CENTER FOR SPACE POLICY AND STRATEGY

APRIL 2019

GOT RELIABILITY? OFF-THE-SHELF (OTS) ELECTRONIC PARTS FOR RESILIENT SPACE SYSTEMS

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Summary

A confluence of events has drawn increased interest in off-the-shelf (OTS) electrical, electronic, electromechanical, and electro-optical (EEEE) parts for use in resilient, reliable, short-duration space systems and other missions. Yet, those who specify, design, build, deploy, and operate such platforms often lack key technical guidance that would help them make informed, timely, and cost-effective decisions regarding these OTS parts to support optimum, agile mission assurance.

We emphasize that OTS EEEE parts may not be appropriate for every mission (e.g., long-duration or critical operational missions). Here we offer an overview of the key drivers that motivate the space sector to use OTS parts (i.e., automotive, aviation, commercial, medical, and industrial) in resilient missions. Initially, it may seem counterintuitive to use such parts in an environment (e.g., space radiation) for which they were not designed. We describe how their advanced capabilities, ready access and low purchase cost can indeed make them attractive for resiliency, and discuss the previous, current, and emerging business practices and models that have evolved to address the key drivers. Following this, challenges and considerations are outlined for those who influence the selection, procurement, or use of OTS parts. Rather than offering prescriptive closed-form solutions or one-size-fits-all answers, the strategy focuses on encouraging technical discussion that high-level decisionmakers and developers of resilient systems can use to make pragmatic mission-specific policy and technical choices. Finally, we propose steps that the community can take to integrate the use of OTS EEEE parts while managing risk. Throughout, we share insights from industry and government leaders with first-hand experience in successfully using OTS parts in their missions. For the reader's convenience and clarity, a list of definitions and acronyms is provided.

Overview of OTS Parts and Why Their Time Is Now

A confluence of events is driving mission developers toward the use of off-the-shelf (OTS) parts. Emerging global threats dictate the need to develop and refresh on-orbit capabilities quickly. In turn, U.S. national priorities have come to value resiliency—especially for constellations, short-duration (<5 years), or fault-tolerant space missions and systems, which incorporate OTS electrical, electronic, electromechanical, and electro-optical (EEEE) parts.

To date, OTS EEEE parts are widely used in aviation, medical, automotive, commercial, and industrial applications. Indeed, small satellites have been designed, built, and flown with OTS parts for many years.[1] Now, other space programs can benefit from these inexpensive, high-performing, and readily available parts. Initially, it may seem counterintuitive to use such parts in an environment as harsh as space (e.g., radiation) and for which they were not designed. However, OTS parts' advanced performance, ready access, and low purchase cost make them attractive for resiliency, and they undergo frequent design iterations, allowing more opportunities for technology refresh. That said, these parts generally operate within limited design criteria and may have little to no radiation tolerance. Furthermore, the relevant supply chain can be highly susceptible to market forces and generally provides little insight into design changes or quality control testing.

In the transition to resilient systems, managing versus eliminating risk should be a key consideration.

In the transition to resilient systems, managing versus eliminating risk should be a key consideration. If their risks are managed, OTS parts can fit into space programs and potentially provide more options for managing system-level risk in current applications. Admittedly, OTS EEEE parts are not feasible for every mission. They must be evaluated in the context of the mission-specific requirements and constraints.

> "L3 CE Space Avionics and other L3 Divisions have a significant and positive history of utilizing industrial (automotive)-grade devices in high-reliability military applications. A mil [military-grade] part does not automatically give assurance of robustness. Low-volume runs do not benefit from the feedback loop of many users. High reliability [is] more a function of design and robustness of packaging/attachment vs. failures per billion hours of the standalone part."
>
> *—Mark Dapore*
> *L3 Space & Sensors, CE Space Avionics*

This document is intended for those who influence the selection, procurement, or use of OTS parts, and can address these challenges. It is designed to guide technical requirements discussions with decisionmakers and stakeholders and to support translation into specifications and capabilities. The content is meant to engender thoughtful policy discussion and informed, purposeful decisionmaking, sometimes with incomplete data. The authors have leveraged public-domain and readily available, non-sensitive technical information and best practices observed in industry. They have combined this with hands-on scientific and engineering experience and direct input from members of industry and government.

