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Where COTS Meets Hi-Rel for RF/Microwave Active Devices

White Paper

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Where COTS Meets Hi-Rel for RF/Microwave Active Devices

Introduction

The process of designing and producing high reliability (Hi-Rel) military/aerospace (Mil/Aero) and space-grade RF and microwave active devices has historically been a long and expensive endeavor focused on small or medium quantity manufacturing. Adding to this, the cost of ensuring the highest standards of reliability for these applications requires stringent qualification and verification, which increase costs on a per unit basis. This process, however, is not ideal for many emerging Mil/Aero and space use cases, which are pushing for shorter design/production cycles and much higher volume deployments.

Hence, projects with limited budgets or even high-volume manufacturing requirements are forced to upscale Commercial-Off-The-Shelf (COTS) components to meet Mil/Aero and space physical, electrical, environmental, and other ruggedness standards. Though the reliance on COTS RF/Microwave active devices may at first appear to lead to weak links in the chain of electronics of modern Mil/Aero and space systems, this approach can also be a boon to projects by opening the doors to automotive, industrial, and commercial-grade active devices that benefit from the fast technological development and competition of the open market. Unlike many Mil/Aero and space RF/Microwave active device manufacturers these industries experience pressure to release enhanced products on a yearly basis, or even more frequently, to stay ahead of the competition and are a hotbed of innovative solutions that may result in improved size, weight, power, and cost (SWAP-C) for more rugged use cases.

This whitepaper aims to provide the reader with an overview of the general trends of COTS in Mil/Aero and space applications, and what requirements RF/Microwave COTS active devices may need to meet to find themselves in the next government or New Space project.

Deciphering Hi-Rel, Space-grade, Rad-Hard, Rugged, and other common RF Active Device Descriptors.

What is Hi-Rel?

The term high reliability (Hi-Rel) is used extensively to market RF/microwave active devices to potential military, aerospace, and space customers. In some cases, the term high reliability is bandied around with the same terms “space-grade” and/or “space quality”. Generally, the requirements for military, aerospace, and space applications are extremely varied, with the ultimate reliability requirements depending on the specific use case, mission parameters, or environment the technology is intended to be deployed in. Moreover, reliability is only one of the many concerns associated with these parts.

In many cases, high reliability just means that a device may fit one or more potentially qualifying requirements for Mil/Aero or space applications. Often, this means that a device can be screened to a Mil/Aero or space standard, or standards that may make the part viable for use in a given range of applications.

Possible Hi-Rel Features:

- High-volume production flow
- Full traceability and long-term supply
- Hi-Rel qualification following AQEC recommendations
- On-demand screening options
- Extended temperature range -55C to 125C for testing, characterization, and qualification
- Plastic and hermetic ceramic packages available with same/compatible pinout and sizes
- Neutron latch immune and SEU characterization by functional blocks (digital)
- High MOQ level in the hundreds to thousands of units

More generally, the term high reliability is used to describe a range of products from a manufacturer that may meet one or some Mil/Aero or space qualifications, as that manufacturer may have the ability to manufacture to these standards with a COTS part, or otherwise upscreen device(s) to certain standards. This may be due to the possible overlap in environmental or mechanical performance of a given automotive, industrial, or commercial device and the requirements in a Mil/Aero or space application. Often, this has to do with a mission requirements budget or availability of devices being limited, and the appeal of building-in a COTS device is attractive from a performance, size, weight, power, or cost standpoint.

What is Space-grade, Radiation-Tolerant, or Radiation-Hardened?

Unlike in the commercial markets, space applications have favored high reliability and risk reduction, often at the cost of performance and parts availability. This is especially true for RF/microwave active devices, as well as other electrical, electronic, and electromechanical (EEE) components. There are many levels of evaluation and qualification for “space-grade” devices, which aim to ensure reliability when exposed to space radiation. The goal of this is to have a highly refined ability to predict failure in long duration missions that may take place in higher earth orbit or even interplanetary missions.

