacecraft may fall off the crane
- Technical - a part may fail
- Programmatic - cost of an item may grow, or delivery may be delayed

A risk is the concern put into a context. It is the combination of

- the probability (qualitative or quantitative) that an undesired event will occur

[3] GSFC-HDBK-8005, "Guidelines for Performing Risk Assessments", September, 2017.

– the consequence or impact of the undesired event

– a factual context or scenario that exists to cause the risk to be present

In short, risk is an expectation of loss in statistical terms based on an existing condition. A *concern* does not become a *risk* until *likelihood and consequence* are established for the risk.

#### 7.10.2.2 Example Parts Risk Statements

A common parts-related risk emanates from an advisory that warns of a problem that has occurred in some location and context. If the context from the advisory overlaps with the current project context, the overlap can define a context for a new risk.

Example risk statement 1 – technical risk:

*Given that* 20 38534 MLCCs within the affected scope of GIDEP xx are used on the project

*It is possible that* three parts will fail in the combined critical locations after successful completion of I&T with no apparent problems, and subsequent launch

*Resulting in* mission failure

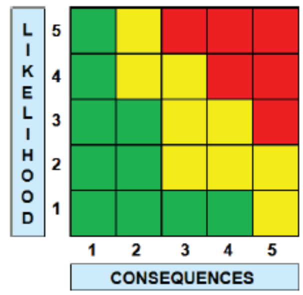
In this case, GIDEP xx identifies a problem that affects some percentage of lots over a 10-year period and some percentage of parts within the affected lots. The data provided are reviewed and an estimate of the likelihood of getting a problematic lot, and then the likelihood of having a part failure if a problematic lot is encountered. The conditions (and supporting data behind them) lead directly to the likelihood of realizing the "it is possible that …" event, while the "resulting in …" provides the ultimate threat to mission success criteria.

In the example above, assuming

- Three part failures are required to cause a mission failure;
- There are 20 parts in the application, out of which any three can cause failure;
- 10% of lots in the time frame are affected, and
- There is a 20% chance of latent (after extended usage in application) part failure in an affected lot.

then, the likelihood of mission failure due to this area of concern, if it is not known if there is an affected lot, becomes $1\text{-}C(20,0)*(0.1*0.2)^{0}(1\text{-}0.1*0.2)^{20}\text{-}C(20,1)*(0.1*0.2)^{1}*((1\text{-}0.1*0.2)^{19})\text{-}C(20,2)*((0.1*0.2)^{2}*(1\text{-}0.1*0.2)^{18}=$ 0.00707 or 0.707%. Using GSFC risk matrix, this would be a 1x5 (yellow) technical risk, shown in Figure 7.10-1.

| Likelihood | Safety<br>Estimated likelihood of Safety event occurrence | Technical<br>Estimated likelihood of not meeting performance requirements | Cost Schedule<br>Estimated likelihood of not meeting cost or schedule commitment |
|---|---|---|---|
| 5 Very High | $(P_{SE} > 10^{-1})$ | $(P_T > 50\%)$ | $(P_{CS} > 75\%)$ |
| 4 High | $(10^{-2} < P_{SE} \leq 10^{-1})$ | $(25\% < P_T \leq 50\%)$ | $(50\% < P_{CS} \leq 75\%)$ |
| 3 Moderate | $(10^{-3} < P_{SE} \leq 10^{-2})$ | $(15\% < P_T \leq 25\%)$ | $(25\% < P_{CS} \leq 50\%)$ |
| 2 Low | $(10^{-5} < P_{SE} \leq 10^{-3})$ | $(2\% < P_T \leq 15\%)$ | $(10\% < P_{CS} \leq 25\%)$ |
| 1 Very Low | $(10^{-6} < P_{SE} \leq 10^{-5})$ | $(0.1\% < P_T \leq 2\%)$ | $(2\% < P_{CS} \leq 10\%)$ |




| Consequence Categories | | | | | |
|---|---|---|---|---|---|
| Risk | 1 Very Low | 2 Low | 3 Moderate | 4 High | 5 Very High |
| Safety | Negligible or not impact | Could cause the need for only minor first aid treatment | May cause minor injury or occupational illness or minor property damage | May cause severe injury or occupational illness or major property damage. | May cause death or permanently disabling injury or destruction of property. |
| Technical | No impact to full mission success criteria | Minor impact to full mission success criteria | Moderate impact to full mission success criteria. Minimum mission success criteria is achievable with margin | Major impact to full mission success criteria. Minimum mission success criteria is achievable | Minimum mission success criteria is not achievable |
| Schedule | Negligible or no schedule impact | Minor impact to schedule milestones; accommodates within reserves; no impact to critical path | Impact to schedule milestones; accommodates within reserves; moderate impact to critical path | Major impact to schedule milestones; major impact to critical path | Cannot meet schedule and program milestones |
| Cost | <2% increase over allocated and negligible impact on reserve | Between 2% and 5% increase over allocated and can handle with reserve | Between 5% and 7% increase over allocated and cannot handle with reserve | Between 7% and 10% increase over allocated, and/or exceeds proper reserves | >10% increase over allocated, and/or can't handle with reserves |

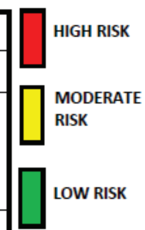



***Figure 7.10-1. GSFC Risk Matrix[4]***

Please note that the latent defect in this context refers to one or a combination of physics of failures induced by parts technology/materials or processes, which is not a latent defect with a failure that is caused by a design corner case that was not encountered in testing or an environmental (e.g., radiation) hit.

One of the historical examples of a latent defect induced part failure is a single ceramic capacitor issue[5] that has now caused failure or serious anomalies (two of which were complete mission failures) for four separate spacecraft, in which the anomalous behavior did not start to appear until months after launch. This problem affected MIL-SPEC Level 1 and Level 2 capacitors. In either case, latent defects are so unusual that the risk of such would only practically defined when it is known that a specific latent defect risk applies.

Example risk statement 2 – programmatic risk:

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[4] Goddard Procedural Requirements (GPR) 7120.4D, August 9, 2020.

[5] GIDEP H6-A-19-01

Since system-level testing assures that most failures of parts occur in I&T, the pertinent risk statement would be programmatic, as in the example above. However, the difference is that it only takes one capacitor failure in ground testing to prompt rework, and in this case, a failure in I&T would be evaluated. Furthermore, for this particular type of part defect, there is a lower likelihood of part failure during I&T, since time and continuous operation is a factor. Lastly, for an I&T failure, we need not only be concerned with the capacitors that will cause mission failure, so there are more that may require replacement. The risk statement is:

*Given that* 20 38534 MLCCs within the affected scope of GIDEP xx are used on the project.

*It is possible that* a part will fail in I&T, then requiring replacement.

*Resulting in* cost and schedule for replacement and regression testing.

In this case, one part failure is required to prompt rework and 100 parts are affected. Assuming

- Same likelihood of encountering a problematic lot (10%);
- Chance of having a failure in I&T is 5%.

This gives a failure likelihood of $1\text{-}C(100,0)*(0.1*0.05)^{0}(1\text{-}0.1*0.05)^{100} = 0.394$ or 39.4%. The consequence of having to perform such a replacement, which would almost certainly be late in I&T would be 3 on the GSFC scale, "Impact to schedule milestones; accommodates within reserves; moderate impact to critical path", thus giving a 3x3 programmatic risk (also yellow) on GSFC risk matrix, shown in Figure 7.10-1.

#### 7.10.2.3 Baseline Risk for Use of COTS Parts

Per GSFC-HDBK-8005[6], the primary means of establishing baseline risk for a particular commodity area is through the use of requirements or specifications that have been proven to enable product development to an acceptable level of risk. It is important to note that baseline risk should always be viewed in the proper context for an area of concern and based on the technical area, it may not appear to align with the risk posture for the project. This view may lead to differing definitions of baseline risk for projects of different risk classifications or risk postures that may not be initially intuitive.

NASA-STD-8739.10 establishes a consistent set of requirements at the Agency level to control risk and minimize reliability impacts of parts in NASA spaceflight hardware and critical GSE. GSFC EEE-INST-002 and MSFC and JPL equivalent parts management and control documents are used at Agency and Center levels for guidance on parts selection, screening and qualification requirements. These documents are considered in this report to establish the baseline risk for use of various levels of parts including use of COTS parts.

[6] GSFC-HDBK-8005, "Guidelines for Performing Risk Assessments," September, 2022.

Those documents recommend MIL-SPEC parts as the first choice or best practice, and specify 1) different levels of MIL-SPEC parts as baseline parts for Level 1-3 parts, and 2) provide detailed requirements to screen and qualify non MIL-SPEC parts to Levels 1-3 (i.e., NASA-screened COTS parts).

#### 7.10.2.4 Risk of Use of COTS Parts

The comparisons between COTS parts versus MIL-SPEC parts and COTS versus NASA-screened parts are highlighted below.

MIL-SPEC parts: Government has control and insight, resulting in part-level verification with full parts knowledge.

COTS parts (defined in Section 7.1.1): Government does not have control or insight, resulting in challenge of part-level verification or guaranteed knowledge of COTS parts. Government control is not prerequisite for high quality and reliability parts, especially when, in recent years, some manufacturers in commercial industry have developed rigorous process controls driven by advanced technologies and commercial market, often equivalent to or exceeding government controls on MIL-SPEC parts. It is equally important to note that this is not universally the case, and may vary from manufacturer to manufacturer.

NASA-screened COTS parts (defined in Section 7.1.1): The COTS parts qualified and screened per NASA Agency, Center or program parts requirements documents, such as EEE-INST-002 or equivalent documents. Such documents typically specify full MIL-SPEC levels of screening and qualification to be performed on COTS parts for them to be used in safety and mission critical spaceflight systems.

As mentioned above, it should be recognized that some COTS parts manufacturers with high volume facilities have advantage over MIL-SPEC parts in that large quantity production and statistical process control can be applied to drive down manufacturing defects, addressing the same concerns that MIL-SPEC level screening and qualification are meant to address. MIL-SPEC parts reliability is achieved by tight controls on proven parts and weeding out parts with features that have been established to represent weakness over a wider temperature range. COTS parts reliability is established through high volume production and field usage, and proven and verified manufacturers. Low volume production and/or unknown or unestablished manufacturers indicate elevated part-level risk. Also note that MIL-SPEC parts are not immune to serious parts problems, which are often, but not always, captured in GIDEP.

Therefore, it is very important for NASA to select and procure COTS parts from those manufacturers who have demonstrated that they are capable of producing parts with high quality and reliability consistently, at least comparable to MIL-SPEC parts.

In this report, the team defined those manufacturers as ***Industry Leading Parts Manufacturers (ILPMs)***. For easy reading purpose, an ILPM is a parts manufacturer that has high volume automatic production facilities and can provide documented proof of the parts' technology, process and product qualification, and its implementation of industry best practices including processes, methods and tools towards "zero defects" approach for parts quality, reliability and workmanship for parts intended commercial applications.

Since all COTS parts are not created equal and the details of the level of part-level verification can be dramatically different, it is best to avoid making broad statements about risk solely based on the word "COTS". Even with COTS parts from ILPMs, there is no Agency requirement or consensus regarding the types of the data, the sources of the data and the level of part-level verification would be sufficient for COTS parts. Current practices vary from no verification at part-level for Class D and sub-Class D missions to full verification at part-level for safety and mission critical spaceflight systems for Category 1-3 and Class A-C missions, depending on Center's practices and project's risk posture.

There is a different philosophy in COTS that can help reduce risk in COTS as compared to MIL-SPEC parts, but context is very important. Therefore, knowing the background of the part you are using and its manufacturer's processes are the most important steps in parts selection (Section 7.10.3), verification (Section 7.10.4) and applications (Section 7.10.5) to get you to lower risk, especially for constrained projects such that sufficient resources will be available for system-level testing and problem resolution.

Please also note that COTS and MIL-SPEC parts are not manufactured or designed for space applications, and that full or partial space radiation qualification and/or evaluation is required for both. Considerations on COTS parts radiation hardness assurance are included in Section 7.10.6.

#### 7.10.2.5 Additional Considerations about Risk Associated with Use of COTS Parts

Outside of parts that have been identified as known problematic parts, what gives rise to elevated risk of use of COTS parts, when they are properly used within the specified bounds per their datasheets? The following cases point to special circumstances that may prompt elevated risk:

1. Highly specialized or high performance parts are typically COTS that go well outside of the capability of anything in the MIL-SPEC. Not only do the performance aspects often provide unpredicted stresses to the part making derating guidelines a challenge, but the parts have features that make it difficult

to provide effective screens especially at part-level. An example would be ceramic capacitors that have exceptionally low ESR or ESL. The low ESR and ESL requirements give rise to extremely sensitive features in the parts that can react to even the slightest manufacturing variations.

2. COTS parts that are hand-produced regardless of lot size are subject to human factor variations. Risks are most likely to be elevated, especially when a project requires production at a higher rate than the manufacturer typically maintains because (1) it may give rise to a rush in production and (2) it may require new, less experienced technicians to be brought in.
3. High voltage and cryogenic-specific parts tend to be only available as COTS, and both of these aspects involve conditions that are very difficult to model and that have inherent material breakdown and extreme sensitivity to workmanship. Furthermore, derating guidance is elusive.

#### 7.10.3 Best Practices on COTS Parts Selection

*First, COTS parts need to meet project's MEAL requirements.*

Circuit Designers should work with EEE Parts Engineers when selecting COTS parts for spaceflight systems. The COTS parts selection should meet **MEAL**[7] requirements, with MEAL defined as **m**ission (mission risk classification, risk posture, schedule, cost, etc.), mission **e**nvironment (radiation, thermal, vacuum, etc.), **a**pplication (fault tolerance, architecture, SWaP, functions, performance, etc.) and **l**ifetime of the mission (lifespan of the mission, system operating conditions during the mission, etc.). This MEAL-based parts selection is not only for COTS parts, but applies to selection of any part type including MIL-SPEC parts. Note that the risk posture comes into play when it is determined that the parts selected are of elevated risk for failure compared to the baseline risk.

There are various types/grades of COTS parts, which are basically any parts qualified and screened by commercial manufacturers or third party without government insight. Figure 7.10-2 shows a Venn diagram of notional COTS parts universe with some percentage of COTS meeting MEAL requirements. If MEAL changes, it changes the size of the red circle, thereby changing the proportions of parts that will meet the requirements.

Some of the Center best practices include:

- Select COTS parts from ILPMs (defined in Section 7.1.1 and detailed later in this sub-section) and the highest commercial grades available from each ILPM (e.g., hi-rel, AEC-Q parts, etc.);
- Select COTS parts in matured technology parts (e.g., technology generations/ nodes between 2-8 years old);
- Select COTS parts that are widely used in the commercial electronics;

[7] NASA/TM–2018-220074, "Guidelines for Verification Strategies to Minimize Risk Based on Mission, Environment, Application and Lifetime (MEAL)," June, 2018.

- Recognize leading edge technology parts may require significant specialized effort to ensure the reliability, and thus, if possible, avoid selection of COTS parts in early technology or not produced in high volume or designed at the limit of their technology (e.g., a 24-bit ADC in a process where the next higher resolution is 16 bits); and
- Select parts with "flight heritage" AND ensure the MEAL for the new mission is within the bounds of the previous mission, as shown in Table 7.10-1.

Those practices provide a way of limiting the parts to those with the highest chance of meeting MEAL requirements and eliminating those least likely to meet the requirements.

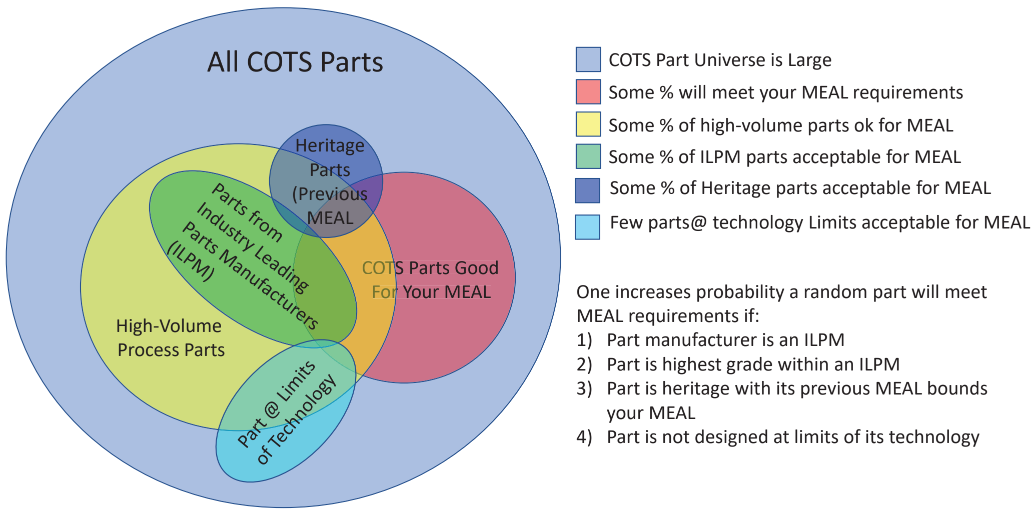


***Figure 7.10-2. Notional Concept of Selecting COTS Parts to Meet MEAL Requirements***

***Table 7.10-1[8]. Parts "Flight Heritage" Assessment by MEAL – MEAL for the New Mission needs to be within the Bounds of the Previous Mission***

| | | TRL # | Description / Description as stated on 7120.5C | (a) New Technology | Mission Examples: Environment, Application, Lifetime (b) | Environment, Application, Lifetime (c) | Environment, Application, Lifetime (d) | Environment, Application, Lifetime (e) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Proposed New Mission MEAL (mission environment, application and expected lifetime) is equal or a subset of the previously flown mission MEAL, including identical concept, form fit, design, interfaces, etc. | Proposed New Mission application and expected lifetime is equal or a subset of the previously flown mission, including identical concept, form fit, design, interfaces, etc., but with an environment outside the previously flown mission. | Proposed New Mission MEAL is equal or a subset of the previously flown mission MEAL, but with different application implementation (i.e. different design outside the previously flown like mechanical, thermal &/or electrical) | Design previously flown but different application, environment and lifetime (where the original application does not envelope the new application) |
| Concept | | 1 | Basic principles observed and reported | V&V | Previous Data Available | Previous Data Available | Previous Data Available | Previous Data Available |
| Concept | | 2 | Technology concept and/or application formulated | V&V | Previous Data Available | Previous Data Available | Previous Data Available | V&V |
| Concept | | 3 | Analytical and experimental critical function and/or characteristic proof-of-concept | V&V | Previous Data Available | Previous Data Available | Previous Data Available | V&V |
| Implementation | Ground | 4 | Component and/or breadboard validation in laboratory environment | V&V | Previous Data Available | Previous Data Available | V&V | V&V |
| Implementation | Ground | 5 | Component and/or breadboard validation in relevant environment | V&V | Previous Data Available | V&V | V&V | V&V |
| Implementation | Ground | 6 | System/subsystem model or prototype demonstration in a relevant environment | V&V | Previous Data Available | V&V | V&V | V&V |
| Implementation | Space | 7 | System prototype demonstration in the real environment | V&V | V&V | V&V | V&V | V&V |
| Implementation | Space | 8 | Actual system completed and "flight qualified" through test and demonstration | V&V | V&V | V&V | V&V | V&V |
| Implementation | Space | 9 | Actual system "flight proven" through successful mission operations | V&V | V&V | V&V | V&V | V&V |
| | | | Comments: | Must undergo through the entire TRL process | Must verify system/subsystem under relevant environment (acceptance verification test) | Must validate component &/or Breadboard under relevant environment. | Must validate component &/or Breadboard under laboratory environment. | Must be treated as the new technology |

Notes:

| | |
|---|---|
| V&V | Must be validated and verified as per TRL Definitions and descriptions. |
| Previous Data Available | Validation data available from previously flown/validated system. Requires Verification at all levels of implementation. |

*Second, select COTS parts from Industry Leading Parts Manufacturers or manufacturers that possess DLA certifications for their other product lines.*

An ILPM was defined in Section 7.1.1.

Those ILPMs have high volume automatic production lines and implement diligent and proven industry practices toward "zero defects" approach, which in turn results in minimized concern of infant mortality or failure during the part's design lifetime and intended environments, and produces parts that exhibit high part-to-part and lot-to-lot homogeneity. One of the references, AEC-Q004[9], "Automotive Zero Defects Framework" describes these practices with details. The list below is some of the industry best practices for "zero defects" approach that an ILPM should have successfully implemented:

a. The parts manufacturer designs parts with an eye toward manufacturability, testability and field reliability, and operating life. Tools that facilitate this are the Design FMEA and Process FMEA.

b. Parts are manufactured on automated, high-volume production lines with minimal human operation. Parts not built on such lines should not benefit from assumptions about sameness part-to-part or lot-to-lot and are candidates for part-level screening and qualification.

c. The manufacturer understands and documents the entire manufacturing process and the impact and sensitivity of each step on product characteristics and quality. A robust manufacturing plan allows for step-by-step

[8] NASA/TM–2018-220074, "Guidelines for Verification Strategies to Minimize Risk Based on Mission, Environment, Application and Lifetime (MEAL)," June 2018.

[9] AEC-Q004, "Automotive Zero Defects Framework", February 26, 2020.

verification and assurance that the in-process work meets standards and is ok move to the next manufacturing step. This is done through the use of Process FMEA, establishment of a robust control plan, process characterization (reference JEP132), SPC (reference EIA-557), and standards for allowable deviations in key process characteristics (i.e., automotive manufacturers commonly require CpK > 1.67 for key processes).

d. The manufacturer's end-product testing includes 100% electrical verification of datasheet parameters, multi-lot qualification (JESD47, AEC-Q100), shift-based, lot-based, daily, weekly, quarterly samples pulled for process monitor testing and ongoing reliability testing, generation of statistically relevant Early Life Failure Rates (JESD74), outgoing Defect Parts Per Million (JESD16), and useful life Failure In Time (JESD85).

e. The manufacturer implements rules for the removal of outlying parts (i.e., AEC-Q001), removal of abnormal lots (i.e., AEC-Q002). These rules may apply at either the finished part level or in-process.

f. The manufacturer implements a robust change system that assures all major changes are properly qualified (JEDEC and AEC and others provide requirements for requalification) and that customers are notified of major changes (JESD46).

g. The manufacturer implements a robust Quality Management System that is acceptable for spaceflight. AS9100 and IATF16949 are examples of certifications that indicate good quality management.

Since COTS parts are not designed or manufactured for space radiation environments, parts from ILPMs need to be evaluated for radiation effects, and it should not be a surprise that an ILPM part does not meet project's radiation requirements. Selecting parts from ILPMs is a starting point for parts reliability, but necessarily for parts radiation responses.

It is important to note, that while there exists some overlap between manufacturers that produce AEC qualified parts, and ILPMs, this is not necessarily a direct relationship. An ILPM does not necessarily need to be an AEC qualified part manufacturer, and conversely an AEC qualified part manufacturer does not necessarily meet all the criteria to be considered an ILPM. AEC specifications consist of a broad range and variability of requirements in terms of process control and verification, and relies heavily on manufacturer self-certification and self-imposed requirements. Further research into the individual manufacturers' processes and parts is needed to determine if they meet the criteria to be considered an ILPM. Many of the concepts described in AEC specifications are also applied in establishing ILPMs, however it is important to verify the criteria have been met for individual AEC qualified manufacturers, it is not guaranteed.

### 7.10.4 Current Practices on COTS Parts Verification

The selection and verification of any parts technology, including COTS, in space flight systems programs should be based on the MEAL, which influence the design, development, integration, implementation, end-of-mission conditions, and verification process. COTS parts verification strategies should be performed at part-, board- and system-level.

There is a lack of NASA consensus in part-level verification Therefore, the Center current and best practices on verification are considered as current practices instead of the best practices at this point.

#### 7.10.4.1 COTS Part-level Verification

Part-level verification for COTS use in spaceflight systems remains a major challenge, since there is no government insight or direct/formal communication channel existing with the COTS parts manufacturers. In addition, part-level verification may require a different set of testing other than MIL-SPEC standards.

There is no Agency requirement or consensus regarding the types of the data, the sources of the data, or the level of part-level verification that would be sufficient for COTS parts verification. Current practices vary from no verification at part-level for Class D and sub-Class D missions to full verification at part-level for safety and mission critical elements in spaceflight systems for Category 1-3 and Class A-C missions, depending on Center's practices and project's risk posture.

GRC, GSFC, JPL, JSC, LaRC, and MSFC emphasize COTS parts verification at part-level.

