National Aeronautics and Space Administration

EEE Parts Database of CubeSat Projects and Kits

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NASA Electronic Parts and Packaging (NEPP) Program
Office of Safety and Mission Assurance

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1. INTRODUCTION

CubeSats in low-Earth orbit are protected from harsh radiation environments by Earth's magnetic field (Lightsey, 2012). Launching in 2016, NASA's twin CubeSats, MarCO, will become the first to embark on interplanetary travel (Jet Propulsion Laboratory, California Institute of Technology, 2015). The absence of Earth's protective magnetic fields increases electronic part susceptibility to high doses of radiation. This presents a challenge for part reliability and extended mission lifecycles relative to current Earth-orbiting CubeSats.

As NASA continues to develop its CubeSat program and its partnership with universities and vendors who deliver CubeSat electronics, it is critical to understand the agency's and suppliers' part procurement, usage, and management practices.

The objective of this task is to:

1) Assess the CubeSat supply chain through quantitative representations of CubeSat suppliers' process capabilities in parts management.
2) Quantify and characterize the types of parts and boards and/or kits procured for NASA CubeSat projects.

The first objective will be addressed by surveying several CubeSat suppliers using a questionnaire. The questions emphasize part procurement, design and testing, and assurance and board-level practices.

The second objective will be addressed by creating a database consisting of part information for various NASA CubeSat missions and analyzing its contents to understand component usage, type, and source. CubeSat projects will be asked about their source of parts for in-house board designs and boards/kits procured off-the-shelf.

2. APPROACH

1. *Contact NASA CubeSat mission representatives for EEE part usage and vendor kit and/or board procurement information*

   Parts lists for NASA CubeSat missions were gathered from project personnel, including Project Managers and Principal Investigators, and compiled to create the parts database. Projects/programs also provided insight on their EEE parts procurement and management practices and the types of kits and/or boards procured from CubeSat suppliers.

2. *Contact CubeSat suppliers*

   A questionnaire focused on EEE parts management and usage practices was distributed to several CubeSat suppliers to understand vendor capabilities.

3. *Database organization and part research*

   The database was organized according to relevant part and manufacturer information. Supplemental information, including qualified operating temperature ranges and IC types, were inputted into the database.

4. *Data analysis*

   EEE part data and responses from CubeSat suppliers were analyzed independently then assessed cooperatively to identify trends and correlations between the data sets.

3. ACCOMPLISHMENTS

3.1 NASA CubeSat EEE Parts Database

Parts lists and BOMs for nine NASA CubeSat missions were compiled into a database. (This data does not represent all CubeSat missions, past or present.) The parts lists and BOMs represent in-house designs for various board types, including ADCS, C&DH, and EPS. Connectors and parts without specific associated part number information were removed from the database. The data was segregated into two categories: IC and non-IC. ICs were further subcategorized into the following categories: digital logic, linear/analog, memory, VLSI, oscillator, line driver, data converter, power converter, pulse width modulator, hybrid, switch/relay, and sensor. In total, the database consists of >1100 individual lines of data. (A line is a part and its corresponding part number; approximately two-thirds of the total parts have a unique part number. Quantities, as specified in the parts lists, were not considered.) A sample of the database is shown in Table 1:

Board	Part Category	IC Subcategory	Qualified Operating Temperature (°C)	Manufacturer	Manufacturer Part Number	Description
Payload Processor Assembly	Capacitor	N/A	N/A	Kemet	C0402C104K8PACTU	CAP 0.1UF 10V CERAMIC X5R 0402
ADCS	IC	Switch/Relay	-40 to +85	IXYS Integrated Circuits Division	LCA717S	RELAY OPTOMOS 2A SPST-NO 6-SMD
C&DH	Resistor	N/A	N/A	Vishay	CRCW020110K0FKED	Thick Film Chip Resistor
EPS	Resistor	N/A	N/A	Maxim Integrated	MAX5490GC01000+T	RES NET 50K OHM 2 RES TO236-3
GPS	IC	Oscillator	-40 to +85	ECS Inc.	ECS-160-20-5PXDN-TR	CRYSTAL 16MHZ 20PF SMD

Table 1: CubeSat Projects EEE Parts Database

3.2 NASA CubeSats: Part and Board/Kit Procurement Practices

For in-house board designs, NASA CubeSat projects and programs reported that parts are procured directly from manufacturers and/or distributors, including Digi-Key, Mouser, Arrow, and Avnet, and without the assistance of a representative from a parts procurement group. Additionally, parts are not inspected by a designated inspection group upon receipt.