Opportunities to Fly OTS Parts in Space: Then and Now

U.S. space missions have historically been divided into types or classes, defining the nature, length, and criticality of the mission. Mission classes range from Class A, which are extremely critical operational systems for which all practical measures are taken to ensure mission success—to Class D, which are often research-oriented, experimental-type missions with minimum mission assurance standards and requirements and a higher risk tolerance profile. Table 1 summarizes some key attributes of the various traditional program classes.

Class A and B missions usually have an optimal mission design and use high-reliability, space-grade parts. Prior to 2015, launch vehicle Parts, Materials, and Processes (PMP) requirements called for the use of space-grade components to ensure the quality and reliability of the hardware.[2] In 2015, the PMP requirements were modified to allow for (1) more flexibility and (2) new technology insertion, since systems used redundant hardware schemes and had short mission lives.[3] The modified requirements allow system developers to utilize a self-defined baseline, provided that specific requirements for non-space-grade electronic parts were met, including redundancy, homogeneity, and traceability.

Class C and D missions are often experimental in nature and may have limited budgets and reduced timelines. In these cases, the PMP baseline consists typically of OTS parts, given the lower cost of procurement, advanced capabilities, and shorter lead times. Class C missions generally use military terrestrial-grade parts, and Class D missions can use any-grade parts—with preference for commercial OTS items. Selected tests and characterizations are performed on an application-specific basis as required. For these Class C and D missions, space-

Table 1: Guideline of Space Vehicle Attributes for Different Mission Risk Classes*

	Class A	Class B	Class C	Class D
Risk Acceptance	Lowest	Low	Moderate	High
National Significance	Extremely critical	Critical	Not critical	Not critical
Payloads	Operational	Demonstrated operational utility; may become operational	Typically experimental	Typically experimental
Acquisition Cost	Highest	High	Medium	Lowest
Development Time	May take 4 years or more	May take 3 years or more	May take 2 years or more	May take 1 year or more
Mission Life	Long. Greater than five years. Typically 8–10 years.	Medium. Up to 5 years.	Short. Less than 2 years.	Short. Less than 1 year.
Launch Constraints	Critical	Medium	Few	Few to none
Specifications and Standards Compliance	Specs/Stds fully incorporated as compliance documents with no or limited tailoring of requirements. All practical measures taken to minimize risk to mission success.	Specs/Stds required as compliance documents, with minor tailoring in application to maintain a low risk to mission success.	Medium risk of achieving mission success may be acceptable. Reduced mission assurance requirements with tailoring acceptable.	High risk acceptance to achieve mission success is permitted. Reduced set of mission assurance requirements acceptable.

**Source: Mission Risk Posture Assessment Process Description, Aerospace Report No. ATR-2015-03151, September 29, 2015.*

grade parts are usually selected for unique or mission-critical applications only.

The government must accomplish missions with increased resiliency and innovation, reduced cost, and on shorter timelines. Therefore, the applied mission assurance must be agile. It must be efficient by keeping verification off the critical path—effective by finding flaws early and reducing re-work—and current by responding to changes in industry, program specifics, and the space enterprise. Integrating wider use of OTS parts could be a key enabler for the success of these missions. If the requirements or operating mode of a mission scenario suggests that more risk is acceptable, then the grade of parts can be lowered and the lifecycle costs reduced. For any mission managing risk, regardless of cost profile, a new OTS parts–based design could do. Here, designers can identify failure modes with a thorough failure modes effects and criticality analysis, and then build mitigations into the design up front.

If the use of OTS parts is an acceptable methodology, the program might be able to do a drop-in replacement for the higher-grade part, with no other board or design changes necessary. However, the worst-case scenario requires modification to the design and board layout to ensure that the system is less susceptible to variations in OTS parts performance. The cost of such changes would need to weighed against performance benefits.