ARC (Section 7.2) focus on selecting parts from ILPMs and parts with past usage with minimum part-level verification except for best effort visual inspection and counterfeit parts control. When a part is not from an ILPM, ARC typically does not perform part-level testing per EEE-INST-002, but rather conduct full qualification and testing at board- and subsystem-level tailored per project requirements.

JSC has an alternative parts plan EDCPAP (Section 7.6.4) that starts with the requirement that every part on flight hardware should be defect-free and should be qualified to the limits of its datasheet. EDCPAP seeks to verify these requirements by gaining insight into the manufacturer's processes. If evidence that the manufacturer is following best practices for process control, screening, defect elimination, periodic testing for reliability monitoring, qualification, process change re-qualification, etc., then the part requirements are met. If such information cannot be obtained, then the "traditional" approach of part-level MIL-SPEC/NASA screening and qualification may be employed.

The NESC team recommends the following current and best practices on part-level verification:

- Perform parts manufacturer assessment. Verify parts manufacturer has documented proof of high standards for quality, ILPMs. The levels of verification can be based on published materials (e.g., Quality Manual, DPPM and FIT rates) published on the manufacturer's website, or unpublished materials obtained through direct contact with the manufacturer, or through third party.

- Perform re-evaluation on verified ILPMs periodically.
- Understand parts technology. When a COTS part's construction is not fully understood or it is not selected from an ILPM, perform DPA and/or parametric/functional testing on sample parts or and any other testing necessary (e.g., x-ray, PIND, etc.) to ensure the part meet MEAL with project risk posture.
- Establish and maintain an ongoing relationship with parts manufacturers, especially with their local offices.
- Monitor manufacturer changes through the monitoring of PCNs, GIDEPs, and other Alerts. Recent changes should be reviewed and the appropriate parties notified.

It should be recognized that part-level verification may require a different set of testing other than MIL-SPEC standards. For example, new technology implementations in packaging of parts are more common in automotive and non-automotive grade devices and require new and specialized techniques during de-processing for DPA. The standard de-processing techniques specified by the military standards (e.g., MIL-STD-1580) used in ceramic/metallic hermetic space level packages are insufficient for properly evaluating the nuances in the more cutting-edge design/construction parts.

#### 7.10.4.2 COTS Board- and System-Level Verification

All Center's system-level verification processes and standards have remained unchanged with use of COTS parts, even when less part-level verification performed.

Some projects performed more testing at board- and assembly-level, and ARC has implemented a Center-wide practice of performing a large amount of board- and subsystem-level testing early on in the design cycle.

For class D missions and below, GSFC (Section 7.4) is flexible on its GOLD rules[10] that requires 1000+ hours power-on testing on hardware while reinforcing a best practice of accumulating as much testing hours (e.g., 500-1000 hours) as possible at system level especially when COTS parts used have less part-level verification. Board- and system-level power-on testing is to verify the design and system, and demonstrate trouble-free parts performance and help reduce the risk of failures after launch.

ARC has demonstrated a successful use of almost entirely COTS parts methodology (Section 7.2) for Class D and sub-Class D projects, focusing on building large quantity of multi-revision engineering units (EDU) and performing testing at board- and subsystem-level early and often.

[10] GSFC-STD-1000G, "Rules for the Design, Development, Verification, and Operation of Flight Systems".

### 7.10.5 Best Practices on COTS Parts Applications

The best practices on COTS parts applications started with COTS parts functional and environmental verification to meet MEAL.

The use of circuit level fault-tolerant design and testing with proper derating practices and radiation hardness assurance (RHA) to assure reliability of a part in an application applies to the use of COTS and MIL-SPEC parts.

Compared to MIL-SPEC parts, COTS parts are typically not designed to withstand the environmental (thermal, moisture, etc.) extremities as their equivalent MIL-SPEC parts. For example, the operating temperature ranges for different flavors of COTS parts, and while some parts may overlap with the traditional military temperature range (-55 °C to +125 °C), other parts may have different and narrow operating temperature ranges. There should be no expectation that most COTS will survive typical MIL-SPEC screening and qualification tests at extreme conditions outside of its specified operational range, and those differences need to be recognized since they may present design, reliability, and radiation challenges if they are not accounted for. Derating and radiation hardness assurance on COTS parts are not much different from MIL-SPEC parts, although COTS parts may need additional derating (e.g., GEIA-STD-0008) compared to their MIL-SPEC counterparts, mainly for passive parts, to achieve comparable reliability. RHA considerations for COTS parts is included in the next Section 7.10.6.

More details (e.g., approach in circuit design, evaluation, verification, design for radiation tolerance, etc.) are included in Center's best practices sections in Center's reports.

- Identify critical parameters for all parts in designs and verify parts parametric and functions by testing over application range, e.g. over operating temperature condition with margin.
- Identify environments (e.g., thermal, vibe, helium, radiation, partial vacuum atmosphere plasma arcing/discharge) that might be problematic for parts in their applications and verify by testing and analysis to address the concern.
- Use manufacturers' SPICE models and demonstration and/or evaluation boards for circuit verification and implement board- and system-level verification early on in the development cycle to avoid negative impact on cost and schedule should any failures occur.
- Use more conservative derating (e.g., GEIA-STD-0008, EEE-INST-002) for COTS parts in comparison to its MIL-SPEC counterpart to achieve comparable reliability, notwithstanding other pertinent attributes of either type of part.
- Use commercial version of radiation-tolerant parts, if available. Some parts are offered in both commercial versions and versions with known radiation tolerance (and often additional screening tests applied). Using the commercial versions of those parts can offer similar radiation tolerance, and

also allow savings in cost and lead time. This needs to be evaluated on a case-by-case basis.

- Design for radiation tolerance at board and subsystem level, if not possible at part level, by using strategic redundancy, circuit mitigation (e.g. watchdog circuits) and power cycling to limit functional disruption during nondestructive radiation upsets, and reduce or eliminate (e.g. over-current protection) the effects of potentially destructive upsets such as micro-latchup and SEB failure, and other mitigations (HW & SW) through circuit designs.
- Radiation-tolerant circuit design should supersede individual part radiation hardness efforts, whether using COTS (or MIL-SPEC parts in this matter). For COTS parts, plan on more extensive radiation testing and mitigation than with MIL-SPEC counterparts, as there should be a greater level of expectation that radiation will cause a problem.
- Follow COTS parts RHA considerations in Section 7.10.6 and the detailed guideline in NESC-RP-19-01489 "Guidelines for an Avionics Radiation Hardness Assurance".

### 7.10.6 RHA Considerations for COTS Parts

The boundary between the atmosphere and the beginning of space is generally taken to be the von Karman line at 100 km altitude[11]. COTS parts and most MIL-SPEC parts are not explicitly designed for space applications.

Some MIL-SPEC parts are designed for atmospheric applications that are sensitive to neutron and alpha particle SEE. TID and total non-ionizing dose (TNID) are currently of no concern for terrestrial and atmospheric technologies with few exceptions, such as nuclear medicine and nuclear/accelerated-based applications. However, in cases where atmospheric radiation effects are addressed during the design process, the space radiation environment is quantitatively and qualitatively more severe than the atmospheric radiation environment. Peak particle fluxes, mainly neutrons in the atmosphere and protons in LEO, are two or more orders of magnitude higher in space than in the atmosphere. In addition, even the most benign space environment also poses the threat of the heavy-ion component of galactic cosmic rays, which can cause destructive SEEs with greater probability than protons or neutrons. Technically, heavy ions can also reach the stratosphere, but fluxes are an order of magnitude or lower than GEO, and LET spectrum is softer.

There is not currently a low impact means of translating from terrestrial use conditions to space applications. Engaging those terrestrial parts to meet space radiation requirements, whether for programmatic and/or technical reasons, will continue to require experiential knowledge combined with effective risk identification and management.

[11] https://www.nesdis.noaa.gov/content/where-space

The microelectronics supply chain also offers other parts grades that are important to keep in mind for appropriate context. Radiation-tolerance implies inherent reliability, but reliability does not imply radiation tolerance.

MIL-SPEC parts may or may not include a radiation hardness (RH) designator, but those with RH designators may not include all radiation issues of interest. For example, a device that has a RH designator for TID, may be sensitive to SEE. From this standpoint, COTS and MIL-SPEC devices without all appropriate RH information may be treated the same with one exception. One is able to specify single lot purchase for MIL-SPEC devices and usually not for COTS. This takes one of the variables for RHA out of the picture: the lot-to-lot variation of radiation sensitivity since space radiation is not designed and optimized for COTS parts.

It is important to note that parts levels in EEE-INST-002 and equivalent documents do not indicate the level of radiation tolerance, and thus the selection of levels 1, 2, or 3 does not imply or provide any type of radiation hardness or mitigation of radiation effects. Even in cases where these parts carry a radiation hardness assurance designator (e.g., MIL-SPEC parts in MIL-PRF-38535), it may only apply to TID and possibly TNID. Items intentionally hardened against TID, TNID, and SEE are rare.

**General RHA Principles**

Radiation threats for COTS parts do not differ qualitatively from any other part fabricated in a similar technology. Any parts intended for terrestrial applications are almost certain to have been designed and fabricated with little or no consideration of their radiation susceptibilities. There may be a few exceptions to this statement, but without specific knowledge on radiation performance it is unwise making assumptions. For RHA principles and guidelines for COTS parts, and MIL-SPEC parts, please refer to NESC-RP-19-01489 “Guidelines for an Avionics Radiation Hardness Assurance”.

**RHA Considerations for COTS Parts**

Compared to MIL-SPEC parts, the factors that exacerbate radiation risk for COTS are:

- Applicable archival radiation data (e.g., TID, TNID, and/or SEE) for COTS parts may be difficult to find.
    - The large number of COTS manufacturers, coupled with their short product life cycle, make it likely that archival radiation data for the part may not exist.
    - Even if a part has been radiation tested, organizations may consider the data sensitive since a SOTA part may be critical to their design architecture. Moreover, even if data are obtained, they may only be applicable for that organization’s application(s).
    - Design mask set or fabrication process-related changes may invalidate archival data even though acceptable form, fit, and function are maintained. COTS manufacturers are not necessarily required to notify

customers of these changes and they can have dramatic effects on radiation performance.

- SOTA parts can have short product life cycles or between die revisions, leaving a very short window for procuring parts once a favorable radiation test outcome is realized. This can impact economy of scale operations that do not have robust periodic characterization processes. One example is SOTA DDR and Flash, when a die revision can completely invalidate past radiation testing results, and die revisions can happen as rapidly as 18 months.
- For heavy ion SEE testing, ensuring that ions penetrate sufficiently to traverse device sensitive volumes often requires the active die surface be exposed and possibly thinned. The close integration of semiconductor and packaging inherent to complex parts often makes such exposure very difficult if not impossible. Moreover, alteration of the part may be sufficiently disruptive that part functionality is affected. This is not unique to COTS parts, but the situation with COTS parts significantly exacerbates the issue, where lead frames and other packaging are integral to the structural stability of the part, and components such as capacitors were epoxied to the die in such a manner that they cannot be removed without destroying the die. It has become more challenging with increasingly sophisticated integration schemes, such as 3D and system-in-package (SIP) COTS parts.
- SOTA COTS parts may pose significant testing challenges, resulting in high testing costs. Radiation-hardened or space parts technology lags behind commercial technology by about 3-4 generations by now. As a result, projects may run into the following issues with advance rad hard parts, which will be worse with SOTA COTS parts.
    - Complicated SOTA parts usually require sophisticated test equipment, which is expensive and difficult to use in radiation test facility environments.
    - SOTA parts may have many different operating modes and conditions, each of which may have different susceptibilities. This can result in either long, expensive test campaigns or incomplete data collection.

Figure 7.10-3 lists a sampling of radiation effects and assigns a color to possible attributes that indicates whether the combination is specific to COTS parts or not. The colors do not necessarily indicate low or high risks. Combinations that are very specific to COTS (red), suggest that users consider a more customized and deliberate approach that may include specific radiation testing and mitigation approaches. Please note that the color scale in Figure 7.10-3 does not classify the severity or risk associated with particular attributes or radiation effects. All radiation effects should be reviewed regardless of whether they are specific to COTS parts or not.

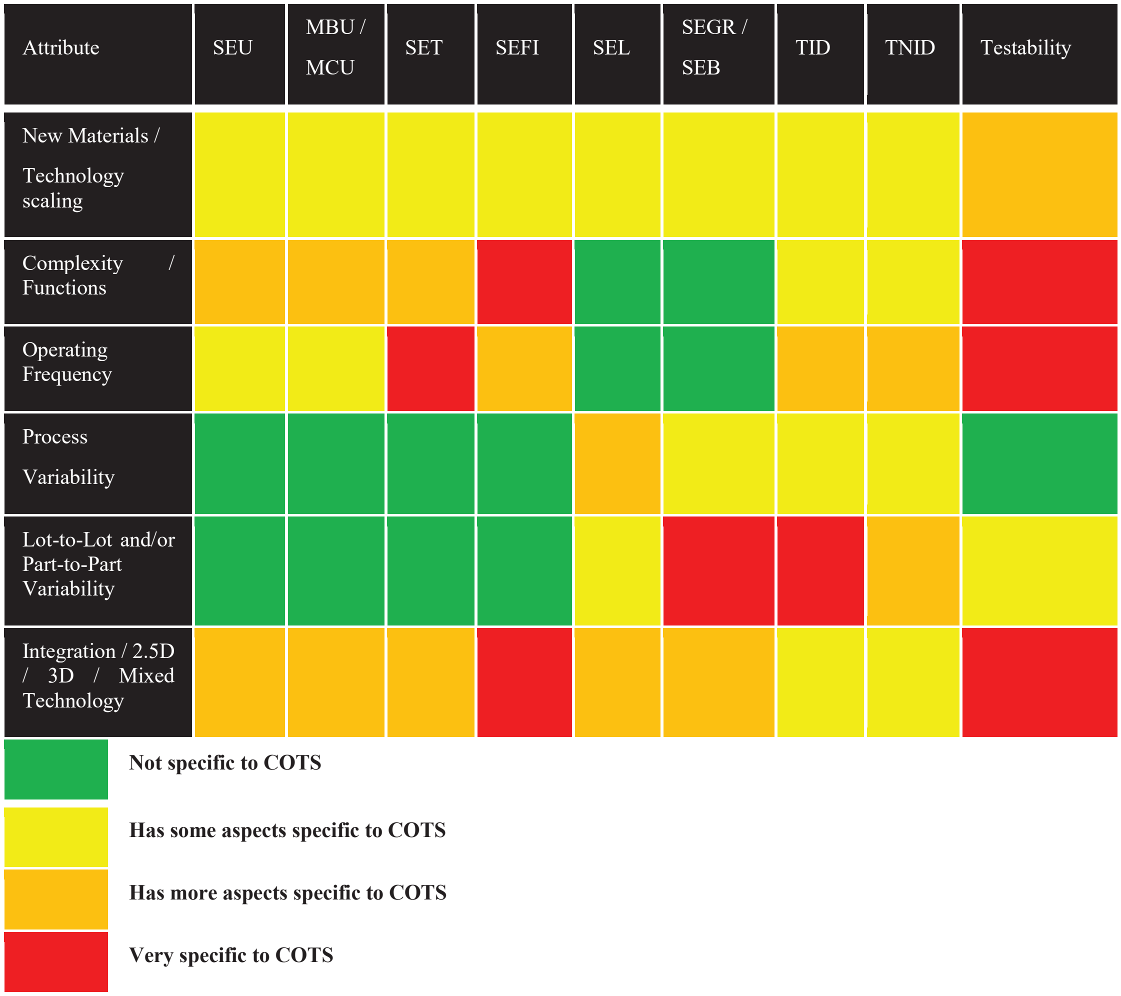


***Figure 7.10-3. COTS Parts Color Codes for Unique Radiation Effects and a Sampling of General Attributes for Consideration***

## Specific RHA Focus Areas for COTS Parts

In addition to the general principles above, the NESC team needs to highlight several other topics in the context of COTS parts RHA. While the NESC team are not treating these in detail, summary information and/or references are provided for more detailed consideration.

- Testing with high-energy proton versus heavy ions[12].
- Coverage issues – protons are a very inefficient means of generating heavy ions. The same heavy ion flux from protons means more than 100x as much ionizing dose on a part as heavy ions from an accelerator. Protons are also poor at detecting

[12] R. L. Ladbury and J.-M. Lauenstein, "Evaluating Constraints on Heavy-Ion SEE Susceptibility Imposed by Proton SEE Testing and Other Mixed Environments," *in IEEE Trans. Nucl. Sci.*, vol. 64, no. 1, pp. 301-308, Jan. 2017.

destructive failure modes. Proton inelastic reaction daughter products have limited LET and range.

- Conducting radiation testing versus investing program resources elsewhere (i.e., no testing).
    - Dose- and SEE-related failures can occur in benign radiation environment applications. More than 50% of COTS CMOS parts suffer SEL at some LET level[13]. It was observed[14] TID functional failures at less than 2 krad(Si). Dose effects can also undermine redundancy-based mitigation schemes. Design teams need to consider MEAL in testing decisions. Engineering judgement is subjective and the next part or application can invalidate decisions.
- Testing at the part, board, or box level[15] [16].
    - Testing at different levels of integration yeilds different information and is sensitive to different failure modes. Failures tend to be more costly when detected at higher levels of integration, so informed risk posture and functional analysis are required to trade risks. Board- and box-level testing may be desireable to validate design approaches, including mitigation. Keep in mind the earlier comments on proton versus heavy ion testing.
- Evaluating part variability in the absence of traceability or a controlled process baseline through larger sample sizes.
    - Some COTS parts have exhibited significant variability[17] [18], and lack of experience with similar parts makes it hard to judge a priori the significance of potential sampling errors. Traceability is not always possible for COTS parts, casting doubt about the validity of qualification testing vice recurring lot acceptance testing.
- Characterizing or performing lot acceptance tests on power and radio frequency (RF) devices, including wide bandgap materials and other new technologies.

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[13] G. R. Allen *et al*., "2017 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group," 2017 IEEE Radiation Effects Data Workshop (REDW), New Orleans, LA, 2017, pp. 1-14.

[14] See "Table VI: The Latest Surprises in SEE Hardness Assurance" in R. L. Ladbury, "Strategies for SEE Hardness Assurance—From Buy-It-And-Fly-It to Bullet Proof," *IEEE NSREC Short Course*, New Orleans, LA, Jul. 2017.

[15] NASA/TM–2018-220074, "Guidelines for Verification Strategies to Minimize Risk Based on Mission, Environment, Application and Lifetime (MEAL)", June 2018.

[16] NASA/TM–2019-220269, "Radiation Single-Event Effects (SEE) Impact on Complex Avionics Architecture Reliability," 2019.

[17] J. S. George, et al, "Response Variability in Commercial MOSFET SEE Qualification", IEEE Transactions on Nuclear Science, Vol. 64, No. 1, Jannuary, 2017.

[18] R. L. Ladbury, et al, "Use of Commercial FPGA-Based Evaluation Boards for Single-Event Testing of DDR2 and DDR3 SDRAMs", IEEE Transactions on Nuclear Science, Vol. 60, No. 6, December, 2013.

- New materials and device topologies, and greater integration and complexity increase the need to consult with subject matter experts on device type and radiation effects. Hybrids and systems on a chip integrate diverse devices and materials, making it difficult to select worst-case test conditions.
- Wide bandgap power transistor technologies, such as GaN and SiC power transistors, continue to be an active area of radiation effects research presenting numerous testing, analysis, and SEE rate prediction challenges in spite of robust TID and TNID performance. Designing with these parts, even in benign radiation environments, requires caution[19].

**Guideposts for Designing with COTS Parts**

Designing for radiation tolerance at the board- and subsystem-level becomes even more important because of the unknowns in terms of tracebility and variability when using COTS parts, regardless of the mission payload risk classification. The NESC has conducted several previous assessments that provide insights into this trade space (e.g., NASA/TM–2018-220074 and NASA/TM–2019-220269). Additionally, the small satellite community has invested effort to understand this problem. The NASA Small Spacecraft Virtual Institute (https://www.nasa.gov/smallsat-institute) and their Small Satellite Reliability Initiative (https://www.nasa.gov/smallsat-institute/reliability-initiative) provide many resources. There are also a host of domain-specifc approaches in proceedings (https://digitalcommons.usu.edu/smallsat/) from the annual Small Satellite Conference (https://smallsat.org/) – see, for example, Sinclair, D. and Dyer, J. 2013. "Radiation Effects and COTS Parts in SmallSats," *Proceedings of the AIAA/USU Conference on Small Satellites, Strength in Numbers*, SSC13-IV-3. https://digitalcommons.usu.edu/smallsat/2013/all2013/69.

Many of these resources include guidance on use of redundancy, types and levels of error correction, over-current / voltage monitoring circuits, and other mitigation paths that touch both H/W and S/W at various levels of integration. In some cases, radiation-tolerant circuit implementation at the board-level may supersede part-level radiation hardness assurance efforts, whether using COTS or MIL-SPEC parts. For COTS parts, it is reasonable to assume the need for more extensive radiation testing and/or mitigation than with equivalent MIL-SPEC counterparts. There should be an expectation that radiation will cause problems. Even radiation-hardened MIL-SPEC parts can produce radiation-induced failures in poor designs, so avoid treating MIL-SPEC parts as a panacea for radiation effects mitigation.

COTS parts provide a wide range of attractive options for space system designers. No matter the motivation, projects leveraging COTS parts must acknowledge that the desireable features come with associated risks that can have dramatic impacts on space radiation environment performance. Understanding how to identify and mitgate COTS parts radiation risks is governed by knowledge of how the chosen parts will perform

[19] J.-M, Lauenstein, "Wide Bandgap Power SiC and GaN Radiation Reliability", IEEE Nuclear and Space Radiation Effects Conference, December 2020.

over time in a given mission, environment, and application. Making assumptions about COTS parts' radiation performance in the absence of necessary or sufficient data can lead to unbounded risks impacting mission success.

#### 7.10.7 Common Concerns on Use of COTS and the Team's Comments

The NESC team listed some common concerns and comments on use of COTS parts. This section has been preserved as originally written during the Phase I study for historical context; however, the information described in this section has been further investigated and evolved as part of the Phase II study. For the most current information, the Phase II report is available at https://ntrs.nasa.gov/citations/20220018183.

***1. The COTS parts are unscreened. They might fail at any moment.***

NESC team's comments: There are different types of "screening", and there is a large variability among COTS parts manufacturers. The team recommend selecting the highest-grade COTS parts from ILPMs (Section 7.10.3), derating parts in circuit design, and performing radiation hardness assurance on the COTS parts for spaceflight systems.

***a) Are COTS parts unscreened?***

Screening is meant to be performed on 100% of parts that are either used in qualification or in applications. In this sense, the screening performed by MIL-SPEC/NASA and COTS manufacturer are different. The team defined "MIL-SPEC/NASA screening" and "COTS manufacture screening" in Section 7.1.1. For easy reference, the definitions are as follows:

MIL-SPEC/NASA screening – Nondestructive tests (electrical and environmental stress), applied to 100% of parts in a lot and intended to remove nonconforming parts (parts with random defects that are at increased risk of resulting in early failures, known as infant mortality) from an otherwise acceptable lot and thus increase confidence in the reliability of the parts selected for use. Specific tests and required thresholds are listed in applicable requirement documents (MIL-SPECS/NASA documents).

COTS manufacturer screening – Nondestructive tests defined and implemented by parts manufacturers, performed on 100% of parts and intended for functional verification of partial or full datasheet parametric specifications typically at room temperature or manufacturer-defined temperature range, or for removal of early failures, or identification of parametric outliers. Nondestructive testing varies among different manufacturers.

As can be seen, MIL-SPEC/NASA screening may be different from COTS manufacturer screening. MIL-SPEC/NASA screening includes burn-in, intended to remove infant mortal or early failures, while COTS manufacturers define their own screening processes, which can vary, especially across different types of parts (e.g., semiconductors, passives, etc.). In most cases, COTS manufacturer screening typically focus on partial or full parametric testing per datasheet, and may only include burn-in on parts for qualification but not on parts for procurement in application.

Therefore, COTS parts are not screened per MIL-SPEC/NASA screening process, but may be screened per COTS manufacturers.

***b) Is COTS manufacturer screening acceptable?***

It depends on the level of verification on the COTS part and its manufacturer required by Project/Center, and MEAL (Section 7.10.3).