However, there are many cases where commercial electronics from the automotive, industrial, or even consumer space may be upscreened to meet certain specific mission qualifications. This is done on a case-by-case basis and involves mitigating the inherent risk of using COTS electronics for space applications. Many of these mitigations have to do with the concerns that COTS electronics may not be provided with a necessary confidence level in regard to material, traceability, homogeneity, long-term performance, availability, and general reliability.

Space Application RF/Microwave Device Considerations:

- Satellite or spacecraft type
- Payload size, weight, and power requirements
- Mission duration
- Orbit
- Radiation Environment
- Program cost & risk

In this way, space-grade just means a part that is qualified for a space mission but may not be radiation-tolerant (Rad-tolerant) or radiation-hardened (Rad-hard) in its own right. That or the technical requirements for the mission may allow for part failure or degraded part performance due to radiation.

This allowance could be a result of several factors, including that a mission may be short-lived enough that reliability isn't essential, or that the mission is to take place in a lower atmosphere where the radiation concerns are far less than in higher orbits or interplanetary space. Another consideration with using COTS for space applications is that it may be possible to enhance the reliability of COTS devices with redundancy, as the cost and availability may make this solution feasible even though individual COTS devices individually may not be reliable enough for a given mission's requirements.

True space-grade devices are generally Rad-hard by design, and even at the semiconductor level. Meaning, traditional space-grade components are likely chosen from semiconductor processes and integration methods that are intrinsically Rad-hard and don't require additional shielding or protections to make them Rad-hard. Moreover, these parts are generally subject to 100% parts-level qualification and screening to rigorous industrial, government agency, and Mil/Aero standards.

Key Standards for Hi-Rel RF/Microwave Active Devices

For many Hi-Rel RF/Microwave Active devices the main US Mil-Spec are defined in MIL-STD-883, MIL-STD-202, and MIL-STD-750 [1,2,3], MIL-STD-883 dictates test methods for microcircuits, MIL-STD-202 describes the test methods for electronic and electrical component parts often part of RF/Microwave active devices and systems, and MIL-STD-750 describes the test methods for semiconductor devices. These test methods apply to virtually all solid state, RF integrated circuits, RFIC, and monolithic microwave integrated circuits (MMIC) devices.

As there is a growing trend of greater integration and digital circuits being assembled alongside RF/Microwave devices, military standards that typically apply to digital circuits and semiconductor performance/manufacturing are becoming increasingly important for RF/Microwave systems. MIL-PRF-19500 covers the performance specifications for semiconductors in general while MIL-PRF-38535 accounts for manufacturing of integrated circuits (microcircuits) [4,5]. These standards do not cover tube devices, such as traveling wave tube amplifiers (TWTAs) or electromechanical relay switches. Crystal Oscillators are covered in MIL-PRF-55310 [6]. Hybrids and module performance specifications are covered in MIL-PRF-38534 [7]. MIL-M-38510 is the general specification for microcircuits and has an amendment and three notices [8].

Additionally, electromagnetic interference (EMI) for active devices is largely covered in MIL-STD-461 and MIL-STD-464 [9,10], and electrostatic discharge (ESD) requirements are found in MIL-STD-1686 and MIL-HDBK-263 [11,12]. In respect to packaging, MIL-STD-2073 describes the standard processes for development and documentation of military packaging and how it is distinct from commercial packaging [13]. There are also two other handbooks that describe the reliability prediction of electronic equipment, MIL-HDBK-217, and general guidelines for electronic equipment, MIL-HDBK-454 [14,15].

There are also many other standards that may apply to the components, circuit board, conductors, connectors, and other elements of an RF/Microwave active device/system that would also have to be considered for assemblies or systems.