Challenges for OTS Parts in Space

Using OTS parts will certainly play a role in reducing costs and enhancing resiliency in space missions. Even so, acknowledging and addressing design changes motivated by the use of OTS parts is critical for mission success. Of the many challenges associated with the transition to OTS parts, we discuss four below: space radiation, supply chain management, unit consistency, and balancing business and mission needs.

Leveraging the benefits of OTS parts requires program managers to pivot the mission assurance approach to focus on the issues that deliver the greatest return on investment for the mission, and manage the risk associated with the rest.

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Challenge #1: Space Radiation and Other Extremes of Space

Radiation performance is a critical factor when considering the use of OTS parts. OTS parts intended for use in other high-reliability applications, such as aviation, medical, and automotive, are not typically designed with natural space radiation effects in mind (though this is changing for the autonomous vehicle industry). There are numerous sources of radiation test data that should be investigated, including NASA, professional society-refereed publications, and parts manufacturers. If no radiation data is publicly available, testing is highly recommended under the radiation conditions for the spacecraft’s orbital environment.

A single high-energy particle impacting a sensitive EEEE component can cause the component to fail and potentially cause loss of mission. In addition to the single-event effects, accumulation of total ionizing and non-ionizing dose (TID and TNID, respectively) over the course of a mission can also lead to part failure. Specifically, in a high-radiation environment, non-hardened OTS parts could lead to data corruption, functional interrupts, latch-up, burnout, or gate rupture.

To mitigate radiation effects, space-grade microcircuits are designed using approaches known as "radiation-hardened by design" and "radiation-hardened by process." If possible, the most sensitive part types, such as processors and clocks, should be procured to these design standards. Additionally, consideration should be given to part types/designs that are known to be more radiation-tolerant than others (e.g., dielectrically isolated, complementary metal oxide silicon [CMOS] on silicon on insulator [SOI] or the use of epitaxial layers). Other mitigation measures include:

- Building in flexibility for additional size, weight, and/or power to accommodate extra metal to shield radiation-sensitive electronic parts
- Introducing system redundancy by hosting multiple backup copies of mission-critical parts, should one fail during the mission
- Assuming the worst-case scenario, i.e., that all EEEE parts are radiation-vulnerable, and planning for alternate maneuvers or operations—in advance—should a part fail on orbit
- Designing for the ability to reconfigure circuits, functions, or constellations on the fly
- Incorporating fault detection, isolation, and recovery algorithms to handle anomalies
- Designing the end-to-end program or mission with access to rapid, re-launch capability so that failed assets can be replaced or replenished on demand

> "The COTS part was a winner in all categories and was incorporated into our standard product line, with no problems identified in any application.
>
> "We have focused on diodes, the simplest and most widely used EEEE parts on our spacecraft. There were many lessons learned during our study [of automotive and commercial diodes].
>
> "'Drop-in' replacements for space-grade parts are difficult to find. Extensive use of COTS would require redesign and requalification.
>
> "Some vendors produce very high-quality, high-reliability COTS parts that can be suitable for space, and offer better affordability and lead times than space-grade equivalents. On the other hand, due to low-cost construction techniques, some COTS parts may not be suitable for long-term use.
>
> "Opportunities abound to provide more affordable systems, but it's important to do a full qualification to avoid reliability problems."
>
> *—James Loman*
> *SSL, a Maxar Technologies Company*

- Architecting systems for interoperability and backup functions for other systems, rather than delivering unique functions that can be vulnerable to obsolescence, attack, degradation, or mishap

In addition to withstanding the radiation environment in space, space-grade electronics must endure severe temperatures, altitudes, vibration, and shock—all with an overall expectation of low failure rates. Table 2 underscores the significant threshold differences between operating environments for EEEE parts categories.