The NESC team's first recommendation is to select the highest-grade COTS parts from ILPM. An ILPM is defined (Sections 7.1.1 and 7.10.3) as a parts manufacturer that has high volume automatic production facilities and can provide documented proof of the parts' technology, process and product qualification, and its implementation of industry best practices including processes, methods and tools towards "zero defects" approach for parts quality, reliability and workmanship for intended commercial applications.

When a parts manufacturer is verified as an ILPM, the manufacturer is expected to exhibit industry best practices toward "zero defects" for their part types, and the concern of infant mortality or failure during the part's design lifetime is minimized. The implementation of "zero defects" approach, along with technology and process qualification and product qualification, are targeted at removal of defective parts and lots from the population and maintain a very low DPPM.

In semiconductor industry, manufacturers typically perform burn-in in their product qualification, and then sample burn-in as a monitor for production line health or consistence and an indicator for early failure rate. Burn-in on 100% of parts is not typically included in COTS manufacturer screening processes. For ILPMs, all parts are expected to be "COTS manufacturer screened" (i.e., not burned-in per MIL-STD or EEE-INST-002) for parts performance and early failures typically at room temperature to the parameters on the datasheets. It is true that testability and test coverage on parts can never be 100%; but they are very close. Most parameters on the datasheets are only tested at nominal test conditions such as voltage and temperature; but these limits are derived from extensive characterization over multiple lots of qualification data so that they meet the extreme limits covered in the datasheets. This is how semiconductor ILPMs assure that their parts are of good quality. High-volume and widely used COTS parts tend to have very low DPPM numbers because issues are expected to be uncovered and dealt with early due to the high volume of production and usage in many different applications.

The majority of passive COTS are not burned-in either, except simple verification electrical testing, also typically at room temperature. It is the NESC team's experience that the lowest level of COTS may not meet many of the test, even within manufacturer advertised limits. Automotive grade parts were surveyed and found there is no 100% screening, but there is significant lot qualification testing. Hi-rel space grade COTS parts get significant screening that may be similar or even equivalent to MIL-SPEC parts.

The NESC team's second recommendation is to identify critical parameters for all COTS parts in designs and verify their parametric and functions by testing over the expected application range with margin, e.g. over operating temperature condition with margin. In addition to parts verification, the performance over temperature could also serve as an indicator for a possible inherent vulnerability arising from low margin in the parts design, or as a signal for potential radiation issue.

***c) COTS might fail at any moment?***

It should be recognized that no qualification or process control or testing can predict when a part fails or guarantee a part not to fail over a period. Such is equally the case for MIL-SPEC parts or NASA-screened parts. Reliability is a probability, not a certainty.

Since COTS parts are not designed or manufactured for space radiation environments, an ILPM part may not meet project's radiation requirements, and all COTS parts need to be evaluated for space radiation environment.

***2. COTS parts are qualified in families. Only a few part numbers out of the family are qualified.***

NESC team's comments: Concur with concern.

In semiconductor industry, the statement is the standard practices that have proven to be solid for decades for ILPMs.

For example, within a family of similar products, an LDO (low drop-out voltage regulator) that is offered at various popular output voltages (1.8V, 2.5V, 3.3V 5V, etc.), typically has one part number fully qualified, while the rest in the LDO family only undergo partial qualification targeting the unique process portion of each part number. This is a well-proven methodology of process and technology qualification for ILPMs.

Similarly, packages used to house dice are not qualified for each part number. Once a package has been qualified at an assembly facility, it is not qualified again when the die inside of it changes. However, if the same package is used in another assembly facility, it is qualified at that facility first before it can go into production.

The statement is true for passive manufacturers as well. Typically, manufacturers have a family with x to z range. First lot/first article evaluation is likely conducted with low-middle-high values x, y, and z. These will pass basic electricals. It is the NESC team's observation that passives do not typically meet MIL-SPEC parameters or deltas even though manufacturers advertise they do. Good manufacturers maintain a good Quality Management System to make sure that everything is operating smoothly, and randomly select the sample parts from the production line to perform testing for process monitoring purpose.

It should be noted that COTS qualification does not address space radiation. In addition, the worst part among the parts family for radiation may not be the same part used for COTS technology and product qualification. Radiation hardness assurance needs to be performed on the COTS parts either as an individual part or as a family for space radiation effects.

3. ***COTS parts can be made in multiple locations. Might not have the same characteristics, reliability, etc. COTS parts from manufacturer site A should be considered different parts from those made at manufacturer site B even from the same manufacturer.***

NESC team's comment: Concur with concern.

In semiconductor industry, COTS parts can be manufactured in multiple locations. For ILPMs, the fact that the manufacturers guarantee that their parts meet the performance specified on the datasheets regardless of where they are made is a strong indicator that they have very good process control in their production. There will always be lot-to-lot, wafer-to-wafer, and die-to-die variations in production; but the datasheet performance limits have already taken that into account. However, please note that those comments are not for radiation characteristics, since when parts are fabricated on a different production line, they may have different SEE and dose sensitivities.

The statement is true for passive parts as well. This means less traceability. Different locations have different base materials, different machinery of different age/wear, different staff that might not have all received the same training or be under the same supervision levels. A CoC from a COTS purchase may not have the manufacturing plant listed.

4. ***COTS parts made in different fabrication facilities can have different radiation characteristics.***

NESC team's comment: Concur with concern.

COTS parts are not designed for space radiation, and hence variations are much wider than the datasheet parameters that are optimized regardless of where they are manufactured. This is not an issue of where COTS parts are manufactured, but due to the fact that COTS parts are not intended to be radiation tolerant and, therefore, space radiation is not a characteristic that is being optimized in process design or monitored in the production flow.

No wafer traceability could be a showstopper for radiation evaluation on COTS. When parts are fabricated on different production lines, they may have different SEE and dose sensitivities. No wafer traceability means it could be mixed lots with die from different fabrications, or worse, die from one fabrication for radiation qualification, but mixed lots or entirely lot from other fabrication for the flight units. This would mean the radiation qualification parts are not representative of the flight parts, and in the event of mixed lots, variability may be different from one fabrication to another.

The NESC team suggests procuring COTS parts from OCMs and authorized distributers, and communicate with the OCMs and authorized distributors to ensure the parts are from the same wafer lots, and/or procure one reel of the parts to maximize the probability of wafer traceability. Lack of wafer traceability will require a large sample size for COTS radiation evaluation. Typically, there is larger variability for discrete semiconductors COTS parts, such as FETs, bipolar, bipolar liner microcircuits.

***5. Manufacturer can change the part at any time. Maybe we know, maybe we do not.***

NESC team's comment: Concur with concern.

Wafer process change in semiconductor industry is a rather rare case for catalog parts, although it could happen. The team has less confidence that the process changes for non-silicon wafer processes, packaging or other parts types would be as rare. For passive parts, manufacturers do not have any requirements to notify end users that a part has changed. As long as the footprint and main electrical characteristics have remained within advertised tolerances, changes may never be known.

A 2016 study[20] by The Aerospace Corporation "was to look for failures that were attributed to seemingly inconsequential or innocuous process changes (procedure, tooling, process improvement, supplier changes, materials changes, etc.) directly linked to the failure of the assembly or system" and listed 22 examples of failures from unreported changes to various manufacturing processes. It cautions that COTS parts "purchased from distributors need to be treated as a higher risk, as the ability to get process change information could be difficult."

Please also note that, even though ILPMs would typically make sure that they do diligence to ensure any wafer fab process changes do not impact parts datasheet parameters or quality and reliability, it does not mean that the change would not impact space radiation characteristics, since space radiation characteristics are not monitored by commercial industry.

## 7.11 Phase II

This Phase I report captured NASA Centers' current and best practices and lessons learned on the use of COTS parts in spaceflight systems and COTS parts and assemblies for GSE, and provided a set of current best practices on use of COTS based on the Centers' practices and the NESC team's discussions. The NESC team had extensive and open discussions on the topics, and made 11 major findings, 8 observations and 13 NESC recommendations. The NESC recommendations identified in the original Phase I report were updated in the Phase II report. For the final NESC recommendations, please refer to the Phase II report at https://ntrs.nasa.gov/citations/20220018183.

There is a lack of consensus between Centers' in two areas.

There is a lack of consensus within NASA on the perception of risk of using COTS parts for safety and mission critical applications in spaceflight systems. It varies from feelings of "high risk" when part-level MIL-SPEC/NASA screening and space qualification are not fully performed to "no elevated risk" when sound engineering is used and part application is understood (See F-4 in Section 8.1). There is a lack of

[20] N.J. Ho, "Process Change Assessment Techniques", June 6, 2016, Aerospace Report No., TOR-2016-02187

consensus within NASA regarding the type and source of the COTS parts data that would be sufficient for part-level verification on COTS parts (see F-5 in Section 8.1).

Multiple factors influence risk posture on use of COTS parts, such as project risk classifications, project resources, system and avionics architecture, fault tolerance requirements, etc. At part-level, there is government insight on MIL-Spec parts, but not on COTS parts, large variability among COTS parts and COTS parts manufacturers, lack of full knowledge about COTS parts and COTS parts manufacturers impact the risk perception. Without full knowledge of the part and its manufacturer, the confidence of using a COTS part or criteria of verifying a COTS part for spaceflight systems now heavily depends on experiences, which may vary from person to person and Center to Center.

The Phase II work addressed the following items and the Phase II report is available at https://ntrs.nasa.gov/citations/20220018183:

1. Capture the knowledge of use of COTS from other government Agencies.
2. Provide criteria of an ILPM.
3. Provide further guidance on COTS part-level verification and criteria.

# 8.0 Findings, Observations, and NESC Recommendations

The NESC team provides the following findings, observations and NESC recommendations.

## 8.1 Findings

**COTS parts for spaceflight systems**

**F-1.** For safety and mission critical systems on missions with Category 1-3, Class A-D, and sub-Class D, NASA has a long history of using NASA-screened COTS parts (i.e., by performing additional and full part-level screening and space qualification on the COTS parts per GSFC EEE-INST-002 or equivalent documents before incorporating them into the spaceflight system(s).

- **F-1a.** For safety and mission critical systems on Category 1-3 and Class A-C missions, NASA Center current practices typically use NASA-screened COTS parts.
- **F-1b.** For mission critical systems on Class D and sub-Class D missions, there is a wide range of differences in current Centers' practices on COTS selection and part-, board-, and system-level verification.
  - Most NASA Centers (i.e., ARC, GRC, JPL, LaRC, MSFC) emphasize COTS parts selection from ILPMs (defined in Section 7.1.1 and detailed in Section 7.10.3), COTS parts past usage, and/or NASA-screened COTS parts (defined in Section 7.1.1), and/or focus on part-level verification.
  - All Centers' system-level verification processes and standards have remained unchanged with use of COTS parts, even when less part-

level verification performed. ARC has implemented a Center-wide practice of selecting mostly COTS parts and performing a large amount of board- and subsystem-level testing early in the design cycle.

- GSFC (Section 7.4) is flexible on their GOLD rule that requires 1000+ hours testing on hardware while reinforcing a best practice of accumulating as much testing hours (e.g., 500-1000 hours) as possible at system level especially when COTS parts used have less part-level verification.
- JSC has an alternative parts plan EDCPAP (Section 7.6.4) that starts with the requirement that every part on flight hardware should be defect-free and should be qualified to the limits of its datasheet. EDCPAP seeks to verify these requirements by gaining insight into the manufacturer's processes. If evidence that the manufacturer is following best practices for process control, screening, defect elimination, periodic testing for reliability monitoring, qualification, process change re-qualification, etc., then the part requirements are met. If such information cannot be obtained, then the "traditional" approach of part-level MIL-SPEC/NASA screening and qualification may be employed. This process is currently used primarily on low-criticality or highly failure tolerant systems due to the lack of specific criteria for vendor-provided data.

**F-2.** For non-safety or non-mission critical systems, current Center use of COTS practices range from using NASA-screened COTS parts to the best effort on part-level verification, or using COTS parts without any further MIL-SPEC/NASA screening and qualification at part-level, depending on mission classification level, project requirements and risk posture.

**F-3.** NASA has more than 15 years of using COTS without additional part-level MIL-SPEC/NASA screening and qualification in space systems in sub-Class D missions and some Class D payloads, and other non-critical applications, some in complex systems operating for years. Most of those COTS parts were from *Industry Leading Parts Manufacturers* (ILPMs).

- ARC has demonstrated a successful use of COTS methodology (Section 7.2) for Class D and sub-Class D projects, focusing on risk mitigation by designing and building spaceflight system using almost all COTS parts from ILPMs, and performing large amount of testing at board- and subsystem-level. The methodology takes full advantage of availability and low-cost nature of COTS parts to build large quantity of multi-revision EDUs, so that concurrent engineering development of flight software, payload software, subsystem interface, form and fit, and system test procedures get started early.
- GSFC, through the evolution of multiple SpaceCube hardware builds and revisions, has substantial experience using COTS parts in flight

applications on Class D and sub-Class D missions. The SpaceCube program is rooted on a robust design and test philosophy, regardless of the parts used in each assembly. All aspects of the design contain appropriate margins (parts stress and derating, thermal, interface, structural, timing, FPGA/processor/memory utilization, etc.). As a result, no system failures based on individual part performance or reliability were experienced on any mission, nor were they encountered in I&T.

**F-4.** There is a lack of consensus within NASA on the risk of using COTS parts for safety and mission critical applications in spaceflight systems.

- Varies from feelings of "high risk" when part-level MIL-SPEC/NASA screening and space qualification are not fully performed to "no elevated risk" when sound engineering is used and part application is understood.
- Center positions are different on use of COTS without any further part-level MIL-SPEC/NASA screening and space qualification by the users, ranging from a to d below:
  - Use of COTS without any further part-level MIL-SPEC/NASA screening and space qualification is considered as unquantifiable risk or may be high risk for Class A-D missions (JPL, MSFC).
  - Program/Project must decide to assess and subsequently accept risk if using COTS parts in critical systems. The concern is that the lack of full verification may allow bad parts to enter flight hardware that may fail in flight (JSC, LaRC, GRC).
  - The use of any arbitrarily-selected COTS part without additional part level testing or proven alternative practices would entail elevated or at least uncertain risk (GSFC, GRC).
  - With proper practices based on good systems engineering and understanding of the parts being used, COTS can be used in critical applications without elevated risk (ARC, GSFC).

**F-5.** Compared to MIL-SPEC parts, part-level verification for COTS parts 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.

- There is a lack of consensus within NASA regarding the types of the parts manufacturer's evidence (e.g., manufacturers' reliability report, quality report, technology and qualification report, third-party testing, etc.) and the sources of data (e.g., manufacturers' web pages, email exchanges, site visit, etc.) that would be sufficient for part-level verification on COTS parts.
- Current practices vary from no verification at part-level to full verification at parts level, depending on Center's practices and project's risk posture.

**F-6.** Not all COTS parts are created equal due to wide variability in parts manufacturers' process control and quality assurance.

- Some commercial manufacturers (i.e., ILPMs as defined in Section 7.1.1 and detailed in Section 7.10.3) with high volume automatic production facilities have well-documented evidence for their process and technology qualification, product qualification, process control, in-line monitor and control, and well established low DPPM values for their catalog parts.
- Not all AEC parts are from ILPMs. AEC specifications and automotive grade part manufacturers alone does not necessarily guarantee all of the quality and production control aspects needed to be considered an ILPM (Section 7.10.3).

**F-7.** COTS parts, and most MIL-SPEC parts, are not designed and manufactured for space environments.

- Compared to MIL-SPEC parts, COTS parts are typically not designed to withstand the environmental (e.g., radiation, moisture, thermal, etc.) extremities as are their equivalent MIL-SPEC parts, so there should be no expectation that most COTS will survive typical MIL-SPEC screening and qualification tests at extreme conditions outside of its specified operational range.
- Radiation effects are excluded from COTS and most MIL-SPEC parts design trade spaces except for specialized subsets of terrestrial and atmospheric avionics applications that are sensitive to neutron and alpha particle SEE. Even in cases where terrestrial radiation effects may be addressed during the design process, space radiation effects are qualitatively and quantitatively severe, impacting preconceived system architectures in unforeseen ways.
- COTS parts may have larger variability compared to MIL-SPEC parts in radiation responses.

**F-8.** Parts derating in electrical and environmental stresses (e.g., power, voltage/current, thermal, etc.), is more critical for COTS parts (compared to MIL-SPEC parts) to lower the stress-induced degradation and failure modes, thus allowing most parts to last longer, as parts and board/system's reliability are driven by how parts are used in the application.

**F-9.** Center current practices on use of COTS include parts source selection, storage conditions for all stages of use, packing, shipping and handling, electrostatic discharge (ESD), screening and qualification testing, derating, radiation hardness assurance, test house selection and control, and data collection and retention for spaceflight systems.

**COTS parts and assemblies for critical GSE**

**F-10.** Large quantities of COTS parts and equipment are selected and qualified for GSE, saving design and development costs and schedule.

**F-11.** Current practice on use of COTS for critical GSE requires qualification per KSC standards. GSE subsystems undergo a rigorous technical review process including verification & validation testing leading to Design Certification or System Acceptance. All GSE systems go through qualification, including functional/performance, EMC, vibration, acoustic and thermal testing, and derating and screening is performed on GSE Critical Items.

## 8.2 Observations

The following observations are provided:

**O-1.** Some, not all, of volume produced COTS parts can achieve a very low failure rate if used per their designed operating specifications and conditions.

**O-2.** Some parts complexity precludes full part-level verification.

**O-3.** Part-level verification may require a different set of testing other than MIL-SPEC standards and/or different failure/acceptance criteria other than those of MIL-SPEC standards.

**O-4.** MIL-SPEC parts have more margin in the data sheet specified limits than some COTS parts, so using a COTS-equivalent part with the same rating may require additional derating to obtain equivalent reliability, mainly for electrical and thermal derating for passive parts or thermal derating only in microcircuits.

**O-5.** The primary drivers for part reliability in a circuit application are early parts failure rate, parts derating, and radiation tolerance in the circuit.

**O-6.** COTS parts are susceptible to counterfeiting issues due to the increased rate of product obsolescence and lack of supply chain traceability.

**O-7.** Using COTS parts and requiring additional screening and qualification may exceed the cost of using standard MIL-SPEC parts.

## 8.3 NESC Recommendations

NESC recommendations were identified in the original Phase I report and updated in the Phase II report. For the final NESC recommendations, please refer to the Phase II report at https://ntrs.nasa.gov/citations/20220018183.

# 9.0 Alternative Viewpoint(s)

There were no alternative viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

# 10.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

# 11.0 Lessons Learned

**NASA ARC Lessons learned (Section 7.2.5)**

**LL-1.** The most important lesson learned over the last 12 years at ARC after launching over 30 small and nanosat projects is that the real-time over-current monitoring circuit used to protect parts has been a key to success. Mission data from several projects have shown that this is an effective way to protect COTS parts from radiation events. On the other hand, the only time that such a real time monitoring circuit was missing in a key block of circuits, the Eucropis payload sustained a part damage from radiation. This happened although there was over-current monitoring function through the spacecraft; but it was only periodic, not real time. The spacecraft over-current protection function probably did help limit the part damage; however, it was not as effective as the local real time over-current protection. After some annealing over time, the part did return to full functionality; however, each subsequent power-on, after being shut down by the spacecraft due to over-current, the part reached over-current status much more quickly. So, it appears to have suffered from an unrecoverable long-term radiation damage.

**LL-2.** The most common problem in orbit for ARC's projects has been software bugs although Class B flight software was usually employed. This reinforces the need to test early and often through concurrent engineering development effort utilizing multi-revision of EDUs. The fact that the system specifications and requirements tend to be moving targets in this kind of projects probably further contributed to this problem; however, given the typical short development schedules, some of this is inevitable although it should not be used as an excuse for sloppy work. Again, this reinforces the need to start concurrent development effort early, which is made possible by using almost entirely COTS parts.

**LL-3.** Since some of the COTS parts used at ARC are very small in size, mechanical failures when undergoing shock and vibration tests can often happen. Hence, special ways must be tried and verified to provide reliable solutions. For instance, the leads on the mini connectors used on the UV-LED project were so tiny and short that they could not go through the thickness of the main board (19 layers). The amount of solder on each lead was so miniscule that it did not provide the mechanical strength needed to keep it in place. Manual touch-ups by highly skilled technicians were tried several times; but that did not yield reliable results. At the end, the only way to fix the problem was to use epoxy to glue the leads in place to pass the shock and vibration tests. Other mechanical failures, such as inductors and capacitors (with small footprints) being too tall, also necessitated either using a different part or special staking to be used. Some BGA and land grid array (LGA) parts also failed shock and vibration tests, and either had to be replaced or the board stiffened by increasing board layer count and/or adding Aluminum stand-offs around the parts. Shock absorbing materials sometimes had to be added in the system assembly to pass the shock and vibration tests.

**LL-4.** Using COTS parts and commercial fabrication and assembly flows for circuit board manufacturing provide short lead time and cost advantage; but there are challenges in trying to customize anything per NASA's requirements. For instance, special instructions given to local manufacturing houses are often neglected because they have standardized flows that churn out products in huge volume each day. Any deviations will slow down their normal workflow and tend to get overlooked unless the person in charge is familiar with producing NASA boards. However, the turn-over rate for the factory workers is very high in the Silicon Valley, so getting boards fabricated and assembled correctly continues to be a hit-or-miss deal. Constant communication with the factories and careful inspection of the fabricated boards become an important part of the workflow at ARC. Even then, issues with boards are happening at higher than 10% of the times, which lead to re-fabrication, rework or fixing them with highly skilled technicians in house. Of course, delays and cost increases are then unavoidable. This continues to happen even though ARC has been using the same handful of local manufacturers over the years.

**NASA GSFC Lessons learned (Section 7.4.5)**

**LL-1.** The likelihood of other issues is much greater than an actual part defects or failures issue.

a. Workmanship, solder shorts, thermal design, cold solder joint, design deficiency, incompatible connectors, improper derating, worst-case analysis deficiency, etc.
b. Most items raised as "part issues" are not issues with the parts.

**LL-2.** Do not need to satisfy long-standing practices or views to fly reliable hardware systems.

**LL-3.** Robust design and test philosophy inject more confidence in end-product than what parts levels are inside the box. Part tolerance issues are fleshed out of a good design and test program.

**LL-4.** High number of EDUs increases the sample size, and the likelihood of finding a design/part issue.

**LL-5.** It is essential to store and trend data that can be used to identify root cause of issues on a unit. This is even more important for projects that have more than one unit (e.g., the SpaceCube program has built over 50 units, many of which include COTS parts).

**LL-6.** Use caution when screening COTS or specialized parts: It has become common practice to screen commercial and specialized parts to comply with project-level parts screening requirements since in many cases military-specification (MIL-SPEC) parts are not available to meet project requirements. Frequently, the screening requirements (e.g., from GSFC EEE-INST-002) are applied to specialized parts, even when performed by the vendor/manufacturer, without a detailed assessment of the parts. For example, many parts are not capable of withstanding the temperatures associated with the pertinent MIL-SPEC testing protocol. A recent project inherited a board design that included specialized parts that had been qualified and proven for the relevant environment, but that were not capable of withstanding the temperature range of the screening. The projects passed the screening processes and were installed in the boards. Later in I&T one of the parts failed during functional testing, and the failure was traced back to overstress that occurred in the screening process. At that point, many of the over-tested parts were installed in many places where the risk of removal is high.

**LL-7.** Additional parts screening, or parts declared to be "high reliability" cannot make up for poor fault-tolerance in a design or inadequate system testing.

**NASA JPL Lessons learned**

**LL-1.** NRE for qualification and screening may be higher for COTS than space parts. This observation has been incorporated into the JPL Component Engineering and Assurance bidding process.

**LL-2.** PEMs Tg may be <125C. Tg is addressed in the JPL Plastic Encapsulated Part Usage Guideline.

**LL-3.** PEMs may require reduced pre-conditioning temperature for bond pull testing. Pre-conditioning temperature is addressed in the JPL Plastic Encapsulated Part Usage Guideline.

**NASA LaRC Lessons learned**

**LL-1.** The most important lesson learned is to start early with COTS selections. Consider them long lead time parts and group them as such with other standard part procurements for timely addressing of unknown issues.

**LL-2.** Purchase plenty of parts for screening, evaluation and familiarization. You cannot understand the weaknesses or how to test for them if the part is essentially unknown or there is little performance experience with the part. Typically – great cost savings can be achieved with COTS, but the total cost for implementation does involve testing when required. In most cases, there is some modification (additional testing) required for most COTS components and parts.