RF/Microwave Active Device US Military Standards:

- Semiconductors & Integrated Circuits (Microcircuits)
    - MIL-PRF-19500
    - MIL-PRF-38535
    - MIL-PRF-38534
    - MIL-M-38510
- Test Methods
    - MIL-STD-883 parts 1-5
    - MIL-STD-202
    - MIL-STD-750
- EMI
    - MIL-STD-461
    - MIL-STD-464
- ESD
    - MIL-STD-1686
    - MIL-HDBK-263
- Oscillators
    - MIL-PRF-55310
- Packaging
    - MIL-STD-2073
- General Guidelines
    - MIL-HDBK-454
    - MIL-HDBK-217

In many cases to produce Mil/Aero active devices the device itself has to conform to the qualification and performance standards, and also comply with a variety of standards that dictate the materials used, lot/material traceability, and aspects of the manufacturing processes. This is often where commercial devices differ significantly from Mil/Aero devices and require additional efforts/exceptions to be deployed.

What are the AEC, AQEC, and IECQ-CECC standards?

In some cases, automotive and other commercial grade RF/Microwave active devices may be used in place of purely military qualified components, and even space components. The main standards body behind automotive standards is the Automotive Electronics Council (AEC). The automotive standards most applicable for RF/Microwave active devices are AEC-Q100, AEC-Q101, AEC-Q103, and AEC-Q104. Though additional standards may apply when passive components are also integrated/assembled with active devices, these passives electronics standards are covered in AEC-Q200. In general, these standards apply to failure mechanism-based stress test qualification, including temperature, ESD, shock/vibration, and other operational dynamics, such as IC latch-up and short circuit reliability. These standards are focused on failure mechanisms and rates, and not device performance or capability, as are many military/defense standards.

RF/Microwave Actives Automotive Standards:

- AEC-Q100
- AEC-Q101
- AEC-Q103
- AEC-Q104

The International Electrotechnical Commission (IEC) also supports a Quality Assessment System for Electronic Components (IECQ system), which is handled by a dedicated organization, the IECQ. The IECQ 03 has seven relevant parts that establish the general requirements, approved process scheme, approved component products/related materials/assemblies scheme, avionics parts and assembly management, hazardous substance process management requirements, independent testing laboratory assessment program requirements, counterfeit avoidance program.

Aerospace Qualified Electronic Component (AQEC) is another qualification that applies to integrated circuits and semiconductors that provides a minimum standard for COTS components, established by the Society of Automotive Engineers (SAE) International [18].

Key Standards & Practices for Space-grade RF/Microwave Active Devices

The typically extremely high cost of space-grade devices and systems, and the evolution of the space industry from being dominated by government and military applications to becoming a burgeoning commercial market, has resulted in a climate where the cost, performance, and accessibility of COTS devices is extremely attractive for New Space applications. Given that many modern RF systems include highly integrated RF devices alongside digital and power electronics, the use of COTS RF systems in space is growing as the footprint and power requirements of RF systems are shrinking while programmability and performance are being enhanced. However, there are some cases where discrete RF devices are needed and cannot be sacrificed for integrated or drop-in versions.