Table 2: Comparison of Selected Operating Parameters for Electronic Parts Categories				
Parameter	COTS	Industrial	Automotive	Space
Operating Temperature	0°C/–5°C to 40°C/70°C	–10°C to 70°C	–40°C to 85°C/160°C	–55°C to 125°C
Operating Lifetime	1–5 yrs	5–10 yrs	15 yrs	10 yrs minimum
Targeted Failure Rates	<10%	<1%	0	0
Humidity	30–85%	15–90%	0–100%	0% (on orbit)
Temp Cycles/Shock	Low	Med	Hi	Highest
Altitude	7k–10k ft	10k–12k ft	12k–15k ft	23k nm
Vibration/Shock	Low	Med	Hi	Highest
Electromigration	Low	Med	Hi	Highest
Electromagnetic Compatibility	Interference/ Susceptibility	Interference/ Susceptibility	DC-Susceptibility	DC-Susceptibility
Natural Space Radiation	No	No	No	Yes

Challenge #2: Supply Chain Risk Management

Many foreign companies are an integral part of the supply chain for space, including design centers, wafer fabrication plants, packaging centers, and testing facilities. Dependence on foreign suppliers presents not only significant opportunities, but also some threats. On one hand, OTS parts, most of which are produced by foreign suppliers, are substantially ahead of space-rated parts and can deliver advanced capabilities and faster technology refresh for missions. On the other hand, while not unique to foreign suppliers, it is often more complicated to get detailed product information, should it be needed in a mission failure or anomaly investigation. Furthermore, reduced control of OTS parts in the chain of custody can contribute to a higher risk of counterfeit parts within the supply chain. Figure 1 lists several of these related concerns.

The OTS products that the government needs and wants do not necessarily fit within the current compliance processes and practices in the OTS marketplace. The key is to identify the likely realistic threats and—based on the specific mission's requirements—determine effective mitigations. These could include procuring from authorized electronic parts distributors, participating in government and industry collaboration groups to gain awareness of ongoing developments, developing strong relationships with manufacturers where possible, performing destructive physical analysis (DPA) of parts on a sample basis from each lot purchased, and taking greater advantage of reliability data published by manufacturers.