The current data does not indicate the tendency or preference of a project to design and build a particular board type versus buy it from a CubeSat supplier. Meaning, boards of the same purpose are being built in-house and purchased off-the-shelf. NASA CubeSat projects reported both building and purchasing solar panels, power boards, and ADC and C&DH systems, among others. Projects are purchasing the boards and assemblies from a variety of suppliers, including, but not limited to:

- Pumpkin, Inc.
- Spaceflight Industries, Inc. (formerly Andrews Space)
- Blue Canyon Technologies
- AAC Microtec
- Tyvak Nano-Satellite Systems, LLC
- GomSpace
- Maryland Aerospace, Inc.
- ISIS
- Clyde Space Ltd.

3.3 CubeSat Supplier Questionnaire

A questionnaire was created to gain insight on CubeSat suppliers' EEE parts management and usage practices. The questionnaire consisted of 24 questions that addressed part procurement and verification, part and board-level testing practices, and quality assurance. For some questions, responses were pre-written. The responses for each question ranged from taking no or minimal action to full precaution. Suppliers selected the response(s) that most closely represented their practices. The remaining questions either followed a "yes," "no," or "I don't know" format or were open-ended. For each type of question, there was a "Comment" field to allow the supplier to provide further explanation and give specifics.

An example of each type of question is provided:

1. *Pre-written response format:*
    a. Are the parts procured analyzed to survive within: (Select the answer that most applies.)
        i. Acceptable failure rates at room temperature? ☐
        ii. Worst case junction temperatures? ☐
        iii. Worst case operating temperatures still yielding acceptable failure rates for individual devices? ☐
        iv. Parts are not analyzed. ☐
        v. I don't know. ☐
2. *"Yes," "no," or "I don't know" format:*
    a. Do you verify that the part markings (e.g., part number and die revision, date/lot code, etc.) match received documentation? Y ☐ N ☐ I don't know ☐
3. *Open-ended format:*
    a. What percentage of parts procured are space-grade ____ %, military-grade ____ %, industrial/automotive/hi-rel ____ %, COTS* ____ %?
    **COTS is defined as a plastic encapsulated part with an 85°C operating temperature.*

Seven CubeSat suppliers completed the questionnaire. These suppliers, located in North America and Europe, offer an array of products, including kits, star trackers, power systems, sensors, RF, reaction wheels, C&DH, ADCS, and solar panels. Each question and associated responses are graphed in Section 4.1 Data Analysis of CubeSat Supplier Questionnaire Responses.

4. DATA ANALYSIS

4.1 Data Analysis of CubeSat Supplier Questionnaire Responses

This section provides an analysis of CubeSat suppliers' responses to the questionnaire. The following notes apply to this section:

1. Supplier identities have been concealed. Each supplier is designated by a letter, A-G.
2. The results presented represent each supplier's perception of their capabilities as reported in the questionnaire.
3. Suppliers B1 and B2 are the same supplier; they completed two separate questionnaires to reflect their parts management approach for radiation-hardened product versus standard product. This approach is dependent on the customer's product requirements – i.e., radiation-hardened product is typically required by NASA/ESA versus standard product which is suitable for the small satellite market. Although they are the same supplier, Supplier B1 and B2's responses will be distinguished and counted separately:
    a. Supplier B1 completed the questionnaire with respect to the NASA/ESA customer who requires radiation-hardened solutions.
    b. Supplier B2 completed the questionnaire with respect to the small satellite customer.
4. Supplier G responded to a limited set of questions (15, 17, 18, 19, 20, 23, and 24). This supplier reported that they "do not currently work with enough EEE programs and systems to justify establishing EEE procurement, testing, qualification, and analysis systems." Additionally, they "currently subcontract EEE products to companies capable of performing the work per the contract." Supplier G will be disregarded for all questions except those for which they provided a response.