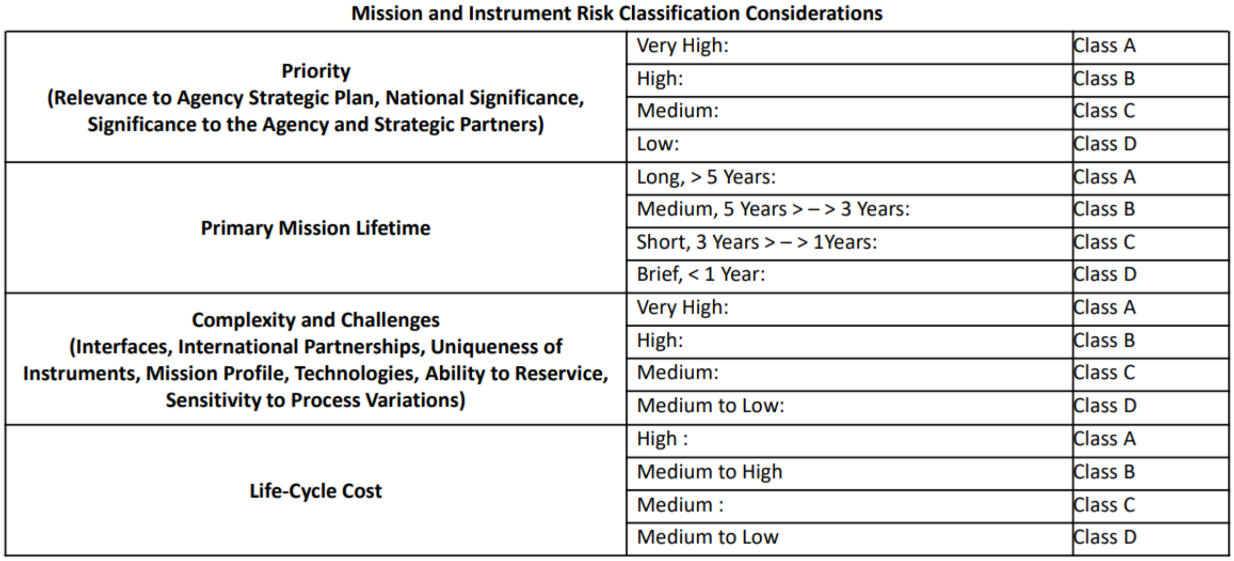
Similar to Mil/Aero applications, COTS RF devices must often meet stringent standards and face 100% parts screening/qualification. However, modern RF devices produced to automotive and aerospace standards can sometimes be upscreened to space-grade with the appropriate screening, qualification testing, and potential shielding and other protections used to enhance reliability. The additional screening, qualification testing, and protections may add substantial cost and engineering time that could mitigate some of the value of employing COTS RF devices. An entire system may need to be designed to account for the intrinsically lower reliability and operational uptime for COTS RF systems when compared to space-grade systems. It is generally advantageous to analyze all of the nuances of bringing in a given COTS RF system/device early on the in the project cycle to avoid delays and rising costs of having to reengineer or replace devices that may not meet mission performance criteria despite an initial favorable outlook.

	COTS/COTS+		Enhanced Intermediate Grades			Space-grade	
	Commercial	**AEC-Q100**	**EP**	**QMLQ**	**Space EP**	**QML-V**	**QMLV-RHA**
Packaging	Plastic	Plastic	Plastic	Ceramic	Plastic	Ceramic	Ceramic
Single Controlled Baseline	No	No	Yes	Yes	Yes	Yes	Yes
Bond Wires	Au or Cu	Au or Cu	Au	Al	Au	Al	Al
Pure Sn Used	Yes	Yes	No	No	No	No	No
Burn-in Performed	No	No	No	No	No	Yes	Yes
Radiation Tested	No	No	No	No	Yes	Yes	Yes
Radiation Assured	No	No	No	No	Yes	No	Yes
Temperature (C)	-40 to 85	-40 to 125	-55 to 125	-55 to 125	-55 to 125	-55 to 125	-55 to 125
100% 3 Temp Tested	No	No	No	Yes	25,125C	Yes	Yes
Extra Qual/Process Monitors	No	Yes	Yes	Yes	Yes	Yes	Yes
Life Test/Lot	No	No	No	No	No	Yes	Yes

Table 1
Source: Texas Instruments

For US military and government applications there are several methods of screening and qualification that describe the “grade” of device or component and the applicability for a given device for space-grade applications. This breaks down to QMLQ for Mil/Aero graded parts and QMLV/QMLV-RHA for space-grade parts. With the rise of COTS purchasing by governments, militaries, and commercial entities, there has arisen intermediate grades between the extremes of space-grade and commercial-grade COTS. Where pure COTS devices are likely the lowest cost and lowest quality/reliability option, true space-grade devices would be the highest tier of quality/reliability and also the highest cost. In the case of Table 1, these variations between the Tiers are broken down into 11 qualifying criteria that includes packaging, bond wire material, radiation assurance, and life tests on a per lot basis.