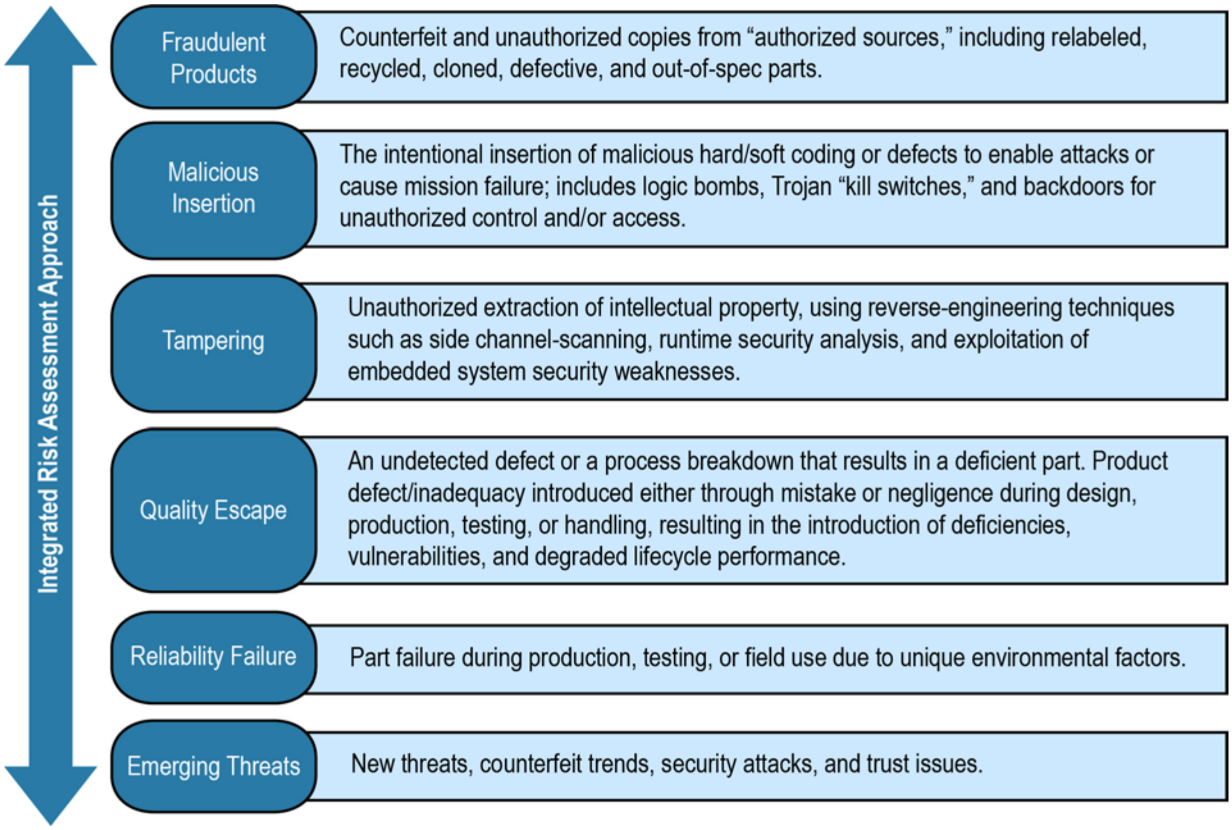

Figure 1: There are many supply chain risks to consider. An integrated risk assessment approach should address all risk categories.
(Adapted from Raymond Shanahan, Deputy Director, Systems Security Engineering Office of the Deputy Assistant Secretary of Defense, Systems Engineering)

Challenge #3: OTS Parts Consistency

Homogeneity within and between lots of OTS parts is not guaranteed, and manufacturing changes might occur at any time. OTS parts manufacturers are motivated to reduce costs, but requirements for homogeneity (significant tracking, documentation, and proximity within the manufacturing process steps) drive costs. Due to the increased part-to-part and lot-to-lot variability in OTS components, mission designs need to include additional margin to account for these variations.

Lot Consistency: In a screening process, devices from every lot are tested, and trends and variations are used as accept/reject criteria. Part characteristics, such as timing performance or leakage current, may vary within lots or between different lots in ways that are within the manufacturer's process quality control limits. However, these variations may reduce the performance margin a mission designer built into a given function or circuit using parts from those lots. The producers of electronic card-level and box-level designs in which these parts will be used must take such inevitable variations into account in advance to ensure they still meet the intended requirements.

Manufacturing Changes: Manufacturers of OTS parts can make changes at any time, without notice, to improve manufacturability, quality, profitability, or performance, though many do regularly issue product change notifications. The parts undergo qualification to validate the design, and the results inform what is published on the parts' data sheets and documentation. For purposes of continuous process improvement, manufacturers may make changes that do not impact the basic form, fit, or function of the part in its *intended* application. However, these refinements and adjustments can cause significant changes to a part's ability to withstand the space environment.

Challenge #4: Balancing Business and Mission Needs

Taking advantage of fast, inexpensive, and reliable OTS supply chains may seem at odds with a program manager's need to understand confidence levels and how much risk is appropriate for a specific class of mission. Yet, this natural tension and the balancing of interests can result in mutually acceptable solutions if issues are managed transparently. As much as possible, all stakeholders should be aware of the costs, benefits, and risks when considering the selection of materials, fabrication processes, testing methodologies, and applications. This can be challenging, since the supply chain is often opaque to some buyers. The following are specific areas where programs need to ask savvy questions to gain greater visibility into OTS parts supply chains. Other related questions and guidance can be found in a paper released by The Aerospace Corporation in July 2017.[4]

Materials: Certain materials present reliability concerns in space applications. For example, pure tin, silver, and zinc can result in whiskers[5] that pose the risk of short-circuit failures. Cadmium can also grow whiskers, but a greater concern is that cadmium can vaporize and redeposit on solid surfaces—such as optics—in extreme environments. During bimetallic (e.g., gold and aluminum) bonding, if materials and processes are not well controlled, intermetallic compounds can form too rapidly and generate voids. Organic materials can outgas and contaminate other surfaces, as well.

"NASA has no overarching COTS assembly assurance policy to cover each mission class and risk profile. Higher risk tolerance missions are individual in their approaches. Typically, the higher the mission class or lower the risk tolerance that is acceptable, the more the assembly requires full upscreening, qualification, assembly-level testing, lot traceability of individual ICs, and some knowledge/testing for radiation."