**LL-3.** Do your homework – COTS are only cost advantageous if you can do little to nothing after purchase. This is highly unlikely – but it depends on the mission risk classification. So, when possible – much data mining for experience and radiation performance analysis can help either 1) reduce testing costs or 2) aid in better understanding risk of usage.

**LL-4.** Know your vendor – this involves not flowing little if any of your project requirements to them for purchased items. Yet, understanding their production yields, SPC data for failure rates and root cause and their general operating/fabrication processes is a must for getting a total quality management understanding of the product you are purchasing.

**Lessons learned from previous assessment:**

**LL-1.** Developing a spaceflight parts program with the use of automotive and non-automotive grade COTS parts, and basing it solely on the performance of a DPA and review of PPAP documentation may not be sufficient to reduce risk to acceptable value. It carries the inherent implementation risk that the detailed PPAP documentation, required to verify device design and process reliability may not be available in a timely manner.

**LL-2.** New technology implementations in packaging of EEE parts are more common in automotive and non-automotive grade devices and require new and specialized techniques during de-processing for DPA. The standard de-processing techniques specified by the military standards (e.g., MIL-STD-1580) used in ceramic/metallic hermetic space level packages are insufficient for properly evaluating the nuances in the more cutting-edge design/construction parts.

**LL-3.** AEC certified devices are vendor self-certified; there is no AEC governing body that verifies the certified device(s) has (have) met all of the AEC specification requirements. This is in contrast to military products, where DLA LAM provides an oversight function for all QML/QPL device qualification data. Hence, the certificate of compliance that comes with either automotive COTS or nonautomotive parts does not clearly specify that the parts meet all data sheet parameters that designers use for their applications.

**LL-4.** Use of an automotive grade device does not automatically guarantee higher quality or reliability than a COTS part. Therefore, use of an automotive grade device may not be sufficient to meet all spaceflight applications or requirements without additional analysis and/or testing.

## 12.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified by the end of Phase I of the assessment.

## 13.0 Definition of Terms

| | |
|---|---|
| Corrective Actions | Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem. |
| Finding | A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation. |
| Lessons Learned | Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. |
| Observation | A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/ Program/ Project/ Organization’s operational structure, tools, and/or support provided. |

| | |
|---|---|
| Problem | The subject of the independent technical assessment. |
| Proximate Cause | The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome. |
| Recommendation | A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk. |
| Root Cause | One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome. |
| Supporting Narrative | A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions. |

# 14.0 Acronyms and Nomenclature List

| | |
|---|---|
| AEC | Automotive Electronics Council |
| AEC-Q | Automotive Qualified |
| AI&T | Assembly, Integration, and test |
| ALBus | Advanced Electrical Bus |
| ARC | Ames Research Center |
| ASIC | Application Specific Integrated Circuit |
| ATP | Acceptance Test Procedure |
| BBO | Black Body Objects |
| BGA | Ball Grid Array |
| BiCMOS | Bipolar Complementary Metal–Oxide–Semiconductor |
| C&DH | Command and Data Handling |
| CCP | Composite Crew Program |
| CDR | Critical Design Reviews |
| CERN | European Council for Nuclear Research |
| CIL | Critical Item List |
| CMOS | Complementary Metal–Oxide–Semiconductor |
| CMP | Configuration Management Plan |
| CoC | Certificate of Conformance |
| CoP | Community of Practice |
| COTS | Commercial-Off-The-Shelf |
| DC-DC | Direct Current to Direct Current |
| DDD | Displacement Damage Dose |
| DFI | Development Flight Instrumentation |

| | |
|---|---|
| DLA | Defense Logistics Agency |
| DoD | Department of Defense |
| DPPM | Defective Parts Per Million |
| DRD | Data Requirements Documents |
| DTO | Demonstration Technology Objective |
| EBOT | EVA Battery Operations Terminal |
| EDCPAP | Engineering Directorate Certified Parts Approval Process |
| EDU | Engineering Development Unit |
| EEE | Electrical, Electronic, and Electromechanical |
| EEL | Engineering Evaluation Laboratory |
| EGS | Exploration Ground Systems |
| ELDRS | Enhanced Low Dose Rate Sensitivity |
| EMC | Electromagnetic Compatibility |
| EMI | Electromagnetic Interference |
| EMIT | Earth Surface Mineral Dust Source Investigation |
| FCM | Flight Control Module |
| FILMRS | Flight Imaging Launch Monitoring Real-Time System |
| FPGA | Field Programmable Gate Array |
| FPIE-D | Focal Plane Interface for Digital Electronics |
| GCR | Galactic Cosmic Ray |
| GFE | Government Furnished Equipment |
| GIDEP | Government Industry Data Exchange Program |
| GPR | Goddard Procedural Requirements |
| GRC | Glenn Research Center |
| GSE | Ground Support Equipment |
| GSFC | Goddard Space Flight Center |
| H/W | Hardware |
| HAST | Highly Accelerated Stress Testing |
| HEOMD | Human Exploration and Operations Mission Directorate |
| I&T | Integration & Test |
| ILPM | Industry Leading Parts Manufacturer |
| ISS | International Space Station |
| IT | Information Technology |
| IT/OT | Security Assessment |
| IVA | Intravehicular |
| IXPE | Imaging X-Ray Polarimetry Explorer |
| JPL | Jet Propulsion Laboratory |
| KDP | Kennedy Documented Procedure |
| KSC | Kennedy Space Center |
| LAM | Laser Air Monitor |
| LaRC | Langley Research Center |
| LCC | Life-Cycle-Cost |
| LED | Light Emitting Diode |
| LEO | Low Earth Orbit |

| | |
|---|---|
| LET | Limited Linear Energy Transfer |
| LGA | Land Grid Array |
| LISA | Laser Interferometer Space Antenna |
| LRU | Line Replaceable Unit |
| LSA | Logistics Support Analysis |
| M&P | Materials and Processes |
| MAR | Mission Assurance Requirements |
| MEAL | Mission, Environment, Applications and Lifetime |
| MMOC | Multi-Mission Operation Center |
| MPCV | Multi-Purpose Crew Vehicle |
| MRAM | Magnetoresistive Random-Access Memory |
| MSFC | Marshall Space Flight Center |
| MTBF | Mean Time Between Failures |
| NEPAG | NASA Electronic Parts Assurance Group |
| NEPP | NASA Electronic Parts and Packaging |
| NESC | NASA Engineering and Safety Center |
| NIC | Network Interface Card |
| NPR | NASA Procedural Requirements |
| OCM | Original Component Manufacturer |
| OEM | Original Equipment Manufacturer |
| OMRSD | Operations & Maintenance Requirements Specification Document |
| PCB | Parts Control Board |
| PCB | printed Circuit Board |
| PDR | Preliminary Design Reviews |
| PEM | Plastic Encapsulated Microcircuit |
| PIND | Particle Impact Noise Detection |
| PLC | Programmable Logic Controller |
| PMAD | Power Management And Distribution |
| QAP | Quality Assurance Plan |
| QMS | Quality Management System |
| QTP | Qualification Test Procedure |
| RF | Radio Frequency |
| RHA | Radiation Hardness Assurance |
| RMA | Reliability, Maintainability, and Availability |
| RNS | Relative Navigation Sensors RNS |
| RRM-3 | Robot Refueling Mission 3 RRM-3 |
| RSAR | Reliability and Safety Assessment Report |
| S/W | Software |
| SAA | System Assurance Analysis |
| SACA | Software Assurance Classification Assessment |
| Saffire | Spacecraft Fire Safety Demonstration |
| SCaN | Space Communications and Navigation |
| SDR | Software-Defined Radio |
| SEB | Single-Event Burnout |

| | |
|---|---|
| SEE | Single-Event Effects |
| SEFI | Single-Event Functional Interrupt |
| SEGR | Single-Event Gate Rupture |
| SEL | Single-Event Latchup |
| SEU | Single-Event Upset |
| SIP | System-In-Package |
| SLS | Space Launch System |
| SMP | Safety & Mission Assurance Plan |
| SOTA | State-Of-The-Art |
| SpaceDOC II | Spaceflight Systems Development and Operations Contract |
| SRR | System Requirements Review |
| SSA | Software Safety Analysis |
| SSP | Space Shuttle Program |
| SSS | Sample Size Series |
| STRS | Space Telecommunications Radio System |
| STS | Silicon Turnkey Solution |
| SWaP | Size, Weight, and Power |
| TID | Total Ionizing Dose |
| TMR | Triple Modular Redundancies |
| TNID | Total Non-Ionizing Dose |
| TRR | Test Readiness Reviews |
| UV | Ultraviolet |
| UV-LED | Ultraviolet Light Emitting Diode |
| V&V | Verification & Validation |
| VSWIR | Visible and Short-Wave Infrared |
| xEMU | Extra-Vehicular Mobility Unit |

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## Appendices

# Appendix A. Example Projects with Use of COTS

## A.1 NASA ARC Example Projects with Use of COTS

**Example Project 1: BioSentinel Free Flyer**

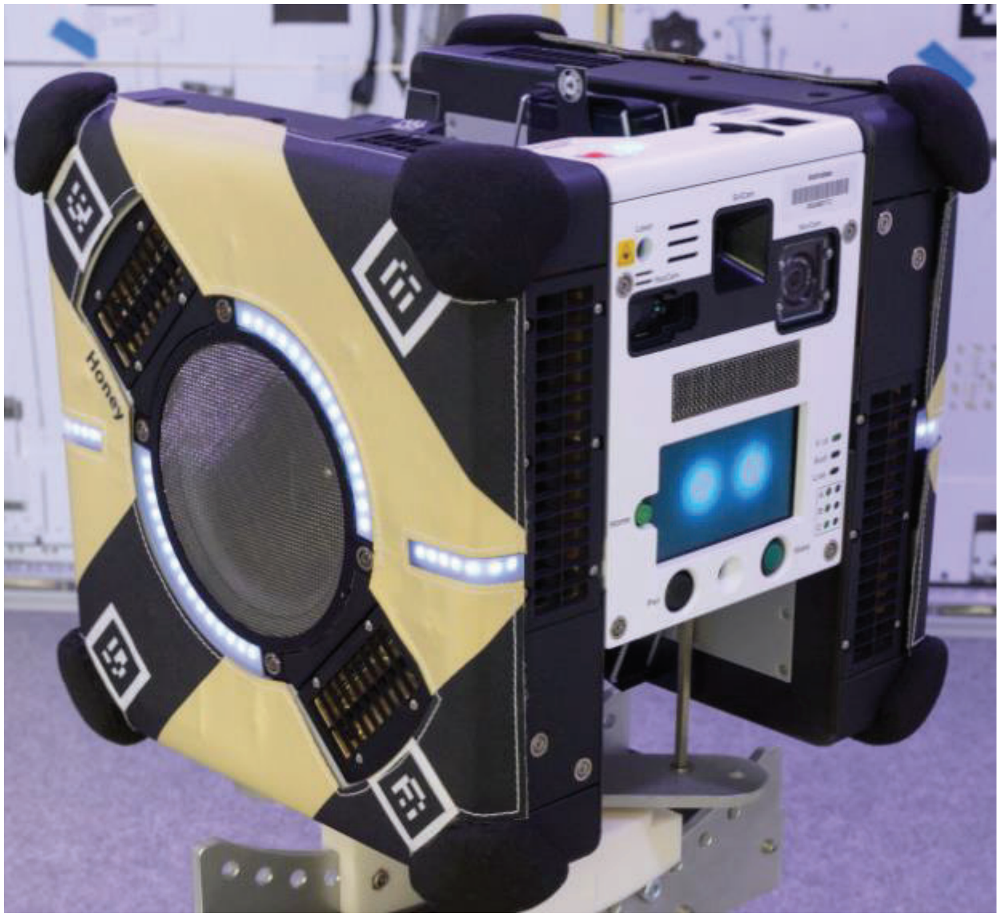
https://www.nasa.gov/centers/ames/engineering/projects/biosentinel.html

This is an active deep-space, long-duration nanosat (6U) project due to launch in March of 2021 on the SLS rocket as a secondary payload on the EM-1 mission. It is ARC's first attempt to send a nanosat into deep space. The biological payload (4U in size with two strains of yeast; one is a mutant) selected will help fill the Human Exploration and Operations Mission Directorate's (HEOMD) strategic knowledge gaps in radiation effects on biology, which is an effort in support of human exploration to Mars and beyond. This mission will likely be targeting an Earth-interior, heliocentric orbit. This is the first time an ARC nanosat hardware (using EDU #5), will be undergoing radiation testing at any level (part, board or system). The beam testing, using a simplified galactic cosmic ray (GCR) simulation, is performed on the fully assembled nanosat hardware.

The mission radio and radiation LET spectrometer are provided by JPL and JSC, respectively, while the rest of the hardware is developed at ARC. The radio (IRIS) has flight heritage and uses mostly space rated parts. The radiation spectrometer uses all COTS parts except the radiation sensor. The rest of the BioSentinel hardware uses COTS parts, along with 22 non-COTS parts in the electrical power system (EPS) and C&DH subsystems.

The entire BioSentinel flight hardware is encased in a 60-mil Aluminum box, with only the biosensor chip being exposed. The worst-case TID expected for the mission is 5-10krad. All the non-COTS parts selected are for radiation tolerance reason. In addition, the strategy of selecting COTS parts that use the same die as their radiation-tolerant counter parts is used whenever possible. This project again adheres to heavily using parts and circuits that have established ARC flight heritage, and selects the highest grade available of the COTS parts.

**Example Project 2: Astrobee Robotic Free Flyer for the ISS**




https://www.nasa.gov/astrobee

The Astrobee robotic free flyer is an upgrade to the three SPHERES 1.0 free flying robots currently being used on the ISS. It can be operated autonomously or via remote control by astronauts, flight controllers, or researchers on the ground. It performs a variety of Intravehicular (IVA) tasks to support crew, such as environmental surveys, inventory, and mobile procedure display. The goal is to minimize astronauts' time spent on maintaining the ISS and, hence, maximizing their valuable time to perform science experiments. The $CO_2$ propulsion system is replaced by fans to get rid of frequent changing of the cartridges. At a minimum, Astrobee will satisfy the following Level 1 requirements:

1. 3D range sensing through a combination of on-board sensing modalities.
2. Stereo image processing.

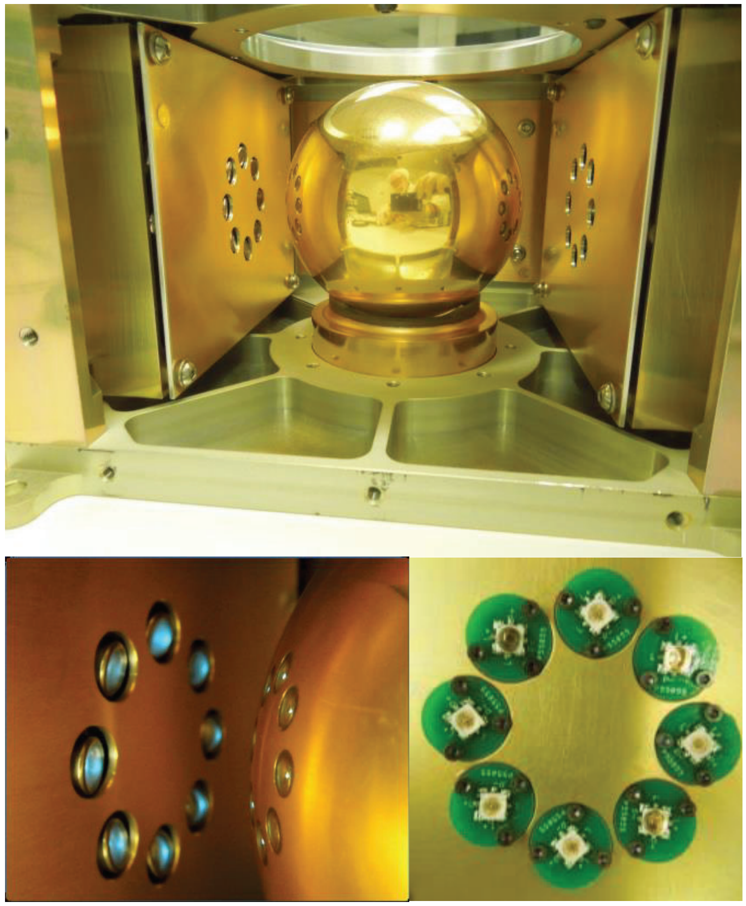
3. Expandable payload and sensing capability.
4. Reduce battery consumables compared to SPHERES 1.0 operation.
5. Increase runtime compared to SPHERES 1.0 operation.
6. Operate with or without current ultrasonic beaconing system.
7. Obstacle avoidance and safe motion in microgravity environment.
8. High-bandwidth 802.11 and IP-based communications.
9. Open source flight software, developer API, development tool-chain, hardware architecture, and operating system.
10. Reverse compatibility with Guest Science Program for legacy SPHERES 1.0 code.

Given these ambitious goals and SWAP limitations, and the mild environment inside the ISS, a design approach using all COTS parts was selected. The EEE part selection requirement was based on the ISS Class 1E policy; however, the standard ISS safety requirements (do no harm to the astronauts and ISS assets) were all followed. As a standard practice at ARC, numerous EDUs were built to allow concurrent engineering to happen between system, mechanical, electrical, and software to resolve any interface issues early, which was very critical for such a complex robot development effort.

These robots can return to their docking stations and recharge their battery power. Each robot also carries a perching arm that allows it to grasp onto the station handrails to conserve energy or to assist astronauts. The visual navigation system fuses data from a forward or rear facing camera, accelerometers, and gyros to produce an attitude and position estimate for Astrobee. In addition, the control system is capable of simultaneous 3-axis position and 3-axis attitude control.

The first two Astrobees were launched in April 2019, while the third one was launched in July 2019. They have been fully operational after the initial startup phase, where mapping out the interior of the ISS took some trial-and-error in the software algorithms, along with calibrations and speed adjustment.

**Example Project 3: UV-LED Physics Payload**



https://iopscience.iop.org/article/10.1088/0264-9381/33/24/245004

This is a 3-way joint spaceflight project between ARC (payload), Stanford University (Principal Investigator) and KACST - Science and Technology Institute in Saudi Aribia (Spacecraft and Mission Operations). This is a technology demonstration project for charge management in space using non-contacting charge control of floating mass with new solid-state ultra-violet (255nm) LEDs. It is a key enabling technology for the Laser Interferometer Space Antenna (LISA) and Black Body Objects (BBO) missions. In 2009, the technology used to make these UV LED devices was not yet available in the commercial industry; in fact, ARC circuit designers were not given detailed specification of the parts except the I-V (current-voltage) curves. The two main goals of the project were to qualify the UV-LED device for space use at TRL8, and the non-contact AC charge management technology to TRL7 level, respectively.

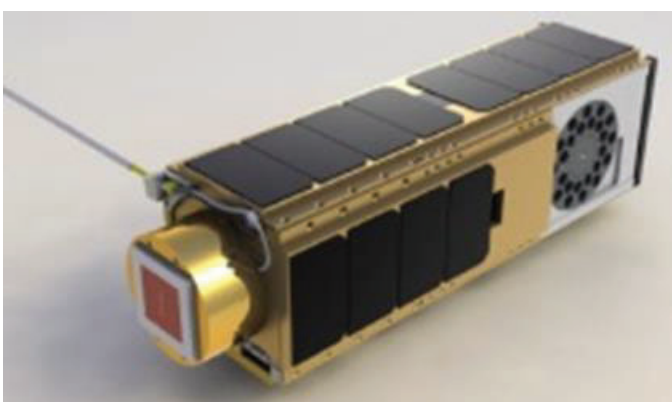
All COTS parts were used on the UV-LED payload except two space rated DC-DC converters for mission critical power supply from the spacecraft to the payload. Only one DC-DC converter was needed since it was a Class D mission and single-point failures were allowed; however, the entire outcome of the mission was riding on it.

Therefore, ARC made a decision to not only use a space rated part, but a second identical part was used for redundancy. The redundancy also included the power and ground pins on the power connector. In fact, redundancy was used in the whole power supply chain on the power distribution board of the payload system.

Two identical sets of experiments were needed for full mission success although only one experiment needed to be operational to achieve minimum success criteria. Each experiment was consisted of eight UV LEDs, two voltage bias electrode plates, and a charge amplifier to read the charge on the reference mass/sphere. The four bias plates (used to induce charges on the sphere) formed a non-touching square box around the sphere with each experiment controlling two bias plates that were facing each other. The UV LED devices were used to shine UV light on the sphere to reset the charges on the sphere; hence, achieving charge control on the sphere. Space limitation was the biggest challenge especially in the charge amplifier board where 0201 sized passive components and two stacked boards had to be used to fit in the tight space close to the sphere. The controlling and processing board for each experiment was limited to 4.5"x 6.5" in size while 900 parts needed to go on it; hence, 19 layers were needed for routing and noise minimization.

The UV-LED payload was launched on the Saudisat-4 S/C on June 19, 2014, onboard a Russian Dnepr rocket in Baikonur. The LCC for the whole mission was estimated to be about $75M, excluding the launch costs. The full mission success goals could be accomplished in 5 hours, which were consisted of collecting one set of V-I-P (voltage, current, power) curves generated and transmitting the data down to mission operations in Saudi Arabia. The payload worked flawlessly for over 2 years, resulting in a paper being published in the Classical and Quantum Gravity Physics journal in November 2016. In fact, the PI's ran every experiment they could imagine before declaring completion of their research work and turning the payload over to KACST, who wanted to keep operating it.

**Example project 4: O/OREOS Nanosatellite**



http://www.nasa.gov/centers/ames/news/releases/2010/10-109AR.html

The goal of the O/OREOS mission was to demonstrate the capability to conduct low-cost astrobiology science experiments on an autonomous nanosatellite in space.

Scientists would apply the knowledge they gained from O/OREOS to plan future experiments in the space environment to study how exposure to space changes organic molecules and biology. This type of experiments will help answer astrobiology's fundamental questions about the origin, evolution, and distribution of life in the universe.

This ARC spaceflight project utilized 100% COTS parts, including free vendor samples. It was built on the knowledge gained from the first two ARC nanosat projects, GeneSat and Pharmasat, which used only COTS parts and without an EEE parts control policy in place at the time. However, the same best practices and strategies that have continued till today were implemented, which included the "test early and often" philosophy by building multiple revisions of EDUs and verifying the design by testing at the board and subsystem levels instead of at individual part level. Fault recovery was incorporated at subsystem level with over-current and over-voltage sensing, along with software resetting and disabling capability to deal with single event effects. The outer cover of O/OREOS is constructed of 60 mil Aluminum to provide not only the structural rigidity and support, but also to serve as a radiation shield for the avionics inside.

O/OREOS was launched on 11/19/2010 into a 640km orbit to perform a 6-month mission; however, it remained functional in space for over 3 years. One system reset that was likely due to an SEL (i.e., over current) event occurred on 12/27/2010. SEUs were also likely, but they were not data-logged and were handled automatically via the watchdog timer function of the microcontroller. There were also four beacon radio failures that required a software reset to clear the fault on 12/19/2010, 3/21/2011, 7/7/2011 and 8/10/2011, respectively, which were likely due to some types of SEEs.

## A.2 NASA GRC Example Projects with Use of COTS

### Example Project 1: CoNNeCT/SCaN Testbed

The Space Communications and Navigations (SCaN) Testbed (originally called CoNNeCT, the Communication, Navigation, and Networking reConfigurable Testbed) was a Space Telecommunications Radio System (STRS) compatible technology platform that resided on the exterior of the ISS from its launch in 2012 to its decommissioning in 2019. The project was designed to advance Software-Defined Radio (SDR) technology. It consisted of three SDRs provided by three different organizations – JPL, General Dynamics, and Harris Corporation. It was a Class D mission with a total project cost of >$100M.

The project defined Grade 2 parts as its standard in the SMAP; however, COTS parts were also cited as acceptable to meet budget/schedule considerations as long as safety, reliability, and environmental requirements could be met. Overall, the project used a mixture of Grade 2 parts and COTS parts and assemblies. Screening was performed at the assembly level, consisting of thermal cycling, a 200-hour burn-in, and vibration testing. De-rating and reliability analyses were performed. The design inherently incorporated mitigations to compensate for SEUs. Radiation testing was performed on select COTS assemblies, including an Ethernet interface and a flash memory module.

A few parts issues occurred, but none interfered with mission success. During integration testing, the project experienced issues with the SpaceWire communications interface; however, these issues were able to be resolved prior to launch. There was also a non-critical failure of a board in one of the SDRs on orbit. Ultimately, a total of 888 reconfigurations were performed on-orbit during operations and the mission was considered fully successful.