Two of the main space agencies are NASA and the European Space Agency (ESA). Both organizations have rigorously developed classification and requirements for space-grade components [19,20,21,22,23]. More recently, given the rise of missions that don’t have the typically long-life cycle of government/military space missions, NASA has introduced various classifications for mission and instrument risk based on several criteria (See Table 2). In general, Class A is for the longest missions with the highest priority, while Class D is the shortest mission life cycle with the lowest priority requirements. Table 3 illuminates more of what standards are leveled for each Class of EEE parts.

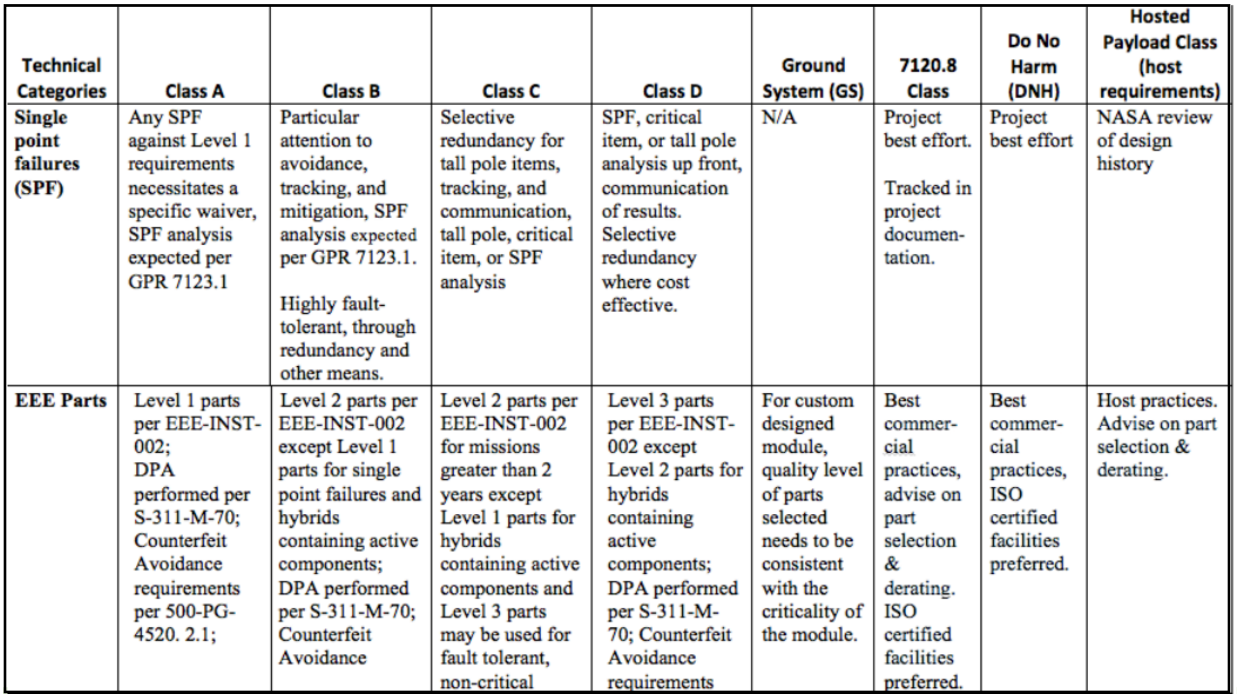


Mission and Instrument Risk Classification Considerations

Priority (Relevance to Agency Strategic Plan, National Significance, Significance to the Agency and Strategic Partners)	Very High:	Class A
	High:	Class B
	Medium:	Class C
	Low:	Class D
Primary Mission Lifetime	Long, > 5 Years:	Class A
	Medium, 5 Years > – > 3 Years:	Class B
	Short, 3 Years > – > 1Years:	Class C
	Brief, < 1 Year:	Class D
Complexity and Challenges (Interfaces, International Partnerships, Uniqueness of Instruments, Mission Profile, Technologies, Ability to Reservice, Sensitivity to Process Variations)	Very High:	Class A
	High:	Class B
	Medium:	Class C
	Medium to Low:	Class D
Life-Cycle Cost	High :	Class A
	Medium to High	Class B
	Medium :	Class C
	Medium to Low	Class D