—Ken LaBel
NASA, Goddard Space Flight Center

Fabrication: Equally important is understanding the processes used to fabricate EEEE parts. High-reliability space programs monitor supplier processes and certify that highly critical processes are understood and well controlled. Processes requiring special consideration are diffusion, packaging, foundry controls, brazing, soldering, plating, heat treatment, cleaning, chemical films and surface treatment, and welding. Except in certain circumstances (e.g., for large or influential customers with purchasing leverage), OTS manufacturers do not generally share details of these processes with customers.

Testing Methodologies: Manufacturers of EEEE components typically screen parts to remove early-life failures. Programs should not assume, just because they are purchasing apparent high-reliability OTS components (automotive, industrial, medical), that the screening is the same. For comparison, space-grade suppliers perform 100 percent screening/testing on parts and look at trends to ensure that processes are stable and that no parameters have shifted beyond established bounds. Furthermore, some space-grade testing is performed at wide temperature ranges (–55°C to +125°C is typical) to account for the space environment. Space stakeholders need to understand the conditions under which OTS parts were tested, and ensure the testing and screening encompass their intended space environment.

Recommendations for Designing in OTS Parts Reliability

The use of OTS parts in space systems can speed development and add valuable capabilities. However, an understanding of the *physics of failure* associated with a particular technology is key to bounding the risks. Physics of failure involves knowledge and understanding of the processes and mechanisms that induce failure in order to predict reliability and meet market expectations for performance over the desired lifetime.[6]

Using knowledge of the physics of failure can accelerate technology insertion by allowing the proactive identification of technologies that can meet mission needs. It is better to "front-load" design improvements by identifying critical manufacturing processes and materials early in the design phase. Combined with knowledge of the mission-specific and application-specific use conditions for a given technology, this information can also support development of appropriate tests and metrics for space usability evaluation, parts screening, and burn-in.

Appropriate screening metrics informed by an understanding of physics of failure can help determine when parts are "out of family" due to unit variability and other supply chain nuances, while reducing cost and schedule for new missions and payloads that rely on previously accepted parts. As our understanding of failure modes of OTS parts grows, our confidence that they will perform reliably in a space mission environment increases. Confidence levels also increase by understanding whether the manufacturing process meets performance needs (speed and power), whether it is suitable for the mission environment (temperature, voltage, and radiation), and whether it will meet reliability requirements (lifetime, uniformity/yield, and availability of design-for-reliability tools).

To eliminate duplication of effort and reduce cost, encouraging organizations to share non-proprietary data paid for by government contracts is highly recommended.

"For many commercial parts, you must rely on the manufacturer's internal systems. You will not have the visibility into the full quality management or fabrication systems. You must review and assess the end products that the manufacturers use to verify and validate their product lines.

"You must use commercial companies that track COTS part changes, and work with them to augment the information collected, as best as possible. Automatic change notification is unlikely.

"Homogeneity through post-receipt screening is expensive and cannot achieve 100% coverage of all latent defects. Homogeneity is better achieved with SPC (statistical process control) and reliability monitor testing to ensure mass-produced parts remain in their control limits."

—Eli Minson
Ball Aerospace

When procuring OTS components, additional, independent work may need to be performed to ensure that the parts meet mission requirements. Although there may be little to no data from OTS parts manufacturers regarding part design and reliability, manufacturers' process design kits and specifications may include some reliability data. Yet, gaps in the data are often present, and it remains prudent to evaluate the design of the test structures used and validate the models presented over the expected mission conditions. In addition, data that may be important for military and space applications, such as radiation data and low-temperature operational data, are unlikely to be included. Much of this data may need to be gathered independently. To eliminate duplication of effort and reduce cost, encouraging organizations to share non-proprietary data paid for by government contracts is highly recommended.