Figure A.2-1 shows the SCaN Testbed payload outside one of the GRC vacuum chambers.

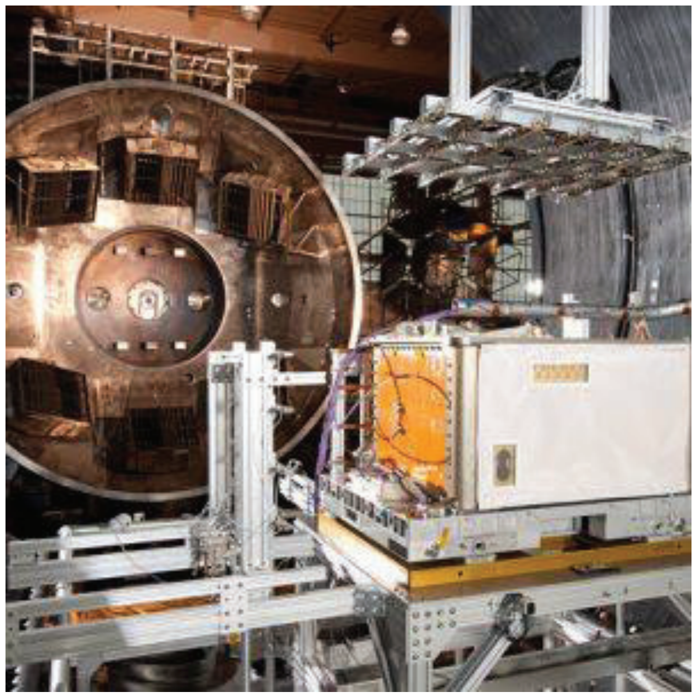


***Figure A.2-1. SCaN Testbed***

**Example Project 2: Spacecraft Fire Safety Demonstration (Saffire)**

The Saffire project was a Class D mission designed to investigate large-scale flame growth and materials flammability in space. This project was an in-house design and build effort that consisted of three separate experiments called Saffire-1, -2, and -3. These experiments were housed in a pressurized Cygnus module. The operational mission time was extremely short. The payloads were in a non-operational mode for several weeks prior to power up and operation, which occurred over a few days. It was a Class D mission with a total project cost of ~$100M.

Grade 2 parts were defined as standard in the SMAP, but the document also allowed for COTS parts to be used due to budget and schedule considerations. In practice, parts used were almost entirely COTS. Due to the short mission duration, there were not radiation concerns.

There were two main parts concerns during project development. The first involved commercial DC-DC converters. These parts contained electrolytic capacitors, which are not space rated, so the project accepted this risk. Measures were also taken to ruggedize the parts, including staking and conformal coating, and the parts were then subjected to environmental testing at the assembly level. The second parts concern involved relays used in a safety critical application. The relays were COTS parts, which was lower than the Grade 1 parts required by the SMAP for such an application, so ERB approval was required. Additional testing was performed on these relays to ensure satisfactory performance.

Ultimately, mission objectives were fully successful and a follow-on set of experiments, called Saffire-4, -5, and -6 are being developed by a contractor, incorporating lessons learned from the first set.

**Example Project 3: ISS Projects**

GRC has developed many ISS payload projects, especially in combustion science and fluid physics. These projects are categorized as either Class C or Class D. GRC also has a contract with a nearby offsite contractor called the Spaceflight Systems Development and Operations Contract (SpaceDOC II) to develop these payloads. There is a common SMAP, which contains the parts control plan for all ISS projects that will reside in the habitable volume of the ISS, for both in-house and contracted projects. The SMAP defines Grade 2 parts as the standard.

The mission environment is well-understood, as it is inside the pressurized volume of the ISS. COTS parts usage is extremely common on these projects.

**Example Project 4: Advanced Electrical Bus (ALBus) CubeSat**

The ALBus CubeSat was a CubeSat mission designed to demonstrate new shape memory alloy materials and a 100W power management and distribution (PMAD) electrical power system. This was a sub-Class D project, and used entirely COTS parts. One of the goals of this project was to give early-career engineers an opportunity to experience a full project life cycle. As this was a low-budget project, traditional S&MA requirements and processes were not levied. The CubeSat was launched in 2018, but never established communication with the ground. However, it is unknown whether this was due to parts or process issues.

Figure A.2-2 shows the ALBus CubeSat.

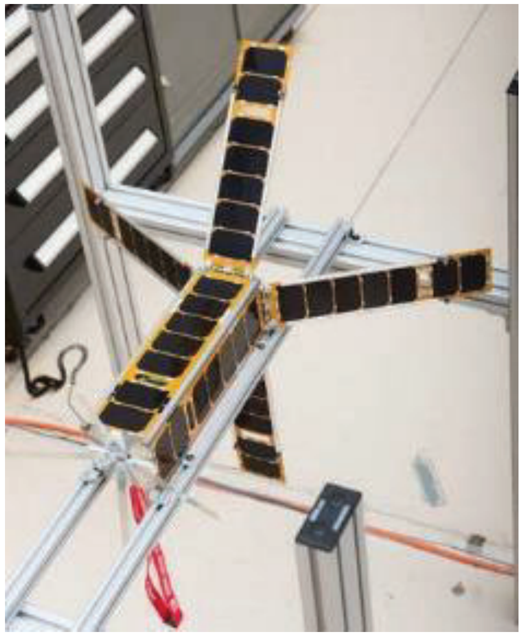


*Figure A.2-2. ALBus CubeSat*

## A.3 NASA GSFC Example Projects with Use of COTS

**Example Project 1: NICER**

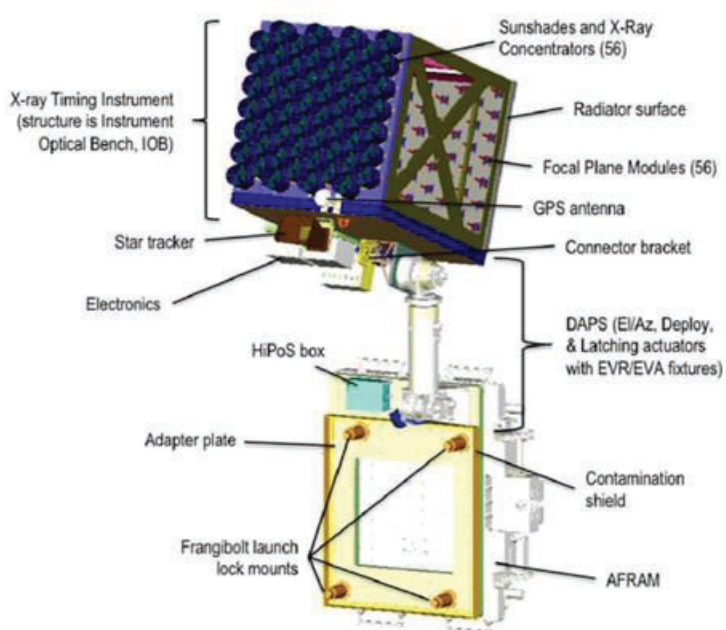
Neutron Star Interior Composition Explorer

- Partnership with GSFC and MIT Kavli Institute
- X-ray timing and spectroscopy instrument mounted on ISS
- Class D mission – 18 months ISS orbit
  - Relatively benign environment
  - Moderately short duration
- Systems include Gimbal Control Electronics, Main Electronics Box, ISS Power Conversion, Star Tracker, Measurement Power Units, and Focal Plane Modules.
- Design (and mission proposal) based on successful prototype x-ray detector electronics. Array of X-ray Detection, 56 total detectors, 8x7 configuration, heavy use of COTS parts.
- Reviewing COTS parts from prototype detector design- attempting to find equivalent MIL or High rel equivalents.
- Became obvious, even for equivalent parts, the packaging change from COTS to MIL would be significant impact on design.
- Did look to swap out passive R's and C's, and connectors for MIL/high rel equivalents.
- Some parts such as Atmel Microprocessor and detectors were presented as deal breaker to replace.
- Perform Selective DPA, Construction Analysis, Manufacturer Site Visits, and conduct board-level testing campaign to identify early part failures.
- Based heavily on COTS parts design.

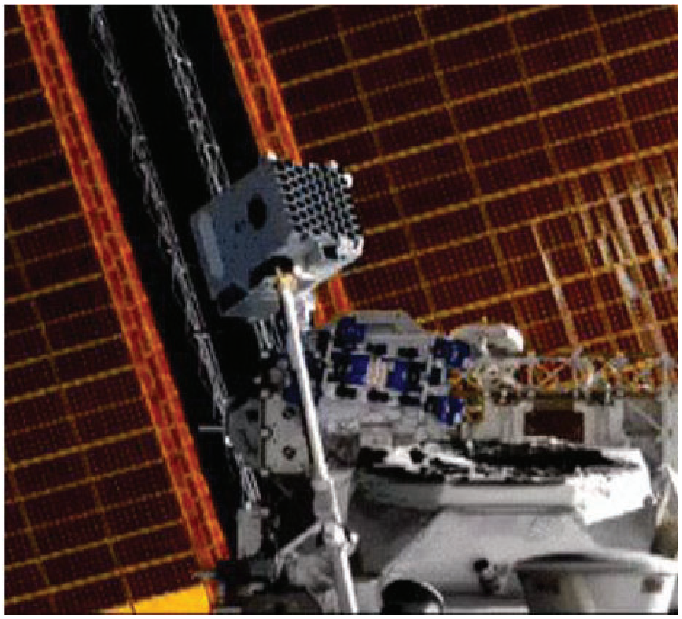
- Each Detector sits on a Preamp Board.
- 8 preamps controlled by 7 Measurement Power Units.
- Detector electronics inherently fault tolerant featuring 56 detectors (minimum 35 needed to meet science objectives) (graceful degradation upon failure).
- Commercial/Custom X-ray Detector- Vacuum sealed, TEC cooled, multi-layer construction Hybrid, sealed in micron thick "glass" window.
- Commercial obsolete Atmel Microprocessor- critical to the hardware, could not be designed out.
- Other COTS diodes, transistors, microcircuits, and passives.
- COTS parts enabled higher resolution/science objectives.
- Kept selected capacitor values within reasonable range (available flight equivalents).
- Attempted to use MIL "ish" capacitors and resistors when available (lead time). Ended with a mix of COTS and screened/MIL parts due to schedule constraints.
- Swapped out COTS micro-D connectors for more suitable MIL parts and plating finishes.
- Class H, rad "tolerant" DC/DC converters over COTS options.
- Board-level testing campaign- accumulate at least 700 hours of operational time, and through environmental test campaign (cycle, vibe, etc.) prior to launch.
- Board-level testing did uncover 1 capacitor failure around 500 hours.

It is noteworthy that after 3 years, no part failures have occurred, although many were expected due to the widespread use of COTS.

**NICER**



**Example Project 2: SpaceCube**



The SpaceCube technology at the GSFC is a family of flight data processors that aim to improve performance and efficiency of space-based computing by orders of magnitude. Five revisions of the SpaceCube technology have all been designed to use parts that could be screened to Level 1 if required by the project. The SpaceCube program has successfully flown COTS parts (with no additional screening) on twelve payloads (as of publication of this report) since 2008.

All SpaceCube revisions are based on Xilinx reconfigurable FPGA technology – a very complex EEE device. All Xilinx devices flown on SpaceCube have been unscreened parts. To date, SpaceCube has successfully flown 66+ Xilinx device-years on orbit.

The SpaceCube timeline is shown in Figure A.3-1. SpaceCube TimelineA.3-1.

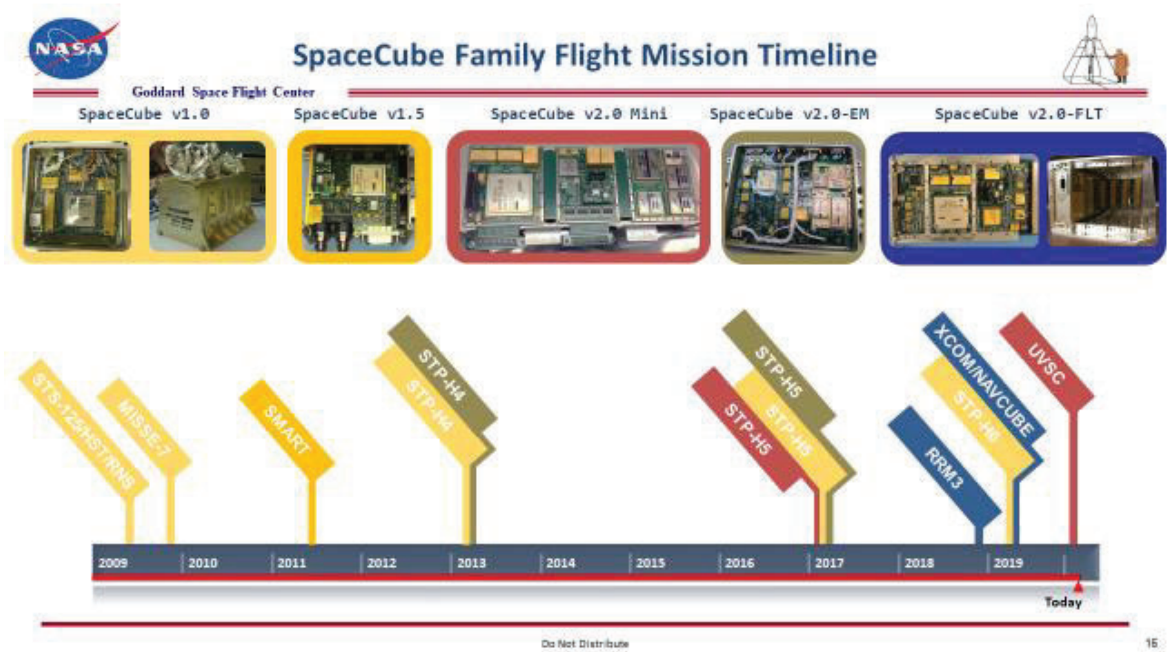



*Figure A.3-1. SpaceCube Timeline*

SpaceCube v1.0 was based on the Xilinx Virtex 4 FX60 devices. Each processor card has two of these FPGAs in a back-to-back configuration. See Figure A.3-2 through A.3-5.

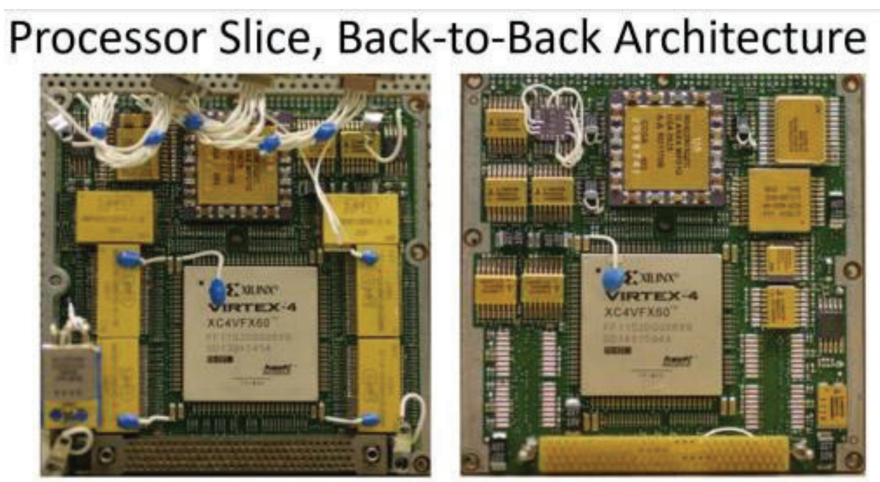



*Figure A.3-2. SpaceCube v1.0 Processor Card*

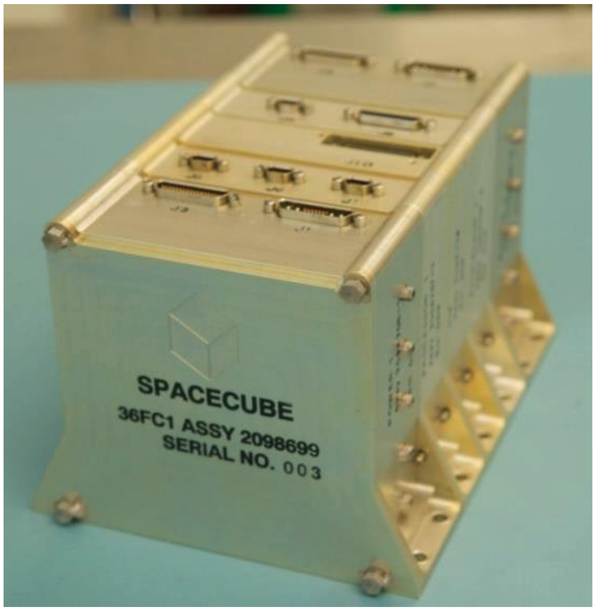



***Figure A.3-3. SpaceCube v1.0 Computer***

SpaceCube v2.0 is based on the Xilinx Virtex 5 FX130 device. Each processor card has two of these FPGAs in a back-to-back configuration. Figure A.3-4.


***Figure A.3-4. SpaceCube v2.0 Processor Card***

*Figure A.3-5. SpaceCube v2.0 Computer*

SpaceCube v1.0 and SpaceCube v2.0 had full parts engineering support throughout the design and test process. SpaceCube v1.0 was built for the Hubble Space Telescope Servicing Mission 4 to control the Relative Navigation Sensors (RNS) system technology demonstration. Although RNS was a tech demo, it was held to the same requirements as the rest of the HST-SM4 payload. SpaceCube v2.0 was built to support multiple missions, and had full parts engineering support from the Restore-L flight project. Being that the SpaceCube v2.0 Mini is a subset of the SpaceCube v2.0 design, all parts were vetted by parts engineering.

The SpaceCube v1.5 was built for a DoD rapid response to space project and did not have full parts engineering support.

SpaceCube v1.0, v2.0 Engineering Model, v2.0 flight, v2.0 Mini, and a GPS variant derived from the v2.0 flight are all flying on ISS conducting cutting-edge data processing applications that standard space processors are incapable of performing. Three SpaceCube v1.0s have been delivered to the USAF for use on the Space Test Program DoD payload pallets. The SpaceCube v1.0 serves as the main command and data handling system for STP-H4, -H5, and –H6.

SpaceCube v1.0 first flew on the ISS on the MISSE-7 payload as an on-orbit radiation mitigation test bed, and was operational for 7.3 years.

SpaceCube v2.0 Engineering Model has flown on ISS twice, once as a pathfinder technology, and second as an operational computer for NASA's Raven payload which conducts real-time vehicle tracking of all inbound and outbound vehicles docking with ISS. The SpaceCube v2.0 flight unit is currently controlling the Robot Refueling

Mission 3 (RRM-3) payload on ISS. A GPS instrument was created using the SpaceCube v2.0 computer platform, and is also in operation on the ISS.

The Kodiak Lidar for the OSAM-1 mission also uses the SpaceCube v2.0 computer platform. OSAM-1 is a Class C mission and has a Level 3 parts program.

With the exception of the Kodiak Lidar instrument, all of the units had some percentage of COTS parts. Most of the SpaceCube v1.0 units only had a few part types that were unscreened COTS. However, all other versions had high percentage use of COTS parts. Figure A.3-6. SpaceCube Flight Use and COTS Percentage provides a summary of all SpaceCube missions, actual mission life, and COTS metrics. Figure A.3-7. SpaceCube COTS Parts Metrics provides a total metric on COTS part-years flown to date on the SpaceCube program.

| Project | Version | Part Req | BOM Count | COTS % | COTS Months |
|---|---|---|---|---|---|
| RNS | v1.0 | 2+ | 3700 | 1% | 12 |
| MISSE-7 | v1.0 | N/A | 3100 | 2% | 22320 |
| SMART | v1.5 | N/A | 1000 | 95% | 32 |
| STP-H4 CIB | v1.0 | N/A | 1500 | 1% | 900 |
| STP-H4 ISE2.0 | v2.0-EM | N/A | 1250 | 99% | 111375 |
| STP-H5 CIB | v1.0 | N/A | 1500 | 1% | 1101 |
| STP-H5 ISEM | v2.0 Mini | N/A | 1000 | 98% | 35966 |
| STP-H5 Raven | v2.0-EM | N/A | 1500 | 99% | 136249 |
| RRM3 | v2.0 | N/A | 1429 | 99% | 41498 |
| STP-H6 CIB | v1.0 | N/A | 1500 | 1% | 295 |
| STP-H6 GPS | v2.0 | N/A | 1157 | 99% | 22527 |
| Restore-L Lidar | v2.0 | 3 | 2000 | 0% | N/A |
| STPSat6 | v2.0 Mini | N/A | 1500 | 98% | N/A |

*Figure A.3-6. SpaceCube Flight Use and COTS Percentage*

| | | |
|---|---|---|
| Totals | Units Flown | 11 |
| | Xilinx FPGAs | 26 |
| | Xilinx Device-Years | 66.64 |
| | Part Years | 141575 |
| | COTS Part Years | 31050 |

*Figure A.3-7. SpaceCube COTS Parts Metrics*

No system failures based on individual part performance or reliability were experienced on any mission, nor were they encountered in I&T. (Some failures and anomalies occurred as a result of either workmanship, design, or other issues.). Therefore, there are no known EEE parts failures, COTS or military/space grade.

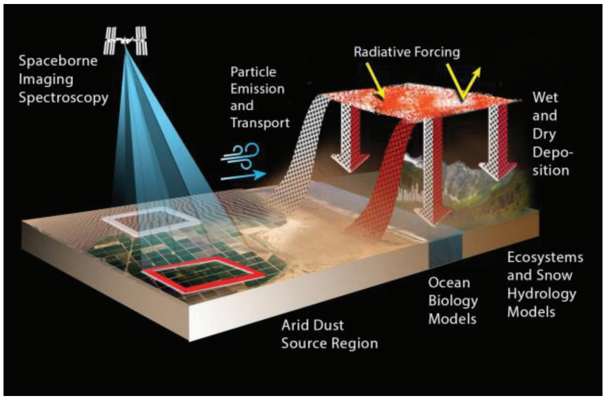
The SpaceCube program is rooted on a robust design and test philosophy, regardless of the parts used in each assembly. All aspects of the design contain appropriate margins (parts stress and derating, thermal, interface, structural, timing, FPGA/processor/memory utilization, etc.).

For more specific information on the SpaceCube program and projects, please visit https://spacecube.nasa.gov/ or refer to the following references:


- Geist, C. Brewer, M. Davis, N. Franconi, S. Heyward, T. Wise G. Crum, D. Petrick, R. Ripley, C. Wilson, and T. Flatley, “SpaceCube v3.0 NASA Next-Generation High-Performance Processor for Science Applications,” 33rd Annual AIAA/USU Conf. on Small Satellites, SSC19-XII-02, Logan, UT, August 3-8, 2019.
- D. Petrick, “Mission Use of the SpaceCube Hybrid Data Processing System,” Military and Aerospace Programmable Logic Devices, San Diego, CA, 2017.
- Schmidt, M. French, and T. Flatley, “Radiation hardening by software techniques on FPGAs: Flight experiment evaluation and results,” IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2017.
- Schmidt, G. Weisz, M. French, T. Flatley, C. Villalpando, “SpaceCubeX: A framework for evaluating hybrid multi-core CPU/FPGA/DSP architectures,” IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2017.
- D. Petrick, N. Gill, M. Hassouneh R. Stone, L. Winternitz, L. Thomas, M. Davis, P. Sparacino, and T. Flatley, “Adapting the SpaceCube v2.0 data processing system for mission-unique application requirements,” IEEE Adaptive Hardware Systems, Montreal, Canada, June 15-18, 2015.
- T. Flatley, “Keynote 2 — SpaceCube — A family of reconfigurable hybrid on-board science data processors,” International Conference on ReConFigurable Computing and FPGAs (ReConFig14), Cancun, Mexico, Dec 8-10, 2014.
- D. Petrick, A. Geist, D. Albaijes, M. Davis, P. Sparacino, G. Crum, R. Ripley, J. Boblitt, and T. Flatley, “SpaceCube v2.0 space flight hybrid reconfigurable data processing system,” IEEE Aerospace Conference, Big Sky, MT, March 1-8, 2014.
- D. Petrick, D. Espinosa, R. Ripley, G. Crum, A. Geist, and T. Flatley, “Adapting the reconfigurable spacecube processing system for multiple mission applications,” IEEE Aerospace Conference, Big Sky, MT, March 1-8, 2014.
- T. Flatley, “Keynote address I: SpaceCube: A family of reconfigurable hybrid on-board science data processors,” NASA/ESA Conference on Adaptive Hardware and Systems (AHS), June 25-28, 2012.
- M. Lin, T. Flatley, A. Geist, and D. Petrick, “NASA GSFC Development of the SpaceCube Mini,” 25th Annual AIAA/USU Conf. on Small Satellites, SSC11-X-11, Logan, UT, August 8-11, 2011.
- J. Esper, T. Flatley, and J. Bull, “Small Rocket/Spacecraft Technology (SMART) Platform”, 25th Annual AIAA/USU Conf. on Small Satellites, SSC11-VII-6, Logan, UT, August 8-11, 2011.