Table 2

Source: [19]



Technical Categories	Class A	Class B	Class C	Class D	Ground System (GS)	7120.8 Class	Do No Harm (DNH)	Hosted Payload Class (host requirements)
Single point failures (SPF)	Any SPF against Level 1 requirements necessitates a specific waiver, SPF analysis expected per GPR 7123.1	Particular attention to avoidance, tracking, and mitigation, SPF analysis expected per GPR 7123.1. Highly fault-tolerant, through redundancy and other means.	Selective redundancy for tall pole items, tracking, and communication, tall pole, critical item, or SPF analysis	SPF, critical item, or tall pole analysis up front, communication of results. Selective redundancy where cost effective.	N/A	Project best effort. Tracked in project documentation.	Project best effort	NASA review of design history
EEE Parts	Level 1 parts per EEE-INST-002; DPA performed per S-311-M-70; Counterfeit Avoidance requirements per 500-PG-4520. 2.1;	Level 2 parts per EEE-INST-002 except Level 1 parts for single point failures and hybrids containing active components; DPA performed per S-311-M-70; Counterfeit Avoidance	Level 2 parts per EEE-INST-002 for missions greater than 2 years except Level 1 parts for hybrids containing active components and Level 3 parts may be used for fault tolerant, non-critical	Level 3 parts per EEE-INST-002 except Level 2 parts for hybrids containing active components; DPA performed per S-311-M-70; Counterfeit Avoidance requirements	For custom designed module, quality level of parts selected needs to be consistent with the criticality of the module.	Best commercial practices, advise on part selection & derating. ISO certified facilities preferred.	Best commercial practices, ISO certified facilities preferred.	Host practices. Advise on part selection & derating.

Table 3

Source: [19]

The two main standards considerations for RF actives are PEM-INST-001, which is the Instructions for Plastic Encapsulated Microcircuit (PEM) Selection, Screening, and Qualification, and EEE-INST-002, which is the Instructions for EEE Parts Selection, Screening, Qualification, and Derating. For higher class qualifications, there are also additional standards that are relevant, such as S-311-M-70 for Destructive Physical Analysis and 500-PG-4520.2.1 for Counterfeit Avoidance requirements [24,25].

Along with complying with appropriate standards, approving COTS devices may also require Justification Documents (JD) with details in regard to the part quality/reliability analysis that provides information on the design, workmanship, and counterfeit status.

Potential Justification Documents (JD) for COTS Devices:

- Production Part Approval Process (PPAP) documents
- Systematic per lot Constructional Analysis (CA)
- Radiation test reports (sensitive RF actives)
- Dispositions to prevent Tin whiskers induced failures
- Special design rules (Derating)

Standards and Considerations Specifically for Coaxial Connectorized Packages

A coaxial connectorized active device is typically constructed of an aluminum, brass, bronze, Invar, Kovar, or stainless steel (possibly gold plated) housing with flange mount coaxial connectors, other interconnect, and internal RF circuitry. The internal circuitry is a combination of packaged components and a PCB or other RF circuit substrate that is connected internally to the interconnect that handles the RF power, control signal, and/or digital communications. To meet military and aerospace standards, each packaged, PCB/substrate, interconnect, housing, and assembly must meet the standards for that component and as a whole.