Conclusion

Until now, the high-reliability space systems communities have emphasized minimizing risk. This priority has been closely followed by delivering performance, maintaining cost and schedule, and protecting resiliency—largely in this order. The exigencies and complexities of today's environment are rapidly and drastically re-ordering these priorities. Going forward, resiliency will likely become a top objective, followed by schedule, performance, cost, and risk, in a still-unclear order of priority. As we have shown at a top level, industry leaders that are successfully navigating the new space landscape with OTS parts have done so using combinations of strong relationships with suppliers; perceptive radiation test data on selected mission-critical parts; knowledge of savvy, practical questions to ask suppliers; effective communication with stakeholders regarding expectations; leveraging previous flight experience; and managing vs. eliminating mission risk. We emphasize that OTS EEEE parts are not appropriate for every mission. They must be evaluated in the context of the mission-specific requirements and constraints. Overcoming the OTS challenges of a harsh space environment, supply chain unpredictability, and associated supply risks and threats might seem daunting; however, the nature, uncertainties, and speed of evolving threats justify these efforts in the planning, development, and fielding of future resilient space systems.

Acknowledgments

The authors wish to acknowledge the following individuals for their support in the form of sharing their technical advice, experiences, and feedback.

Government Reviewers

- Jonathan Pellish – NASA, Office of Safety and Mission Assurance
- Ken LaBel – NASA, Goddard Space Flight Center

Commercial Reviewers

- Eli Minson – Ball Aerospace
- James Loman – SSL, a Maxar Technologies Company
- Mark Dapore – L3 Space & Sensors, CE Space Avionics

The Aerospace Corporation

- Arthur L. McClellan
- Dr. Sung M. Hong
- Craig A. Langford
- Donald H. Yang
- Dr. Donald G. Pierce
- Elizabeth J. Klein-Lebbink
- David C. Meshel

Appendix A. Definitions

Agile Mission Assurance. Agile mission assurance refers to utilizing new tools, methods, and processes—or a combination of existing and new—to respond quickly to program changes and accomplish mission assurance objectives more efficiently and effectively.

Automotive-Grade Parts.[7] Automotive-grade parts meet the specifications established by the Automotive Electronics Council's (AEC's) Component Technical Committee, which defines common electrical component qualification requirements. The purpose of these specifications is to determine that a device can pass the specified stress tests and thus be expected to give a certain level of quality/reliability in the application.

Commercial-Grade Parts. Commercial-grade parts are electronics designed for use in consumer electronic devices such as televisions, computers, or smartphones.

Critical Parameter. A critical parameter is a feature (electrical or mechanical) required in a specific application to be within the specified limits for the design to perform as intended.

Derating. Derating is the intentional reduction of applied stress—with respect to its rated operational limit—to provide margin between the applied stress under worst-case design applications and the demonstrated limit of the part's capabilities.

Design Margin. Design margin is a measure of the difference between the maximum capacity at which a part, circuit, unit, or system can operate, compared to where it actually does operate.

Electronic Parts. For the purposes of this document, electronic parts are all electronic, electromechanical, electro-optical, and electrical parts, including connectors.

Failure Mode Effects and Criticality Analysis (FMECA). FMECA is the analysis of a system, starting at the lowest hardware/software level and systematically working to higher levels. FMECA's purpose is to determine the elements in which failures can occur (failure modes) and the effects of each potential failure on the system element in which it occurs, as well as on other system elements. The analysis includes a study of the relative mission significance or criticality of all potential failure modes.

Lot. A lot of parts is a group of homogeneous parts of the same design, construction revision, and part number that is manufactured in the same facility and tested using the same production processes, tools and machinery, materials, manufacturing and quality controls, and baseline document revisions.

Lot Date Code. A lot date code is typically a four-digit designator that represents the year and week the part or material is manufactured. The first two numbers in the code are the last two digits of the year, while the last two numbers are the calendar week of that year. The lot date code scheme may vary, based on commodity and manufacturer. OTS part lot date codes typically represent only the packaging lot date code and could include materials from multiple assembly test sites as well as multiple foundries.

Material. Material refers to a metallic or nonmetallic element, alloy, mixture, or compound used in a manufacturing operation that becomes a permanent portion of the manufactured item.