4.1.1 Question #1: Part Grade Usage

	Question 1: Check the part grade(s) used:					
	Rad-Hard/Space	Military	Industrial	Automotive/Hi-Rel	COTS	I don't know
Supplier A		X	X	X		
Supplier B1	X	X				
Supplier B2	X	X	X	X	X	
Supplier C			X	X	X	
Supplier D			X	X	X	
Supplier E	X	X	X	X	X	
Supplier F			X			

Comments*:	
Supplier A	No comment provided.
Supplier B1	Within the area of miniaturized electronics (custom made solutions) all of the above components are used depending on the requirements of that particular project, but know we are answering with a rad-hard solution for e.g. NASA or ESA.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	The bulk of the parts are COTS. We'll use industrial or automotive where we can, but those are still very limiting for a complete spacecraft. We only buy COTS from certified distributors.
Supplier E	COTS parts are upscreened. Project EEE part implementations are based on contractual requirements.
Supplier F	No comment provided.
Supplier G	(We) currently subcontract EEE products to companies capable of performing the work per the contract. This involves flowing the procurement, analysis, component testing and qualification, board testing, and radiation testing requirements. The supplier is audited to ensure that the work can be done per the contract, and the requirements are typically a combination of the contract requirements and (our) requirements. (We) do not currently work with enough EEE programs and systems to justify establishing EEE procurement, testing, qualification, and analysis systems.

*Written verbatim from questionnaires received from CubeSat suppliers.

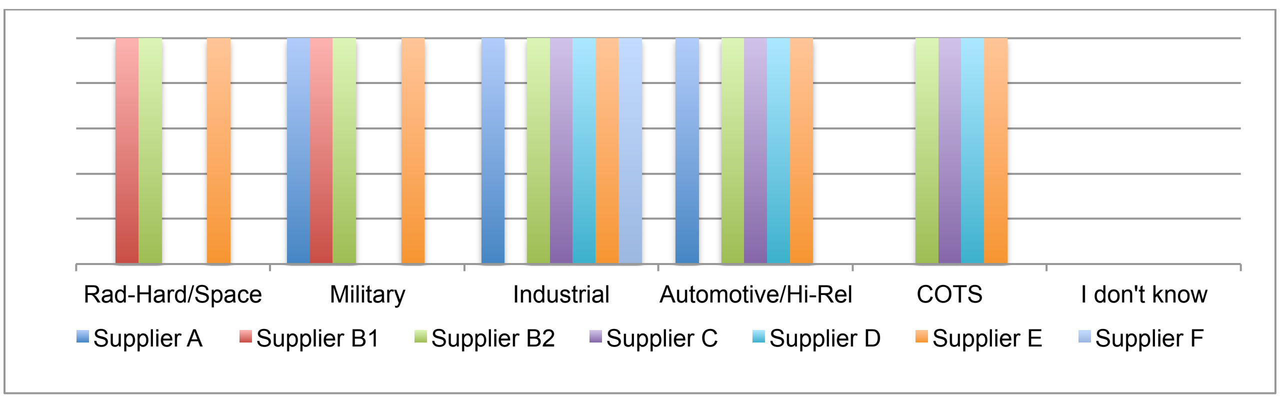

Figure 1. Part grade usage by CubeSat suppliers.

The majority of CubeSat suppliers procure either industrial or automotive-grade parts. Suppliers B2 and E reported that they procure all part grade types. Suppliers B1, B2, and E reported that they procure both space and military-grade parts; Supplier A also reported that they procure military-grade parts. The data suggests that each supplier is aware of their part grade usage as "I don't know" was not selected.