The main military standard for coaxial connectors is MIL-STD-348, which covers the electrical, mechanical, and environmental qualifications for coaxial connectors [30]. Moreover, this standard specifies the dimensional requirements for a variety of RF connector interfaces.

MIL-STD-348 Dimensional Requirements For:

MIL-DTL-3643
MIL-DTL-3650
MIL-STD-3655
MIL-DTL-25516
MIL-PRF-31031
MIL-PRF-39012
MIL-PRF-49142
MIL-PRF-55339
MIL-DTL-83517

MIL-HDBK-1195 is the primary standard for RF shielded enclosures and supersedes MIL-STD-1547 [31]. This handbook specifies the criteria for the design and construction of all RF shielded enclosures for military applications. A similar standard, UFGS-08 56 46.10 20 also covers RF shielded enclosures of the demountable type for USACE, NAVFAC, AFCEC, and NASA. This standard specifically references IEEE STD 299 which is the Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures.

Other standards to consider are soldering and assembly standards, such as QQ-S-571, and standards for PCBs, of which the military standards (MIL-STD-275) have been superseded by IPC standard 2221 for generic designs and substandards 2222 through 2226 for specific PCB types. Smaller component parts often found on PCBs within RF active devices are covered by MIL-STD-202 [32,33].

PPC-2221 Substandards for specific PCB types:
Rigid IPC-2222
Flex IPC-2223
PCMCIA IPC-2224
MCM-L IPC-2225
HDIS IPC-2226

Conclusion

Using COTS RF devices for Mil/Aero or space applications is becoming increasingly common. The market forces driving the evolution of automotive, commercial, and industrial RF devices are continuously pushing toward higher performance, more features/capability, and in ever smaller and more efficient configurations. Naturally, the reliability and operational requirements of commercial RF devices doesn’t compare with traditional Mil/Aero or space requirements, but the potentially low costs, features, and accessibility of COTS RF devices may be significant enough to justify the efforts to upscreen and invest additional engineering effort to qualify select COTS RF devices for deployment.

Ultimately, the decision to use COTS RF devices is derived from the mission or program’s requirements and the accessibility of already qualified parts. For short life cycle and low-priority missions, COTS devices may be an ideal solution and even the additional cost/time of qualifying the parts may not outweigh the value of using them. However, for the highest priority and longest life-cycle missions, traditional Mil/Aero and space devices are still likely to dominate over COTS devices.