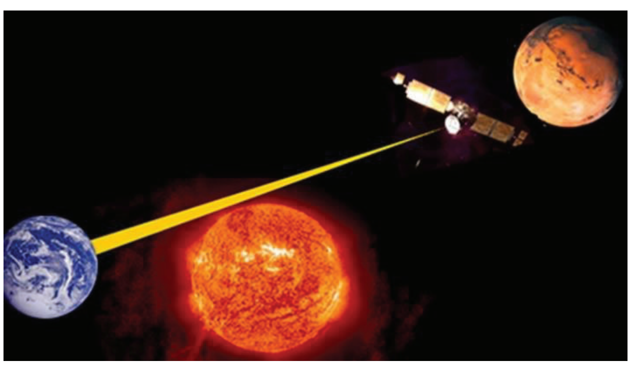
## A.4 NASA JPL Example Projects with Use of COTS

### Example Project 1: EMIT




The Earth Surface Mineral Dust Source Investigation (EMIT) is an Earth Ventures-Instrument (EVI-4) Mission to map the surface mineralogy of arid dust source regions via imaging spectroscopy in the visible and short-wave infrared (VSWIR). The maps of the source regions will be used to improve forecasts of the role of mineral dust in the radiative forcing (warming or cooling) of the atmosphere. EMIT is scheduled for launch to the ISS in 2024. The COTS-based Focal Plane Interface Electronics for Digital (FPIE-D) will use a 28 nM system on chip, which is responsible for the intensive data collection and compression. A tailored qualification and screening plan was developed for this device. Poor radiation performance is mitigated by circuit design. Other COTS were selected and approved based on manufacturer reliability data.

### Example Project 2: DSOC



Deep Space Optical Communication is a Technology Demonstration Mission that will be the first deep space LASER system with look ahead pointing for deep-space communication to Earth. It is intended to communicate high volumes of data from deep space as compared to RF communications. COTS are selected for datasheet specifications, and risk assessed based on manufacturer's reliability data.

## A.5 NASA JSC Example Projects with Use of COTS

**Example Project 1: MPCV Flight Control Module (FCM) and Network Interface Card (NIC)**

The MPCV Flight Computer is a Honeywell design that follows the MPCV EEE Parts Plan, CEV-T-027000. All parts are nominally Grade 1 or Grade 2 with minimal additional screening. The two most critical parts are the FCM processor and the NIC Application Specific Integrated Circuit (ASIC), which are both COTS.

The FCM processor is an IBM 750FX flip chip and the NIC ASIC is an Altera (now Intel) Hardcopy. Both are flip chips and both are COTS. Both followed the CEV-T-027000 plan, which means they were fully screened and each lot was qualified. In addition to the normal datasheet pass/fail criteria, the project added more stringent criteria for timing and power binning. In each case, approximately 1000 parts were procured and screened. It is believed that no parts failed screening or qual. This cannot be known for certain since there was no contractual requirement for screening and qualification summaries to be shared with NASA.

Since being integrated into flight assemblies there have been no known failures of either part. There were two suspected failure of the NIC ASIC. After approximately 6 months and many man-years of investigation involving significant assistance by Altera it was discovered that some flight PCBAs were inserted into test sockets without the test equipment being powered off. This uncontrolled power-up led to failures of the NIC ASIC.

The screening and qualification efforts for these two microcircuits have been discussed as costing several millions of dollars, and taking approximately 2 years.

**Example Project 2: HERA – Hybrid Electronic Radiation Assessor**

HERA is a radiation detector that will fly on all manned missions of MPCV. Each HERA consists of two detectors, 120V power conversion, communications and processing logic, and various other support logic. Two HERA units will fly on each mission. The EEE Parts selection requirement for HERA was EDCPAP. All parts are COTS (including many automotive parts). Few receive part-level MIL-SPEC/NASA screening or third-party qualification.

The key parts are:

- Radiation sensor: Custom CMOS image sensors supplied by the European Council for Nuclear Research (CERN). CERN makes these detectors as part of its Timepix program.
- COTS 64 Mbit Nor FLASH memory
- COTS 4 GB NAND FLASH memory
- COTS fail-safe Microcontroller
- COTS Ethernet Transceiver
- COTS High Voltage (HV) power supply (500 Volts)
- NASA-Screened COTS 120VDC input DC/DC converter

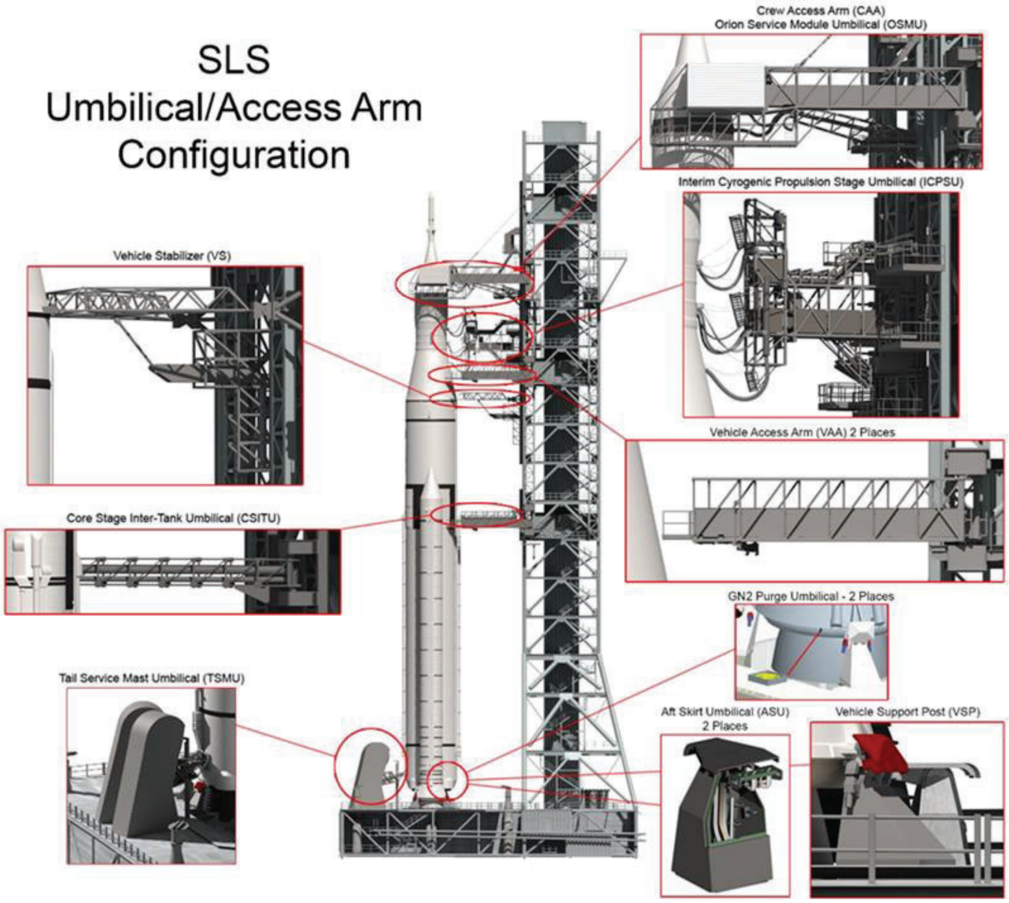
Of the parts listed above, the HV power supply and the DC/DC converter are considered to not come from ILPMs. All others are produced by companies who have demonstrated high quality, are manufactured on highly automated high-volume production lines, and exhibit the other characteristics of ILPMs.
The HV Power supply is hand-built in small quantities. It is not a “part” but is a small assembly. Our review identified it as risky and led to the imposition of burn-in, powered temp-cycles. That testing produced some failures, which led the manufacturer to improve their design and manufacturing. Parts tested after these improvements exhibited no failures.
The 120VDC DC/DC converter provides 20V to power most of the sub-systems in HERA. Its manufacturer is a well-known manufacturer who has experienced several high visibility failures. The part was necessary for HERA due to its size and inclusion of an EMI filter. For this reason, a manufacturing review and full MIL-SPEC/NASA screening and qualification were performed. No failures were observed.
HERA has not flown yet, but has performed without failure in significant ground testing. The allowance of COTS parts, through the EDCPAP, proved beneficial by significantly reducing the cost and schedule of the project, and the size and weight of the hardware.

## A.6 NASA KSC Example Projects with Use of COTS

Exploration GSE Example Projects include Controls for SLS /MPCV Arms & Umbilicals and GSE. COTS parts and assemblies are used throughout.

**Controls for SLS /MPCV Arms & Umbilicals**

Crew Access Arm, MPCV Service Module Umbilical, Interim Cryogenic Propulsion Stage Umbilical, Vehicle Stabilizer, Vehicle Access Arms, Core Stage Inter-Tank Umbilical, GN2 Purge Umbilical, Tail Service Mast Umbilical, Aft Skirt Umbilical, Vehicle Support Post.


SLS
Umbilical/Access Arm
Configuration
Crew Access Arm (CAA)
Orion Service Module Umbilical (OSMU)
Interim Cyrogenic Propulsion Stage Umbilical (ICPSU)
Vehicle Stabilizer (VS)
Vehicle Access Arm (VAA) 2 Places
Core Stage Inter-Tank Umbilical (CSITU)
GN2 Purge Umbilical - 2 Places
Tail Service Mast Umbilical (TSMU)
Aft Skirt Umbilical (ASU)
2 Places
Vehicle Support Post (VSP)

**GSE**

- Hypergolic Servicing Subsystem
- Cryogenics: Liquid Hydrogen & Liquid Oxygen
- Ground Cooling Subsystem
- Thrust Vector Control Hydraulic Servicing Subsystem
- Hydraulic Arms and Accessories Service Pressure
- Environmental Control Subsystem
- Gaseous Helium, Nitrogen, Oxygen, Breathing Air
- Ground Main Propulsion System
- Ground Special Power
- Radio Frequency Telemetry Station
- Range Safety Checkout Subsystem
- Launch Release Subsystem
- Hazardous-Gas Leak Detection Subsystem
- Sensor Data Acquisition Subsystem
- Weather Instrumentation
- Thermal Control Subsystem
- Kennedy Ground Control System

## A.7 NASA LaRC Example Projects with Use of COTS

**Example Project(s): CALIPSO & MEDLI-1&2**

Pressure Transducers from TAVIS and Entran (now Measurement Specialties)

**Example Project 2: CLARREO & CALIPSO**

Laser diodes – Tin whiskers, and Large PDA fallouts.

**Example Project 3: SAGEIII on ISS**

Quartz Contamination Monitor modules – low volume vendor – poor process controls \.

See LaRC COTS usage Presentation 2000-2020 for more details.

## A.8 NASA MSFC Example Projects with Use of COTS

**Example Projects: COTS used on a Category 1 project and on a Criticality 3 project**

**1. Example of commercial EEE parts used on SLS on a Category 1 project**

The Engine controller is using a Xilinx Virtex 5 Field Programmable Gate Array (FPGA) with a PowerPC 440 microprocessor. This particular device is used in Honeywell defense avionics programs. The controller design by Honeywell was supposed to be a custom Class V device (ASIC). But, after consulting with several microcircuit manufacturers, Honeywell determined that it was not cost efficient to build a custom device. Board layouts, box design, and procurement of devices had already occurred. The only alternative was to screen and qualify in accordance with a modified MSFC-STD-3012 Appendix B, "Instructions for Plastic Encapsulated Microcircuit (PEM) Selection, Screening, Qualification and Derating." Screening and Qualification testing was performed by Silicon Turnkey Solution (STS). The Virtex 5 FPGA with a PowerPC 440 microprocessor has some radiation environment limitations, and is not recommended to be used above LEO. Estimated cost after Engineering, Qualification, Screening and Radiation testing is $30K plus per device. 153 Flight parts Part quantity breakdown, (3 lots, 242 devices procured, 86 total test samples, 65 Qualification, 15 DPA, 6 CA).

**2. Example of commercial EEE parts used on SLS on a Criticality 3 avionics**

The Flight Imaging Launch Monitoring Real-Time System (FILMRS) Video Imagery system for SLS was classified as Development Flight Instrumentation (DFI) Criticality 3, not to cause harm to SLS. Commercial video units and camera assemblies were procured, the housings were opened in Electrical Fabrication area, inspected, documented and ruggedized (staked, secured, etc.) where required. In house interface/control and power boards were designed and built using commercial EEE parts, ES43 assisted with EEE parts search. Initial development assembly unit was built and qualification tested for SLS launch environments with success. Subsequently, 5 assemblies have been manufactured and all have passed ATP. Awaiting SLS Artemis missions.

**Example of Class D projects**

1. **Life Science Glovebox (LSG)-ISS**
    - Grade 2 or 3 if available otherwise Grade 4 EEE parts
    - Performed PIND and x-ray screening on most all parts and some external visual inspection
    - Project waived screening for a few parts for first build to meet build schedule
    - Development units built, development testing and Qualification completed

- Two flight units built; units subjected to ATP. One unit currently in use on IS$30M.
- LEO

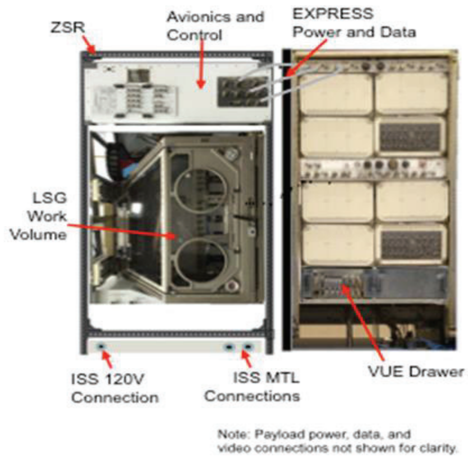



*Figure 1: Life Sciences Glovebox Assemblies*

*Figure 2: NASA astronaut conducting research on the Kidney Cell investigation inside the Life Sciences Glovebox*

**2. 4-Bed $CO_2$ (4BC02)-ISS Demonstration Mission**

- All commercial EEE parts are being procured
- Recommend that designers use Automotive Grade EEE parts when available
- No additional screening performed
- Engineering Models built, Prototypes in work, limited Acceptance testing will be performed
- $15M

- Low Earth Orbit

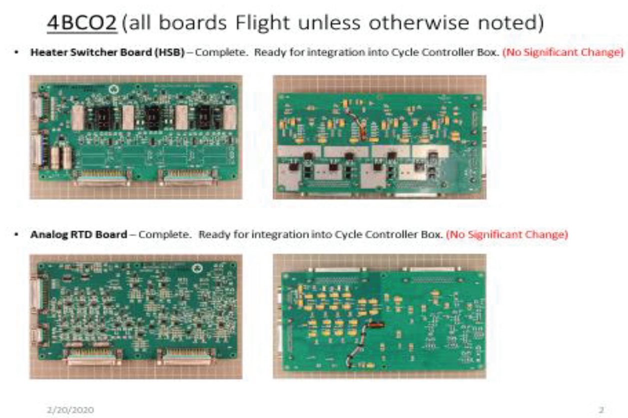



*Figure 3: 4-Bed $CO_2$ Flight Boards*

*Figure 4: 4-Bed $CO_2$ Scrubber*

### 3. OGA Hydrogen Sensor H2ST-ISS Demonstration Mission

- All commercial EEE parts are being procured
- Recommend that designers use Automotive Grade EEE parts when available
- No additional screening performed
- Engineering & Prototype Models built and tested. Flight units being built and will be Acceptance tested
- $3M
- LEO

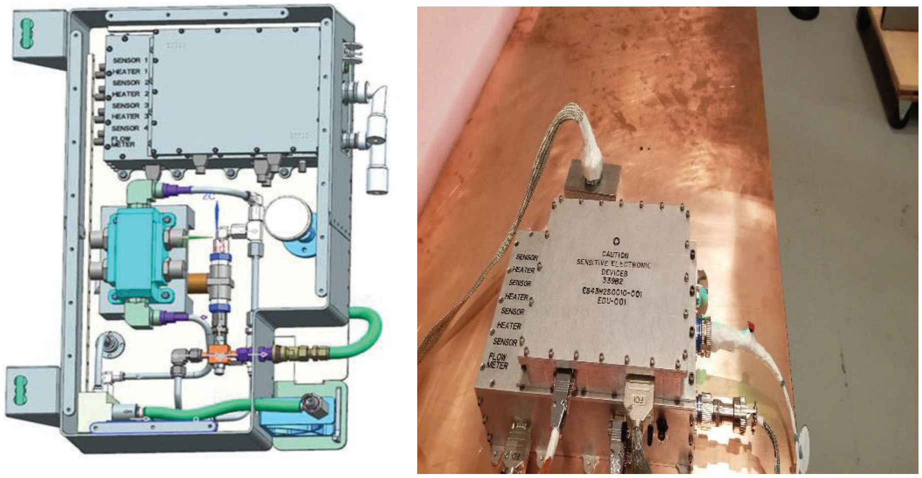


***Figure 5: OGA Hydrogen Sensor***

## 4. Near Earth Asteroid Scout

- Allowed Grades 2, 3 and 4 commercial EEE parts
- CubeSat - Solar Sail
- Performed PIND and x-ray screening on all parts and some visual inspection.
- Engineering Development unit built and successfully tested
- Flight unit built and successfully ATP performed.
- Scheduled for SLS EM1- Artemis 1 payload
- The spacecraft will be jettisoned in cis-lunar space and embark on an ambitious 2.5 year mission to image an asteroid.
- Deep space orbit

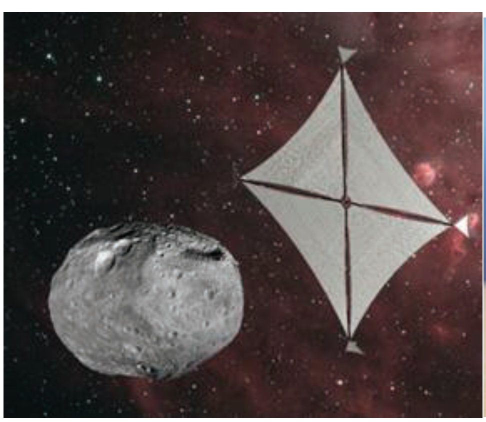


***Figure 6: Example of NEA Scout surveying a target asteroid.***

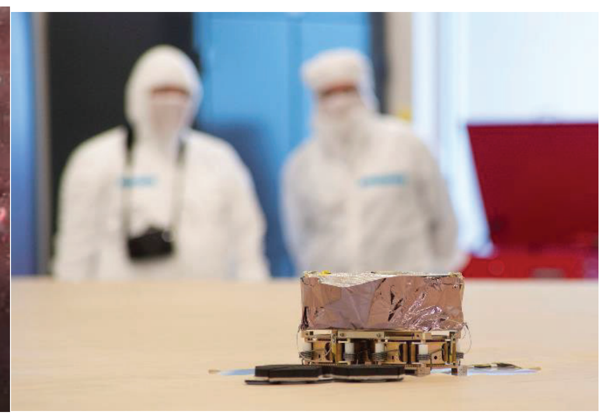


***Figure 7: NEA Scout packaged sail prior to deployment***

**Imaging X-Ray Polarimetry Explorer (IXPE)**

- Mission Assurance Plan classified IXPE as a Class D Experiment, EEE control plan allowed GSFC EEE-INST-002 Level 1, Level 2 or Level 3 parts
- MSFC Managed, built by Ball Aerospace and Italians
- Full Qualification Program, ATP performed on Flight units.
- Pegasus XL launch from Kwajalein
- 540-km circular orbit at 0° inclination

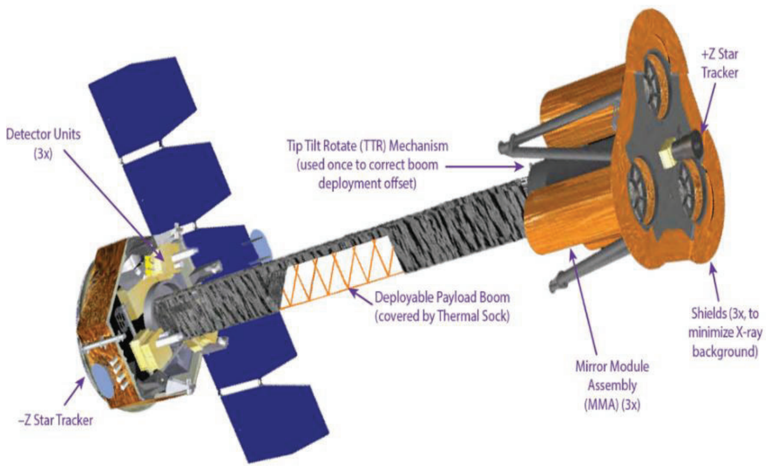



***Figure 8: IXPE Observatory Spacecraft and Payload Hardware***

# Appendix B. Summary of Previous NESC COTS Parts Related Assessments

This appendix summarizes some key conclusions from previous NESC COTS parts related assessments.

## B.1 NASA/TM–2018-220074 // NESC-RP-16-01117

**"Guidelines for Verification Strategies to Minimize Risk Based on Mission, Environment, Application and Lifetime (MEAL)", June 2018.**

This paper describes a MEAL and risk posture base verification process for selection and verification of avionics technology including COTS parts, board and/or box technologies. The paper presents a set of common verification tests and inspections matrix with comparisons of each verification test or inspection by describing the capabilities, advantages and limitations of the test or inspection depending on the level of integration (i.e., part, board, box, etc.) being used. When properly implemented, these tests and inspections ensure that the technologies passing these tests can be safely used on the given flight program with acceptable risks even in safety-critical spaceflight applications. Key take away messages are:

1. *MEAL (**m**ission, mission **e**nvironment, **a**pplication and **l**ifetime of the mission or application)*
   a. The understanding of the MEAL requires a complete picture of how avionics and technologies are to be used effectively. The considerations summarized in the MEAL allow designers to effectively choose parts for their best performance in a given architecture. Emphasizing one of the MEAL elements without understanding the others can compromise the integrity and performance of the parts and the mission success.
2. *Verification process driven by MEAL and mission risk posture*
   a. The MEAL suggests appropriate strategies for mission design, development, implementation, and defines end-of-mission conditions. It also informs/bounds the verification approach and processes through all stages. The selected verification processes must ensure the adequacy of the design is commensurate with the risk that is acceptable to the project.
   b. Verification processes should show that the end-product conforms to its specified requirements at all levels (i.e., part-, board-, box-level, subsystem-level, and system- level).
   c. Skipping part-level testing is often done to reduce the cost and schedule of testing. However, cost savings will be realized only if *no* failures are detected during testing at the higher integration level, assuming this higher integration level testing is sufficient to catch individual parts that could fail during a mission. If there were any failures detected at a higher level, then it would have a *negative impact on cost and schedule*. Moreover,

testing at higher integration levels reduces knowledge of design margin and margin to failures. Vulnerabilities not detected during verification process may lead to adverse consequences ranging from degraded performance to LOM or LOC.

d. In general, the higher the integration, the lower the overall acceleration factor. If tested at the part level, then each individual part could be subjected to maximum stress to achieve the largest possible acceleration factor.

e. The same test conducted at different integration levels yields different information, both quantitatively and qualitatively.

3. *Heritage assessment by the TRL concept centered on MEAL*

a. The use of the TRL concept centered on MEAL to assess flight heritage provides the steps required to qualify any design and could help assess if the "heritage design" is or is not suitable for the given mission.

b. To claim "heritage", the previous mission's characteristics must bound those of the new mission in terms of environment, application, and lifetime. If these bounds are not realized, then the new system would have to regress to the appropriate TRL and be certified/verified to the predicted conditions of new mission.

c. As noted in Government Accounting Office Best Practices reports, "The incorporation of advanced technologies before they are mature has been a major source of cost increases, schedule delays, and performance problems on weapon systems. Demonstrating a high level of maturity before new technologies are incorporated into product development programs puts those programs in a better position to succeed".[2,3]

Understanding **MEAL and risks**, and adopting an attitude of "**always verify**" (trust, but verify), is crucial.