Mission Assurance. Mission assurance is the disciplined application of proven scientific, engineering, quality, and program management practices toward the goal of achieving mission success. It follows a general systems engineering framework and uses risk management and independent assessment as cornerstones throughout the program lifecycle. It is any disciplined process that contributes to a successful program.

Mission-Critical Component. A mission-critical component is any system or circuit used to perform a function required to meet the mission objectives or flight safety requirements, regardless of redundancy or implementation scheme.

Off-the-Shelf (OTS) Parts, Materials, and Processes (PMP). These are parts designed for applications in which the specifications, materials, and processes are established solely by the manufacturer or vendor pursuant to market forces not specific to space. These parts are not explicitly designed for space applications and may have additional requirements imposed by users or external organizations (e.g., screening to assess product quality and qualification to establish reliability baselines). Examples of such parts include OTS automotive-, aviation-, commercial-, industrial-, and medical-grade components.

OTS PMP is of the same form, fit, and function with quality and reliability that allows the end-to-end mission needs to be met.

Operating Temperature Range. Operating temperature range is often used to quickly distinguish among the various OTS parts categories. Manufacturers specify and control the temperature range at which their parts operate, depending on their target applications and markets. The range can be as wide as –40 to +160°C (as is the case for some automotive parts) or as narrow as 0 to 70°C (consumer electronics for personal use). Other parts categories or grades commonly referred to include industrial, from –40 to 85°C; space, from –55 to 125°C; and aviation, from –55 to +85°C.

Piece Part. A piece part is one piece, or two or more pieces joined together, which are not normally subjected to disassembly without destruction or impairment of their designed use. For the purposes of this document, all uses of the term "part" shall mean "piece part."

Process. A process is an operation, treatment, or procedure used during the fabrication of parts, subassemblies, and/or assemblies that modifies an existing configuration or creates a new configuration that alters the form, fit, function, and/or physical and/or chemical properties of the parent material.

Qualification. Qualification refers to sample-based mechanical, electrical, and environmental tests typically conducted at the piece-part level, intended to verify that materials, design, performance and long-term reliability of parts on the same production line are consistent with the specification and intended application until a major process change.

Redundant System/Circuit. A redundant system/circuit is any system/circuit containing multiple independent paths performing the same function that allows the continued performance of the system/circuit within the required limits when a failure occurs in any one path.

Resiliency. Resiliency is the characteristic wherein mission capability is achieved by architectures such as a large constellation of simpler satellites tolerant of a few failures, instead of a few highly capable vehicles that must all work in order to be successful. It also describes the capacity to recover quickly from failures, anomalies, and other unexpected events or to tolerate graceful degradation, regardless of the system architecture.

Screening. A screening is a series of tests and inspections typically performed at the piece-parts level, intended to remove nonconforming parts and/or early failures (parts with defects that are likely to result in early and/or cluster failures) and thus increase confidence in the reliability of the parts selected for use.

Short Duration. A short duration describes a mission lasting less than five years. Some mission durations, such as those for missiles or launch events, may last only a few hours.

Single-String System/Circuit. A single-string system/circuit is any system/circuit path that performs a required function that can no longer be performed within the required limits should a failure occur.

Single-Point Failure. A single-point failure is a system failure mode that can be induced by a failure mechanism in a single piece-part, interconnect, circuit board, or assembly, causing system performance degradation or failure to meet mission requirements.

Space-Grade Parts. Space-grade parts are electronic parts designed, built, tested, qualified, and procured in full accordance with the space quality-level requirements as specified in the part's general and detailed military specification, and is listed on the appropriate military specification's Qualified Products List or Qualified Manufacturers List.

Supplier/Vendor. A supplier/vendor is any organization that provides parts, materials, processes, or services for use in higher-order assemblies, and that is not a subcontractor.

Traceability. Traceability is the ability to trace the build and test history, application, or location of an electronic part by means of documented recorded identification. It is about being able to recreate the history and pedigree of an electronic part's production and/or use. Traceability is important because, in the event of a failure or anomaly, it enables tracing back to the genesis of the potential failure or anomaly.

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