Resources

1. MIL-STD-883L, DEPARTMENT OF DEFENSE TEST METHOD STANDARD: MICROCIRCUITS (16-SEP-2019)
2. MIL-STD-202H (CONSOLIDATED), DEPARTMENT OF DEFENSE TEST METHOD STANDARD: ELECTRONIC AND ELECTRICAL COMPONENT PARTS (18-APR-2015) [SUPERSEDING MIL-STD-202G (W/ CHANGE-1)]
3. MIL-STD-750E, DEPARTMENT OF DEFENSE TEST METHOD STANDARD: TEST METHODS FOR SEMICONDUCTOR DEVICES (20 NOV 2006)
4. MIL-PRF-19500P, PERFORMANCE SPECIFICATION: SEMICONDUCTOR DEVICES, GENERAL SPECIFICATION FOR (20-OCT-2010)
5. MIL-PRF-38535K, PERFORMANCE SPECIFICATION: INTEGRATED CIRCUITS (MICROCIRCUITS) MANUFACTURING, GENERAL SPECIFICATION FOR (20-DEC-2013)
6. MIL-PRF-55310F, PERFORMANCE SPECIFICATION: OSCILLATOR, CRYSTAL CONTROLLED, GENERAL SPECIFICATION FOR (20-NOV-2018)
7. MIL-PRF-38534L, PERFORMANCE SPECIFICATION: HYBRID MICROCIRCUITS, GENERAL SPECIFICATION FOR (03-DEC-2019)
8. MIL-M-38510J, MILITARY SPECIFICATION: MICROCIRCUITS, GENERAL SPECIFICATION FOR (15 NOV 1991)
9. MIL-STD-1686C, MILITARY STANDARD: ELECTROSTATIC DISCHARGE CONTROL PROGRAM FOR PROTECTION OF ELECTRICAL AND ELECTRONIC PARTS, ASSEMBLIES AND EQUIPMENT (EXCLUDING ELECTRICALLY INITIATED EXPLOSIVE DEVICES) (25-OCT-1995) [SUPERSEDES DOD-STD-1686]
10. MIL-HDBK-263B, MILITARY HANDBOOK: ELECTROSTATIC DISCHARGE (ESD) CONTROL HANDBOOK FOR PROTECTION OF ELECTRICAL AND ELECTRONIC PARTS, ASSEMBLIES, AND EQUIPMENT (EXCLUDING ELECTRICALLY INITIATED EXPLOSIVE DEVICES) (31 JUL 1994)
11. MIL-STD-461G, DEPARTMENT OF DEFENSE INTERFACE STANDARD: REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT (11-DEC-2015)
12. MIL-STD-464C, DEPARTMENT OF DEFENSE INTERFACE STANDARD: ELECTROMAGNETIC ENVIRONMENTAL EFFECTS, REQUIREMENTS FOR SYSTEMS (01 DEC 2010)
13. MIL-STD-2073/1E, DEPARTMENT OF DEFENSE STANDARD PRACTICE FOR MILITARY PACKAGING (23 MAY 2008)
14. MIL-HDBK-217F, MILITARY HANDBOOK: RELIABILITY PREDICTION OF ELECTRONIC EQUIPMENT (02-DEC-1991)
15. MIL-HDBK-454B, DEPARTMENT OF DEFENSE HANDBOOK: GENERAL GUIDELINES FOR ELECTRONIC EQUIPMENT (15 APR 2007)
16. AEC Documents
17. INTERNATIONAL ELECTROTECHNICAL COMMISSION QUALITY ASSESSMENT SYSTEM FOR ELECTRONIC COMPONENTS (IECQ)
18. Aerospace Qualified Electronic Component (AQEC) Requirements, Volume 1 - Integrated Circuits and Semiconductors(STABILIZED Mar 2015) GEIASTD0002_1A
19. Risk-Based SMA
20. EEE-INST-002: Instructions for EEE Parts Selection, Screening, Qualification, and Derating
21. PEM-INST-001: Instructions for Plastic Encapsulated Microcircuit (PEM) Selection, Screening, and Qualification
22. ECSS-Q-ST-60-13C Rev.1 DIR1 (17 May 2021) “Commercial electrical, electronic and electromechanical (EEE) components”: Public Review from 10 June – 31 August 2021

23. ESCC (European Space Components Coordination)
24. S-311-M-70, Destructive Physical Analysis
25. 500-PG-4520.2.1, Electrical, Electronic and Electromechanical (EEE) Counterfeit Parts Avoidance Plan (CPAP)
26. http://everyspec.com/MIL-PRF/MIL-PRF-030000-79999/MIL-PRF-39012F_AMENDMENT-3_55804/
27. http://everyspec.com/MIL-STD/MIL-STD-0300-0499/MIL-STD-348B_CHG-3_55562/
28. https://blog.pasternack.com/uncategorized/whats-hype-high-reliability-hi-rel/
29. https://www.fairviewmicrowave.com/rf-products/mil-dtl-17-high-reliability-rf-cable-assemblies.html
30. http://everyspec.com/MIL-STD/MIL-STD-0300-0499/MIL-STD-348A_420/
31. http://everyspec.com/MIL-HDBK/MIL-HDBK-1000-1299/MIL_HDBK_1195_2112/
32. https://www.ipc.org/TOC/IPC-2221A.pdf
33. http://everyspec.com/MIL-STD/MIL-STD-0100-0299/MIL-STD-202G_2397/