- The MEAL and risk posture based verification process applies to any avionics technology system verification, including COTS part-, board-, and box- technology and previously flown technology.

A comprehensive verification program bounded by MEAL and risk posture requires a full understanding of the capabilities, advantages, and limitations of verification testing conducted at different levels of integration.

## B.2 NASA/TM-2019-220269 // NESC-RP-17-01211

**"Radiation Single Event Effects (SEE) Impact on Complex Avionics Architecture Reliability", April 2019.**

Whether in terms of size, weight, power, speed, precision or a range of other metrics, commercial state-of-the-art (SOTA) electrical, electronic, and electromechanical (EEE) parts are outperforming their space-qualified counterparts by increasing margins. More and more, these performance advantages are becoming crucial for space missions to achieve ambitious performance goals. However, most of these parts are designed for terrestrial applications, and their use in space environments often introduces susceptibilities to single event effects (SEE) that may pose significant threats to mission success.

Unless space mission design teams develop sufficient understanding of SEE susceptibilities and model their effects on a system, these fault and failure modes can overwhelm intended system-level reliability and safety, resulting in system failure.

SEEs can cause a broad range of anomalies and irrecoverable failures, including momentary disturbances of a part's output to data corruption, recoverable loss of functionality, or catastrophic failure. Resulting system-level consequences may depend on the operating state of the affected part, its application in the system, and even the system's state at the time of the SEE. This complex behavior has made it difficult to include SEE in most reliability estimates. However, the increasing use of SOTA and COTS parts has made such inclusion increasingly important.

System-level modeling can explore system sensitivity to SEE rates and consequences when details of the performance of constituent parts remain uncertain, and can establish upper bounds on the SEE rates necessary for acceptable system performance. Such sensitivity modeling results can guide comprehensive SEE testing of critical parts driving system performance, reliability, and safety. This facilitates ensuring EEE component rates remain within acceptable bounds.

System-, element-, unit-, and component-level redundancy are approaches to mitigate SEE. Bounding the SEE threat is especially important when using system-level redundancy to mitigate errors and failures that are non-reparable at the element or individual unit level.

This NESC study focuses primarily on:

1) Developing methodologies for including non-reparable SEE rates and reparable SEE rates (with anticipated repair times) in system-level risk modeling to ensure that the radiation effects in electronics are not a significant mission risk contributor.
2) Applying the results of parametric system-level risk modeling to guide the SEE component test and analyses efforts to ensure the bounding limits used in the model are appropriate.

The NESC team developed guidelines for using system-level modeling to develop insights into system vulnerabilities before SEE becomes a significant threat to mission success, for identifying characteristics that may render a system particularly vulnerable to SEE, and for using results of system-level modeling to optimize testing, analysis, and verification efforts in terms of system-level risk reduction. These guidelines are summarized below.

Based on the studies done, the following guidelines were developed to ensure system modeling yields results that provide useful guidance for radiation and reliability analysis:

1) Irreparable and reparable SEE rates should be included in system models.
2) Reliability and availability model sensitivities should be investigated over a range of rates for reparable and irreparable events and recovery times to determine the level at which they significantly detract from mission success.
3) System-level models should be sufficiently complex to reflect impacts of operating through different mission phases and with different levels of resilience.
4) If system redundancy serves multiple purposes, all of these purposes must be included in the system models, along with their interferences with each other.

The following guidelines were developed to ensure that SEE testing and analysis efforts make efficient use of system modeling results:

1) Use results of system-level reliability and availability assessments to guide SEE test and analysis efforts.
2) Bound unit and system failure rates using available data to determine whether system SEE rates could affect failure rates unacceptably based on system modeling results.
3) Use testing and analysis approaches that are consistent with the program's risk position and risk factors
4) Prioritize testing based on system-level simulation results and risk, ranking, and expected benefits.
5) To minimize disruption to the design process, develop work-around or redesign strategies for use if one or more of the parts selected for test exhibit unacceptable SEE.

# Appendix C. Use of COTS Practices from Centers

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ames Research Center** | | | | | | | | | | | | |
| VIPER/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Important agency robotic lunar resource exploration mission. | Lunar surface | 100 days | Not required, single-string designs permitted | Over 90% COTS parts | **Standard ARC COTS practices:** 1. Use mostly COTS EEE parts, build multiple revisions of EDU's prior to fully qualifying flight hardware. 2. Select widely used COTS parts from major semiconductor OCMs directly or through their authorized distributors. 3. No piece-part screen, qual. Concurrent engineering development (S/W, H/W, interfaces, etc.) using the EDUs at sub-assembly level. | Standard ARC practices: 1.)Sense currents into subsystems: shut down and reset in h/w & s/w. 2.)Reuse avionic designs after successful missions; flight legacy a strong/prime consideration. 3.)Strategically using space rated parts and/or redundancy for single-point failures. 4.)Modularize subsystems with separate power feeds so damages can be quarantined & minimized to allow partial mission success. 5.)Peer review circuit design informally often & share lessons learned. | Detailed mission radiation environment analysis completed. No part level radiation testing planned; but may do some subsystem-level testing if needed. | **ARC standard testing practices**: From prototype to multiple EDU level board testing to sub-assembly level testing. Followed by subsystem level testing to flat-sat testing prior to AI&T (assembly, integration and testing), qualification and flight h/w testing. ARC guideline is minimum 200 hours testing on the flight system, in addition to environmental testing of TVAC, vib and shock. | $200M | Launch date set for December 2022 |
| LCROSS | Class D mission | Not Serviceable; Important lunar impactor to confirm water presence. | Lunar orbit | 110 days | Not required, single-string designs permitted | 90% COTS parts | Use most of the ARC COTS practices | Use most of the ARC best design practices | Similar to VIPER | ARC standard testing practices | $89M | Launched on June 18, 2009; confirmed water on the moon |
| Eucropis/ARC | Payload for Class D mission (DLR Sat.) | Not Serviceable; Important secondary payloads, space biology expt. | LEO | 1 year | 2 identical P/L; one can fail | All COTS | Standard ARC COTS practices. | Standard ARC practices but over current sensing done by spacecraft instead of on payload boards. | Radiation specification given by DLR. No part level radiation testing done. | ARC standard testing practices | $5M | Exceeded full success criteria. The RS422 chip (MAX3491EESD) did experience TID damage at end of mission. |
| UV-LED/ARC | Payload for Class D mission (Saudi Sat.) | Not Serviceable; Mission critical, space physics expt. | LEO | 1 set of data, 3hrs | Not required; 2 identical expts. | All COTS except 2 parts | The unique UV LED parts were fully qualified for the spaceflight mission, while the rest followed ARC standard COTS practices. | Standard ARC practices. | Radiation specification given by KASCT. No part level radiation testing done. | ARC standard testing practices | $3M | Far exceeded the highest expectation, operated fully for 3 years! Resulted published in Classical and Quantum Gravity Physics journal. |
| SporeSat/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Not critical, space biology expt. | LEO | 1 month | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | Mission radiation environment analysis completed. No part level radiation testing. | ARC standard testing practices | $10M | Spacecraft operated successfully the payload failed due to a workmanship issue (LED lighting). |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EDSN/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Not critical, tech demo. | LEO | 2 months | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | Mission radiation environment analysis completed. No part level radiation testing. | ARC standard testing practices | $5M | Lost all 8 satellites due to launch rocket failure. |
| PhoneSat/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Not critical, tech demo. | LEO | 1 day | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | Mission radiation environment analysis completed. No part level radiation testing. | ARC standard testing practices | $1M | Met basic success criteria. |
| O/OREOS/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable | LEO | 1 month | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | Mission radiation environment analysis completed. No part level radiation testing. | ARC standard testing practices | $5M | Exceeded full success criteria, spacecraft operated for 3 years before de-orbiting. |
| PharmaSat/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Not critical, space biology expt. | LEO | 1 month | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | Mission radiation environment analysis completed. No part level radiation testing. | ARC standard testing practices | $4M | Exceeded full success criteria, spacecraft operated for more than a year before de-orbiting. |
| GeneSat/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Not critical, space biology expt. | LEO | 1 month | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | Mission radiation environment analysis completed. No part level radiation testing. | ARC standard testing practices | $3M | Exceeded full success criteria, spacecraft operated for more than a year before de-orbiting. |
| BioSentinel/ARC | Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Not critical, space biology expt. | Deep Space | 1 year | Not required, single-string designs permitted | All COTS except 22 parts | Standard ARC COTS practices. | Standard ARC practices. | Detailed mission radiation environment analysis completed. No part level radiation testing. Some Aluminum shielding used. Using a radiation sensor board to monitor TID level. | ARC standard testing practices | $45M | Launch date set for February 2021 |
| NIRVSS-CLPS/ARC | Instrument for Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Mission critical instrument. | Lunar surface | 100 days | Not required, single-string designs permitted | All COTS except 3 parts | Standard ARC COTS practices. | Same as VIPER, which are ARC standard practices. | Same as VIPER | ARC standard testing practices | $10M | Launch date set for December 2021 |
| NIRVSS-VIPER/ARC | Instrument for Sub-Class D (NPR 7120.8) spaceflight project | Not Serviceable; Mission critical instrument. | Lunar surface | 100 days | Not required, single-string designs permitted | All COTS except 9 parts | Standard ARC COTS practices. | Same as VIPER, which are ARC standard practices. | Same as VIPER | ARC standard testing practices | $10M | Launch date set for December 2022 |
| BioSentinel-ISS/ARC | ISS payload | Not Serviceable; Not critical, space biology expt. | LEO | 1 year | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | No radiation analysis done. No part level radiation testing either. | ARC standard testing practices | $2M | Launch date set for August 2020 |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Astrobee/ARC | ISS payload | Serviceable; Safety critical and mission critical; Critical system (JSC) | LEO | 10 years | Not required, single-string designs permitted | All COTS | Standard ARC COTS practices. | Standard ARC practices. | No radiation analysis done. No part level radiation testing either. | ARC standard testing practices | $25M | Operating fully for almost a year and expected to last for 10 years. |
| | | | | | | | | | | | | |
| **Glenn Research Center** | | | | | | | | | | | | |
| ISS Payloads | Class C/D | Experiments within ISS pressurized volume; ISS Science Experiments | LEO - ISS | Varies | Varies | Level 1 for safety critical; Level 2 standard; COTS acceptable | Try to select parts with known spaceflight heritage; purchase form manufacturer or authorized distributor; visual inspections; functional testing | Parts selection appropriate for application and mission environment; Test on breadboard and engineering hardware prior to building flight units | ISS radiation environment; Typical ISS radiation design/analysis practices | 100 hour burn-in, mission simulation test, end-to-end compatibility test, vibration test, thermal cycling, EMI/EMC testing | Varies | Varies, typically fully successful |
| CoNNeCT/SCaN Testbed | Class D | ISS ELC Payload; Space Communications and Navigation Testbed to advance Software-Defined Radio technology | LEO - ISS | Designed for minimum 2 years operation | Single fault tolerant for safety critical systems | Level 1 for safety critical; Level 2 standard; COTS acceptable | Used mostly level 2 parts; where COTS used, try to select parts with known spaceflight heritage; purchase from manufacturer or authorized distributor; visual inspections; reliability and worst case analyses performed; functional testing | Parts selection appropriate for application and mission environment; Test on breadboard and engineering hardware prior to building flight units | ISS radiation environment; Rad-tolerant design practices except on certain COTS avionics assemblies that were tested at IU | 200 hour burn-in, vibration testing, thermal cycling, EMI/EMC testing | ~$120 Million | Fully successful; operated 2012 to 2019 and was de-commissioned |
| Saffire | Class D | Payload on Cygnus resupply vehicle; Investigate flame spread of microgravity fires and examine flammability limits in ug | LEO - ISS | 0-14 days operations and data download | Single fault tolerant for safety critical systems | Level 1 for safety critical; Level 2 standard; COTS acceptable | Used COTS sensors to collect data that had spaceflight heritage; purchase from manufacturer or authorized distributor; visual inspections; de-rating analysis; functional testing at part/subsystem level; ruggedized COTS DC-DC converters and relays, performed additional testing to verify performance | Parts selection appropriate for application and mission environment; Test on breadboard and engineering hardware prior to building flight units | ISS radiation environment; Typical ISS radiation design/analysis practices | 100 hour burn-in, vibration testing, thermal cycling, EMI/EMC testing | $100 Million | Fully successful; three separate experiments during 2016-2017 |
| ALBus CubeSat | Class D | CubeSat; 100W PMAD EPS, demonstration of new shape memory alloys; non-critical | LEO | 4 months | None | COTS | N/A - pure COTS | Parts selection appropriate for application and mission environment; breadboard prior to flight unit development | N/A | 100 hour burn-in, vibration testing, thermal cycling, EMI/EMC testing | $5 Million | Never established communication with ground after launch; reasons unknown |
| | | | | | | | | | | | | |
| **Goddard Space Flight Center** | | | | | | | | | | | | |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Swift | Class C | not serviceable, important science mission | 600 km, 20.6 DEG | 2 yeas | selective redundancy | Level 3 per 311-INST-001 Rev A, (~15% COTS with added screening) | all COTS were screened to level 3, screening report stated: "SWIFT BAT parts engineering successfully executed a parts control and test program that assured that all parts met or exceeded Grade 3 program requirements, including radiation tolerance. There were a few scattered failures during parts testing, but the subsequent failure analyses revealed that the failures were due to mishandling or improper testing at the board or box level" | GSFC standard practices | streamlined, selective radiation testing | GOLD rules | ~$250M | On orbit since Nov. 2004, still going, no parts failures or issues, no radiation problems. Thermoelectric Cooler DOA once on-orbit (not one of the COTS elements), but worked around. |
| James Webb Space Telescope/GSFC | Class A Spacecraft | Not serviceable; "Extreme consequences to high priority national science objectives" | L2 | 10 years goal | Autonomous Single Fault Tolerance Required | Level 1 | No COTS – all parts either screened and/or procured to meet Level 1 requirements . PEMs were used but screened per EEE-INST-002. | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | $8B | successful so far |
| WFIRST/GSFC | Class A Spacecraft | Not serviceable; Critical national asset. | L2 | 5 years planned, 10 years goal | fully redundant | Level 2. Level 1 parts used for known single point failures, and for critical design applications without redundancy. | Adopting high performance commercial parts, but performing full screening and lot acceptance testing (including, pre-cap inspection and/or DPA) per EEE-INST-002 | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | $3.5B | |
| GPM/GSFC | Class B Spacecraft | Not serviceable; National asset. | LEO | 5 years goal | fully redundant avionics, mostly redundant across the board | level 2 | Not much TRUE COTS- most commercial parts would get SCD generated and specific procurement requirements, screening, and lot qualification testing applied | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | $1B | fully successful |
| JPSS/GSFC | Class B Spacecraft | Not serviceable; National asset. | LEO | 5 years planned, 10 years goal | fully redundant | Level 2 | Not much TRUE COTS- most commercial parts would get SCD generated and specific procurement requirements, screening, and lot qualification testing applied | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | multi $B (series of 4) | successful so far |
| SMAP Radiometer/GSFC | Class C Instrument | Not serviceable; "loss or delay of some key national science objectives" | Polar Orbit | 3 years planned | selective redundancy | Level 2 | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | | radiometer fully successful |
| MMS/GSFC | Class C Multi Spacecraft (4) | Not serviceable; Important science mission. | HEO (apogee beyond GEO) | 2.5 years planned | Four spacecraft formation, redundancy and fault-tolerance | level 2 | Not much TRUE COTS- most commercial parts would get SCD generated and specific procurement requirements, screening, and lot qualification testing applied | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | $1.2B | fully successful |
| TESS/GSFC | Class C Spacecraft | Not serviceable; "loss or delay of some key national science objectives" | Lunar Resonant Orbit - "P/2" | 2 years planned | selective redundancy | Level 2 | COTS screened and qualified parts per EEE-INST-002, several waivers | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | | fully successful |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PACE/GSFC | Class C Spacecraft | Not serviceable; Important science mission. | LEO | 3 years planned | selective redundancy | Level 2 | Not much TRUE COTS- most commercial parts would get SCD generated and specific procurement requirements, screening, and lot qualification testing applied | GSFC standard practices | Full radiation effects engineering support, environment modelling, component testing. | GOLD rules | $1B | |
| NICER/GSFC | Class D Instrument | Not serviceable; Accessible (on ISS), but serviceability was never in scope or budget; "Failure to meet Level 1 requirements prior to minimum lifetime would be treated as a mishap" | ISS - LEO | 18 months | ISS Safety related mechanisms- deployment mechanisms, stowage locks, etc. required 2 fault tolerance. | Level 3 | Higher Criticality systems relied on closer to grade 2 parts, from heritage/flown electronics designs. Newer tech detector and science systems relied on closer to grade 4-COTS parts, maybe receiving some DPA, and checkout conducted at higher assembly levels. | GSFC standard practices | radiation effects engineering support, environment modelled, radiation susceptibility by analysis. Minimal test. | total on-time 700 hours | | fully successful, years beyond lifetime |
| Dellingr/GSFC | Do no harm | Not serviceable; Do no harm, failure acceptable. | ISS - LEO | best effort | none | COTS | pure COTS | none, not built based on a specific plan to launch | none | unknown | | varied |
| MISSE-7 SpaceCube / Space Test Program | DoD Tech Demo | MISSE-7, MISSE-8; Demonstration of radiation mitigation techniques, and FPGA reconfiguration on orbit. | ISS - LEO | 1 year goal, 7.3 year actual | No requirement; many fault-tolerant applications were tested. | None. This was the HST-SM4/RNS flight spare, so it was essentially Level 2 parts | | Robust design, analysis, and thorough testing on the ground. | | Vibe, 2 cycles of TVAC | $1M | Successfully demonstrated different mitigation techniques, reprogrammed FPGAs in space many times, collected realistic radiation SEE data on Xilinx FPGAs, availability of processor at 99.9999% of the mission. 7.3 years of realizable operation. |
| Operational Responsive Space (ORS)/SMART/ DoD | DoD Tech Demo | SMART; Payload controller. Streaming gigabit video to the ground, sensor control and data logging. | Sounding Rocket | 1 day | None. Single string | None. 98% parts had no added screening. | | Robust design, analysis, and thorough testing on the ground. | N/A | Vibe, 2 cycles of TVAC | $5M | fully successful. |
| STP-H4, Communication Interface Box / GSFC/ USAF DoD | DoD Tech Demo | Space Test Program - Houston 4; Main avionics for all DoD and customer payloads. | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application was single string. | None. However this was the reflight of the unit flown on HST-SM4, so it was essentially level 2 parts | | Robust design, analysis, and thorough testing on the ground. | | Vibe, 2 cycles of ambient thermal testing | $10M for entire mission, $1M for SpaceCube | Fully successful. |
| STP-H4, Communication Interface Box / GSFC/ USAF DoD | DoD Tech Demo | Space Test Program - Houston 5; Main avionics for all DoD and customer payloads. | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application was single string. | None. Most parts were left over from HST spares, so essentially level 2 parts | | Robust design, analysis, and thorough testing on the ground. | | Vibe, 2 cycles of ambient thermal testing | $10M for entire mission, $1M for SpaceCube | fully successful. |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STP-H6, Communication Interface Box / GSFC/ USAF DoD | DoD Tech Demo | Space Test Program - Houston 6; Main avionics for all DoD and customer payloads. | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application was single string. | None. Most parts were left over from HST spares, so essentially level 2 parts | | Robust design, analysis, and thorough testing on the ground. | | Vibe, 2 cycles of ambient thermal testing | $10M for entire mission, $1M for SpaceCube | fully successful to date. Still in operation |
| ISS SpaceCube v2.0 Experiment (ISE2.0) / GSFC | GSFC Tech Demo | Space Test Program - Houston 4; Demonstration of SpaceCube v2.0 technology, new GSFC instrument | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application was single string. | None. 98% parts were COTS with no added screening | COTS microcircuits were selected based on heritage, and what was known about similar devices. SEL current limiters were placed in front of a few parts that were thought to be susceptible to SEL. (testing was done after the mission) | Robust design, analysis, and thorough testing on the ground. | used proven sensitive parts, no lot specific testing | Vibe, 2 cycles of TVAC | $1M | SpaceCube fully successful. Met all objectives. COTS Ethernet Hub (external to SpaceCube) failed after one year in operation. |
| ISS SpaceCube Experiment Mini (ISEM) / GSFC | GSFC Tech Demo | Space Test Program - Houston 5; Demonstration of SpaceCube Mini technology, new GSFC instrument. | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application was single string. | None. 98% parts were COTS with no added screening | | Robust design, analysis, and thorough testing on the ground. | | Vibe, 2 cycles of TVAC | $1M | fully successful. |
| Raven, SpaceCube v2.0 / GSFC | GSFC Tech Demo | Space Test Program - Houston 5; Demonstration of Relative Proximity Operations (RPO) system, real-time tracking of inbound/outbound vehicles. | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application was single string. | None. 98% parts were COTS with no added screening | The program selected SpaceCube v2.0 based on its past history in space.<br>Most of the other subsystems in Raven had screening/qual | Robust design, analysis, and thorough testing on the ground. | used proven sensitive parts, no lot specific testing | Vibe, 4 cycles TVAC | $20M+, $1-2M for SpaceCube | fully successful. Tracked all vehicles that visited ISS since March 2017 |
| NavCube / GSFC | GSFC Tech Demo | Space Test Program - Houston 6; Demonstration of GPS instrument technology based on the SpaceCube v2.0 computing platform. | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application is single string. | None. 98% parts were COTS with no added screening | | Robust design, analysis, and thorough testing on the ground. | used proven sensitive parts, no lot specific testing | Vibe, 8 Cycles TVAC, EMI | $1M | fully successful to date. Still in operation |
| SpaceCube v2.0 / RRM-3 / GSFC | GSFC Tech Demo | Robotic Refueling Mission 3; RRM-3 will demonstration refueling technology on orbit. SpaceCube: Payload controller, instrumentation control, wireless ethernet host, etc. | ISS - LEO | 2 years planned | SEE EDAC, watchdog, config scrubbing. Application is single string. | None. 95% parts were COTS with no added screening | The program selected SpaceCube v2.0 based on its past history in space.<br>Most of the other subsystems in Raven had screening/qual | Robust design, analysis, and thorough testing on the ground. | used proven sensitive parts, no lot specific testing | Vibe, 4 cycles TVAC | $30M, $2M for SpaceCube | SpaceCube has been fully successful during its operation. Still in operation. |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HST-SM4, Relative Navigation Sensors, SpaceCube/GSFC | Tech Demo on Shuttle | HST Servicing Mission 4; Demonstration of Autonomous Rendezvous and Docking system capability. | LEO/HST orbit | 14 days (shuttle mission) | SEE detection and correction, watchdog, configuration scrubbing, redundant AR&D applications | Level 2+ | Due to the nature of the manned mission, we were held to high requirements in all areas. Only two part types were unscreened. All other parts (including some COTS) were screened. | Robust design, analysis, and thorough testing on the ground. | Virtex-4 radiation testing, AD654JR TID | Typical GSFC requirements per GEVS (EMI, Vibe, TVAC 8 cycles) | $10M+ | Exceeded all mission objectives |
| | | | | | | | | | | | | |
| **Jet Propulsion Laboratory** | | | | | | | | | | | | |
| Mars Exploration Program/Mars2020/JPL | Class A Spacecraft | Not serviceable; "Extreme consequences to high priority national science objectives" | Martian surface | 10 years goal | Autonomous Single Fault Tolerance Required | Level 1, Level 2 parts | Very little COTS- most commercial parts would get SCD generated and specific procurement requirements, screening, and lot qualification testing applied | Qual and screening | Full radiation effects engineering support, environment modelling, component testing. | | >$1B | Launch date set for July 2020 |
| Earth Systematic Missions (ESM) Program Office/SWOT/JPL | Class C Instrument | Not serviceable; Loss of Mission would impact some key national science objectives | LEO | 3 years planned | fully redundant avionics, mostly redundant across the board | Level 2 | COTS used where there is no space alternative. | Qual and screening | radiation effects engineering support, environment modelled, radiation susceptibility by analysis. Minimal test. | | $100M-$250M | Launch date set for February 2022 |
| Space Technology Research and Development/Deep Space Optical Communication/JPL | Class D payload | Not serviceable; Not critical - demonstration mission | Deep space | 1 year planned | selective redundancy | Level 3 | Commercial parts + screening and qual tests. Some COTS used as-is with waiver. | Qual and screen critical parts | Full radiation effects engineering support, environment modelling, component testing. | | $100M | Launch date set for August 2022 |
| Earth System Science Pathfinder (ESSP) Program/EMIT/JPL | Class C Instrument | ISS; Loss of Mission would impact some national science objectives | ISS - LEO | 3 years planned | ISS Safety related mechanisms- deployment mechanisms, stowage locks, etc. required 2 fault tolerance. | Level 3 | Commercial parts + screening and qual tests. Some COTS used as-is with waiver. | Qual and screen critical parts | Full radiation effects engineering support, environment modelling, component testing. | | $100M | Launch date set for November 2022 |
| | | | | | | | | | | | | |
| **Kennedy Space Center** | | | | | | | | | | | | |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EGS (Exploration Ground Systems) | Category 1 | SLS/Orion Processing and Launch; Safety critical or mission critical systems. | Ground Systems | 20 years | Single Fault Tolerant: fail safe or fail operational | Mil-Spec & Commercial | Selection, Qualification, Screening, Derating<br>Procurement Pedigree,<br>Obsolescence Management<br>Reliability and Maintainability Analysis,<br>Qualified Parts List | Understand your operational environment.<br>Select parts that fit not only functional requirements, but fit operational and environmental requirements.<br>Qualify Parts early and apply mitigations as necessary<br>Understand Part Pedigree.<br>Perform Obsolescence analysis when considering a part. Maintain warranties and vendor support (HW & SW).<br>Implement redundancy. This increases system reliability and availability. Maintain a qualified parts list database. | N/A | Qualification:<br>•Functional/Performance<br>•Electromagnetic Compatibility<br>•Vibration<br>•Acoustic<br>•Thermal | > $3B for Artemis I | Successful to date. Multiple systems have completed qualification, verification and validation culminating into design certifications. Completed 39 of 56 scheduled Artemis-1 GSE Design Certification Review (70%). |
| | | | | | | | | | | | | |
| **Langley Research Center** | | | | | | | | | | | | |
| CERES /<br>Flight Model#6 (FM6) /<br>LaRC | Class C | JPSS-1 /<br>Earth Science /<br>Atmospheric Instrument/Loss of Mission would impact some key national science objectives. | LEO - Polar | 7 Year Mission Requirement<br>-<br>>7 Year Mission Goal | Single Fault Tolerant:<br>fail safe or fail operational;<br>single-string designs permitted | Level 1, Level 2 parts, COTS upscreened | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Full Radiation Effects Engineering Support, primarily via component heritage/pedigree, analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $150M | All CERES instruments are still functional (NPOESS & JPSS) and continue to generate science data available to the public |
| MARS2020 /<br>MEDLI-2 /<br>LaRC | Class C | Interplanetary / RE-entry Vehicle Instrumentation/Loss of Mission would impact MARS Re-entry Vehicle knowledge/Design objectives. | Mars - Planetary Re-entry | 1 Year Mission Requirement<br>- | Single Fault Tolerant:<br>fail safe or fail operational;<br>single-string designs permitted | Level 1, Level 2 parts,<br>Modified-COTS | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Full Radiation Effects Engineering Support, primarily via component heritage/pedigree, analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $100M | Launch date set for July 2020 |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ESSP / ISS / SAGE III on ISS / LaRC | Class C | Earth Science / Atmospheric Instrument / Loss of Mission would impact some key national science objectives. | LEO - ISS | 1 Year Mission Requirement - 3 Year Mission Goal | Don't damage ISS - Generate Science Data per Duration Requirements | Level 1, Level 2 parts, Modified-COTS | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | Understand your operational environment. Select parts that fit not only functional requirements, but fit operational and environmental requirements. Use Redundancy for even M-COTS when you can. Qualify Parts early and apply mitigations as necessary | Full Radiation Effects Engineering Support, primarily via analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $175M | Exceeded full success criteria, instrument operated for more than a year, exceeded 3 year goal of operation - still operational. |
| JPSS2 / (RBI) Radiation Budget Instrument / LaRC | Class C | Earth Science / Atmospheric Instrument /Loss of Mission would impact some key national science objectives. | LEO - Polar | 7 Year Mission Requirement - >7 Year Mission Goal | Fully Redundant Avionics | Level 1, Level 2 parts, Upscreened-COTS | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Full Radiation Effects Engineering Support, primarily via component heritage/pedigree, analysis & environmental modeling. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | Initial $100M With Cost Over Runs Proposed Increase to $200-$300M | De-Scoped |
| CERES / Flight Model#5 (FM5) / LaRC | Class C | NPOESS / Earth Science / Atmospheric Instrument / Loss of Mission would impact some key national science objectives. | LEO - Polar | 7 Year Mission Requirement - >7 Year Mission Goal | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | Level 1, Level 2 parts, COTS upscreened | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Full Radiation Effects Engineering Support, primarily via component heritage/pedigree, analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $250M | All CERES instruments are still functional (NPOESS & JPSS) and continue to generate science data available to the public |
| MARS2012 / MEDLI-1 / LaRC | Class C | Interplanetary / RE-entry Vehicle Instrumentation /Loss of Mission would impact MARS Re-entry Vehicle knowledge/Design objectives. | Mars - Planetary Re-entry | 1 Year Mission Requirement - | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | Level 1, Level 2 parts, Modified-COTS | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Full Radiation Effects Engineering Support, primarily via component heritage/pedigree, analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $100M | Mission was successful - generated Re-entry data that is still used today to predict and design the existing MARS aeroshell performance characteristics |
| ESSP / CALIPSO / LaRC/CNES | Class D | Earth Science / Atmospheric Instrument /Loss of Mission would impact some key national science objectives. | LEO | 1 Year Mission Requirement - >3 Year Mission Goal | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | Level 2, Level 3 parts, COTS | Upscreen/Test parts in advance of system use when possible - or - Test Parts at system level within Safe-Operating-Area(SOA). | Ensure all parts needing system level testing have heritage or some lower level analysis information available for approvals. Use Redundancy for pure COTS when you can. | Full Radiation Effects Engineering Support, primarily via analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $200M | Mission was successful - Not only did it meet the 1 year requirement and exceed the 3 year goal, it continued to operate for 11 years. |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
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| Shuttle/(Orbiter) / EVA-IR Camera / LaRC | Class D | Orbiter (RCC) Thermography Inspection Instrument / Loss of Mission would impact mitigation of new proposed RCC inspection method. | LEO - ISS | 12 Day Mission Requirement - during Orbiter Flight | Don't damage Orbiter - Do No Harm to Astronaut | All COTS - some Level 3 parts | Test Parts/Components at system level within Safe-Operating-Area(SOA). | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. Use Redundancy for pure COTS when you can. | Full Radiation Effects Engineering Support, primarily via analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $10M | Mission was successful - Orbiter demonstration was successful - built more cameras for use on ISS and is still used today for orbital thermography. |
| Shuttle/(Orbiter) / ISS / STORRM / LaRC | Class D | Orbiter - ISS (Docking) Navigation Instrument; Loss of Mission would impact Orion System Design knowledge/objectives | ISS - LEO | 12 Day Mission Requirement - during Orbiter Flight | Don't damage ISS - Don't damage Orbiter | Level 3 parts, Modified-COTS | Test Parts/Components at system level within Safe-Operating-Area(SOA). | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Full Radiation Effects Engineering Support, primarily via analysis & environmental modeling with some component testing. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $75M | Mission was successful - Orbiter/ISS Docking was successful and data was made available for future designs |
| ESSP / CYGNSS / LaRC | Class D | Earth Science / Atmospheric Instrument /Loss of Mission would impact some key national science objectives. | LEO | 1 Year Mission Requirement - 3 Year Mission Goal | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | Level 3 parts, COTS, Modified-COTS | Test Parts/Components at system level within Safe-Operating-Area(SOA). | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Full Radiation Effects Engineering Support, primarily via analysis & environmental modeling. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $75M | Constellation of 8 Birds, Lost 1, the remaining are functional and have met their one year requirement and their 3 year goal |
| ESSP / ISS / CLARREO-Pathfinder on ISS / LaRC | Class D | Earth Science / Atmospheric Instrument /Loss of Mission would impact some key national science objectives | LEO - ISS | 1 Year Mission Requirement - 3 Year Mission Goal | Don't damage ISS - Generate Science Data per Duration Requirements | Level 2, Level 3 parts, Modified-COTS | Commercial parts + screening and qual tests. Custom/commercial parts purchased to SCDs. | Understand your operational environment. Select parts that fit not only functional requirements, but fit operational and environmental requirements. Qualify Parts early and apply mitigations as necessary | Full Radiation Effects Engineering Support, primarily via component heritage/pedigree, analysis & environmental modeling. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $125M | Launch date set for December 2021 |
| STMD / TALISMAN / LaRC | Class D | Robotic Demonstration Not Critical - robotic mission | Deep Space | 1 Year Mission Requirement - | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | Level 3 parts, Modified-COTS | Test Parts/Components at system level within Safe-Operating-Area(SOA). | Understand your operational environment. Select parts that fit not only functional requirements, but fit operational and environmental requirements. Qualify Parts early and apply mitigations as necessary | Full Radiation Effects Engineering Support, primarily via component heritage/pedigree, analysis & environmental modeling. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $10M | De-Scoped |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STMD / LOFTID / LaRC | Class D | Space-Aeronautic Demonstration Re-entry Vehicle Not Critical - demonstration mission | LEO | 12 Hour Mission Requirement - | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | Level 3 parts, COTS | Test Parts/Components at system level within Safe-Operating-Area(SOA). | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Minimal Radiation Effects Engineering Support, when possible primarily via component heritage/pedigree, analysis & environmental modeling. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $50M | Launch date set for December 2021 |
| STMD / NDL – Navigational Doppler LiDAR / LaRC | GPR8705.4 7120.8 Class Do No Harm | Space-Aeronautic Demonstration Vehicle Landing Instrument Not Critical - demonstration mission | Sub-LEO | 12 Hour Mission Requirement - | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | COTS, Engineering Grade Parts | Test Parts/Components at system level within Safe-Operating-Area(SOA). | Select Parts that meet functional, operational and environmental requirements. Qualify High Risk & Critical Parts as early as possible to understand and apply mitigations as necessary. | Minimal Radiation Effects Engineering Support, when possible path to flight - primarily via component heritage/pedigree, analysis & environmental modeling. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $25M | Launch date set for Fall 2020 |
| ESSP / SHIELDS / LaRC | not rated | Cube-Sat Demonstration/Not Critical - demonstration mission | LEO | 1 Year Mission Requirement - >1 Year Mission Goal | Single Fault Tolerant: fail safe or fail operational; single-string designs permitted | COTS | Test Parts/Components at system level within Safe-Operating-Area(SOA). | Ensure Quality/Reliability Requirements match Mission Budget and Duration expectations. | Minimal Radiation Effects Engineering Support, primarily via component heritage/pedigree when possible. | Langley Standard / Project Specific Tailored System Level Burn-in and Environmental Testing | $5M | Exceeded full success criteria, spacecraft operated for more than a year - and is still operational. |
| | | | | | | | | | | | | |
| **Johnson Space Center** | | | | | | | | | | | | |
| ISS | Category 1 | ISS; Safety and mission Critical | LEO - ISS | 30 years | 2 Fault Tolerant | Grade 2+ | COTS required full parts level qualification and screening | Full, detailed, robust prototyping, derating, WCCA. | Full testing or data to LET 37 | Based on SMC-S-016, but allows 300 hour room temp burn-in. | More than you can count | OK so far |
| Orion | Category 1 | Orion; Safety and mission Critical | Deep Space | 10 years | 2 Fault Tolerant | Grade 1 | COTS required full parts level qualification and screening | Full, detailed, robust prototyping, derating, WCCA. | Full testing or data to LET 75 | Based on SMC-S-016. | More than you can count | Launch 2021 |
| EBOT | Category 1 | ISS EMU battery charger; Mission critical (Crit 2) | LEO - ISS | 10 years | Single fault tolerant; 4-6 modules in EBOT unit | Grade 2* | Manufacturer data allowed to take place of qual and lot conformance. Assembly level allowed to take place of part screening. | Standard JSC GFE practices, box level acceptance testing | Protons | Follows ISS | < $1M (TBC) | Launch 2020 |
| LAM | Category 1 | Orion air monitor; operating 24 hours per day; Safety and mission Critical | Deep Space - Orion | 10 years | Single fault tolerant | Grade 2 | COTS required full parts level qualification and screening | | Full testing or data to LET 75 | Follows Orion | | Launch with Orion |
| AGA | Category 1 | ISS air monitor; Safety and mission Critical | LEO - ISS | 10 years | box-level redundancy | COTS (EDCPAP) | EDCPAP - Manufacturer investigation to determine if best practices are in place. | | Protons | Follows ISS | | Launch 2020 |
| T2 | Category 1 | ISS Treadmill; Mission critical | LEO - ISS | 20 years | zero fault tolerant | COTS (EDCPAP) | EDCPAP - Manufacturer investigation to determine if best practices are in place. | Standard JSC GFE practices | Protons | Follows ISS | | 10 years no fails |
| ISS laptops | Category 1 | ISS non-critical laptops | LEO - ISS | best effort | zero fault tolerant | none | na | | Protons | TBC | | 20 years, replace as fails (not many) |
| HERA | Category 1 | Orion Radiation Monitor; Safety and mission Critical | Deep Space - Orion | 10 years | Single fault tolerant (box level) | COTS (EDCPAP) | EDCPAP - Manufacturer investigation to determine if best practices are in place. | Standard JSC GFE practices | VDBP - NSRL | Follows Orion | | Launch with Orion |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MEDUSA | Category 1 | Orion DFI; Non critical | Deep Space - Orion | 10 years | zero fault tolerant (box level redundancy) | COTS (EDCPAP) | EDCPAP - Manufacturer investigation to determine if best practices are in place. | Standard JSC GFE practices | Protons (or none) TBC | Follows Orion | | Launch with Orion |
| GRFW | Category 1 | ISS Food Warmer; Non critical | LEO - ISS | 10 years | zero fault tolerant | COTS (EDCPAP) | EDCPAP - Manufacturer investigation to determine if best practices are in place. | Standard JSC GFE practices | Protons | Follows ISS | | 10 years no fails |
| PWD | Category 1 | Potable Water Device; Non critical | LEO - ISS | 10 years | zero fault tolerant | COTS (EDCPAP) | EDCPAP - Manufacturer investigation to determine if best practices are in place. | Standard JSC GFE practices | Protons | Follows ISS | | 10 years no fails |
| Orion Flywheel | Category 1 | Orion Flywheel; Non critical | Deep Space - Orion | 10 years | zero fault tolerant | COTS | | | none | TBC | | Launch with Orion |
| Ammonia Scrubber | Category 1 | ISS ammonia leak recovery; 1S - used in case of accident | LEO - ISS | 10 years (storge) | zero fault tolerant | COTS | EDCPAP - Manufacturer investigation to determine if best practices are in place. | Replaced wet Aluminum Electrolytic caps with poly. | none (or Protons) TBC | Follows ISS | | Launch 2020 |
| Shuttle | Category 1 | Not serviceable on orbit; Could be in the ground in hours; Safety critical or mission critical; Critical system (JSC) | LEO | Up to couple of weeks | Mostly 2-FT | B+ parts | Full parts level qualification and screening and lot conformance; full radiation characterizations? | | | | | |
| ISS | Category 1 | Very serviceable on orbit; Lifeboats constantly available; Safety critical or mission critical; Critical system (JSC) | LEO | long mission length | Multi-FT | Critical systems mostly S parts, B+ allowed | Full screening, qualification, radiation characterization at parts level | | | | | |
| Orion | Category 1 | Not serviceable; No ability to come home quickly during most mission phases; Safety critical or mission critical; Critical system (JSC) | Deep Space | Varies | 2-FT | Minimum requirement is B+; radiation mostly forces S parts | Full screening, qualification, radiation characterization at parts level | | | | | |
| ISS payloads | Class A-D | Not serviceable; Safety critical or mission critical; Critical system (JSC) | LEO | Varies | Don't damage ISS | | | | | | | |
| Commercial Cargo | | Not serviceable; Safety critical or mission critical; Critical system (JSC) | LEO | About 1 month | Don't damage ISS | Very few parts requirements; 1553 Interface to ISS | | | | | | |
| Commercial Crew | | Not serviceable; On the ground in hours; Safety critical or mission critical; Critical system (JSC) | LEO | complicated? | 2-FT; Don't damage ISS | Meet the intent of SMC-S-010 | | | | | | |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
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| Typical JSC-created hardware | | 1. Usually not critical system, e.g. cameras for inspection, radiation monitors, exercise equipment, non-critical data.<br>2. Some is safety critical, but only after a hazardous event (Crit 2S), e.g. air monitor, ammonia scrubber, AED | LEO | varies? | | | 1. Usually use commercial parts, build and fly multiple copies, check operation periodically.<br>2. Use best effort to pick parts from known, trusted, investigated OCMs. These include use non-mil Parts from industry leaders, and try to understand their qual, ongoing reliability monitor, defect prevention methods.<br>3. Usually no piece-part screen, qual. | | | | | |
| Artemis | | Safety critical or mission critical<br>Critical system (JSC) | LEO | | | Meet SMC-S-010 | | | | | | |
| **Marshall Space Flight Center** | | | | | | | | | | | | |
| Shuttle Main Engines | Category 1 | Propulsion for the Orbiter. Not serviceable during launch or on orbit; Could be in the ground in hours; Safety and mission Critical System (MSFC) | LEO | Months of testing, 10-plus minutes flight duration, 7-10 day orbit | 2 Fault Tolerant | Grade 1 | COTS required full parts level qualification and screening and lot conformance for critical devices. | Robust design to achieve ample margin. Qual and screen critical parts | Full radiation effects engineering support, environment modelling, component testing. | Complete Rigorous Qualification and Acceptance testing regiment to ensure survivability. | $196 Billion | 2 catastrophic failures<br>133 successful missions |
| Space Shuttle External Tank | Category 1 | Propulsion system for the Orbiter. Not serviceable. External Tanks are jettisoned after SSME's completes burn, tanks burn up during re-entry; Safety and mission Critical System (MSFC) | < LEO | Months of testing, 10-plus minutes flight duration | 2 Fault Tolerant | Grade 1 | COTS required full parts level qualification and screening and lot conformance for critical devices. | Robust design to achieve ample margin. Qual and screen critical parts | Radiation characterizations for critical devices. | Complete Rigorous Qualification and Acceptance testing regiment to ensure survivability. | $196 Billion | 2 catastrophic failures<br>133 successful missions |
| Shuttle Solid Rocket Booster | Category 1 | Propulsion system for the Orbiter; Not serviceable during launch; Boosters recovered and refurbished; Safety and mission Critical System (MSFC) | < LEO | Months of testing, 3-plus minutes flight duration | 2 Fault Tolerant | Grade 1 | COTS required full parts level qualification and screening and lot conformance for critical devices. | Robust design to achieve ample margin. Qual and screen critical parts | Radiation characterizations for critical devices. | Complete Rigorous Qualification and Acceptance testing regiment to ensure survivability. | $196 Billion | 2 catastrophic failures<br>133 successful missions |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Space Launch System | Category 1 | Propulsion launch service for the Orion Spacecraft. Not serviceable during launch or on orbit; Could be in the ground in hours; Safety and mission Critical System (MSFC) | LEO MOON | Months of testing, 10-plus minutes flight duration for Core Stagem, 20-plus minutes flight duration for Exploration Upper Stage | 2 Fault Tolerant | Grade 1 for Criticality 1 applications Grade 2 for Criticality 1 R applications | COTS require full parts level qualification and screening and lot conformance for critical devices. | Robust design to achieve ample margin. Qual and screen critical parts | Launch Vehicle radiation characterizations for Critical Devices. Above, LEO requires full radiation effects engineering support, environment modelling, component testing. | Complete Rigorous Qualification and Acceptance testing regiment to ensure survivability. | $15 Billion | Scheduled for November 2021, SLS EM-1 |
| Space Launch System | Criticality 3 | Video Imaging during launch; Criticality 3 cause no harm | LEO | Verification checkout and 10 minute launch insertion | Single string | COTS | COTS EEE parts used as is with bread board evaluation and performance tested | Recommend that designers use AEC components | none | Design is subjected to Qualification environments. Production units are subjected to Acceptance Testing at the Assembly level | $5 Million | Scheduled for November 2021, SLS EM-1 |
| Life Science Glovebox | Class D | Serviceable; Science Experiments on the ISS. | LEO | 5 years | none | COTS | Use best effort to pick parts from known, trusted, investigated OCMs. These include use non-mil Parts from industry leaders, and try to understand their qual, ongoing reliability monitor, defect prevention methods.<br>PIND and X-Ray screening performed. | Recommend that designers use AEC components | none | Used a combination of Military and commercial parts, built brassboard assemblies for evaluation and performance. Performed acceptance testing to validate workmanship and system level performance. | $30 Million | On orbit success in the International Space Station. Delivered to ISS Crew on October 1, 2018. |
| 4-Bed CO2 monitor | Class D | Serviceable; ISS Technology Demonstration Demonstrate capability to detect CO2. | LEO | < 3 years | none | COTS | 1. Usually use commercial parts, build and test multiple copies, check operation periodically.<br>2. Use best effort to pick parts from known, trusted, investigated OCMs. These include use non-mil Parts from industry leaders, and try to understand their qual, ongoing reliability monitor, defect prevention methods.<br>3. Usually no piece-part screen, qual. | Recommend that designers use AEC components | none | Used commercial parts, built brassboard assemblies for evaluation and performance. Performed acceptance testing to validate workmanship and system level performance. | $15 Million | Currently in manufacturing and production phase. |

| Program or Project/ Lead Center | Category /Classification | Mission/Criticality | Mission Environment | Mission Lifetime Goal | Fault Tolerance Requirements/ Implementations | Baseline or Minimum Parts Level Required by Project | Use of COTS Current Practice (Selection, Evaluation, Screening, and Qualification processes) | Best Design Practices | Radiation Environment Analysis and Testing | Assembly Level Testing Requirements/Implementations | Life Cycle Cost excluding Launch Cost | Mission Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogen Sensor | Class D | Serviceable; ISS Tech Demo. | LEO | < 3 years | none | COTS | 1. Usually use commercial parts, build and test multiple copies, check operation periodically.<br>2. Use best effort to pick parts from known, trusted, investigated OCMs. These include use non-mil Parts from industry leaders, and try to understand their qual, ongoing reliability monitor, defect prevention methods.<br>3. Usually no piece-part screen, qual. | Recommend that designers use AEC components | none | Used commercial parts, built brassboard assemblies for evaluation and performance. Performed acceptance testing to validate workmanship and system level performance. | $15 Million | Currently in manufacturing and production phase. |
| NEAS | Class D | Lunar craft to image and survey Near Earth Asteroids; Science Information | Deep Space | 3-5 years | Critical item redundancy | commercial | Use best effort to pick parts from known, trusted, investigated OCMs. These include use non-mil Parts from industry leaders, and try to understand their qual, ongoing reliability monitor, defect prevention methods.<br>PIND and X-Ray screening performed. | Recommend that designers use AEC components | Selected critical components were characterized for Radiation susceptibility | | $20 Million | Scheduled for November 2021, SLS EM-1 |
| IXPE | Class D | Study X-ray images from Black Holes and Neutron Star; Science Information to help determine the creation of the Earth. | 540 KM at 0 ° Inclination | 3-5 years | Critical item redundancy | Level 1, 2 or 3 EEE parts. | Designers used mostly Level 2 Military components that did not require any piece part evaluation or screening. | Select devices that were not available were chosen from well-known manufacturers with significant previous usage history. | Benign radiation environment determined from evaluation | Full up Qualification testing performed, Acceptance testing performed on Flight units. | $31 Million | Launch Scheduled for Spring 2021 |

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Minor updates to Sections 4.0 and 7.10.7. Section 8.3 (removed NESC Recommendations and pointed the reader to the Phase II final report). Added Appendix C, Use of COTS Practices from Centers.

**14. ABSTRACT**
The NASA Electronic Parts & Packaging Program Manager, requested a NASA Engineering and Safety Center independent assessment to summarize Commercial Crew Program and NASA Centers' current and best practices, and lessons learned, on use of commercial-off-the-shelf (COTS) for all mission risk classifications, and provide recommendations that could lead to future NASA Electronic Parts and Packaging Program and/or Agency guidance on COTS parts. This document contains the outcome of the assessment.

**15. SUBJECT TERMS**
Commercial-Off-The-Shelf; Best Practices; Lessons Learned; Electrical, Electronic, and Electromechanical

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