4.1.2 Question #2: Percentage of Part Grades Procured

	Question #2: What percentage of the parts procured are space, military, industrial/automotive, and COTS grade?			
	Space	Military	Industrial/Automotive	COTS
Supplier A	0%	10%	90%	0%
Supplier B1	80%	20%	0%	0%
Supplier B2	5%	5%	20%	60%
Supplier C	0%	0%	40%	60%
Supplier D	0%	0%	10%	90%
Supplier E	Percentage not given.			
Supplier F	0%	0%	100%	0%

Comments*:	
Supplier A	No comment provided.
Supplier B1	If the requirements are to MIL standard there are only components to that standard. For systems with lower standards components of all grades can be used.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	This has been driven by currently funded programs and their associated, scope, and risk posture.
Supplier E	This completely depends on contractual requirements.
Supplier F	No comment provided.
Supplier G	See the question 1 comment. (We) do not procure EEE parts for flight use.

*Written verbatim from questionnaires received from CubeSat suppliers.

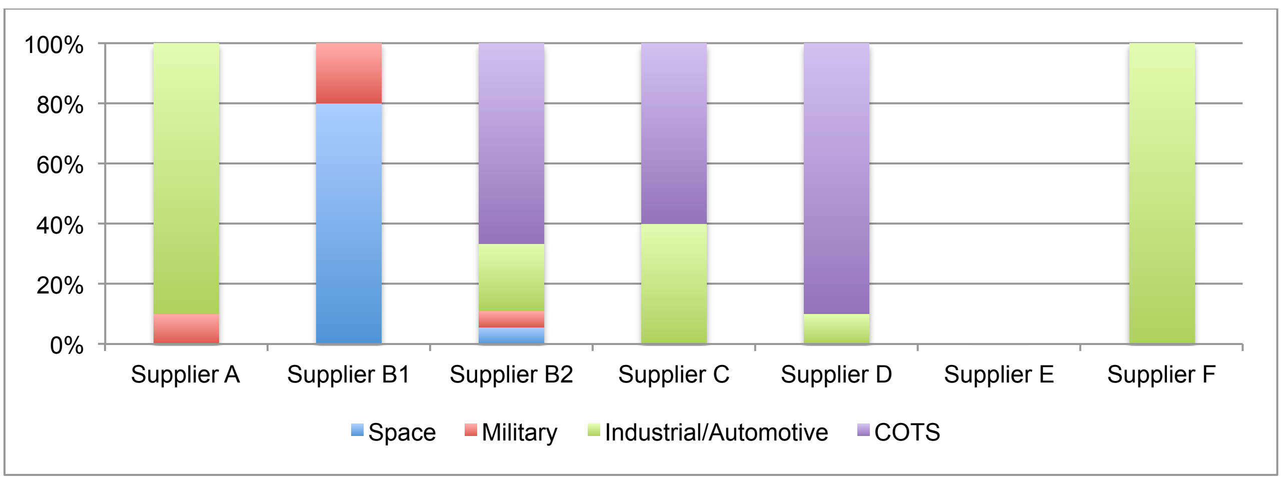

Figure 2. Percentage breakdown of part grades procured by CubeSat suppliers.

The majority of parts procured are either industrial/automotive or COTS grade. Supplier A reported that they primarily procure industrial/automotive grade parts; Supplier F reported that they procure industrial/automotive grade parts exclusively. Suppliers B2, C, and D reported that the majority of parts procured are COTS grade. Supplier E did not report a percentage but commented that the grade of parts procured is "completely dependent on contractual requirements."

4.1.3 Question #3: Percentage of RoHS Compliant Parts Procured

	Question #3: What percentage of components procured are RoHS?	
	%	I don't know
Supplier A	90%	
Supplier B1	100%	
Supplier B2	100%	
Supplier C	85%	
Supplier D	80%	
Supplier E	20%	
Supplier F	100%	

Comments*:	
Supplier A	No comment provided.
Supplier B1	ROHS components are selected where available.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	Most follow a ROHS process. Where possible we will use a non ROHS assembly process.
Supplier E	Critical parts/ long lead parts are typically space or military grade. ROHS parts are re-tinned per J-STD-001 Space Addendum.
Supplier F	Non-ROHS components are generally hard to find with parts we typically use due to current standards
Supplier G	See the question 2 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

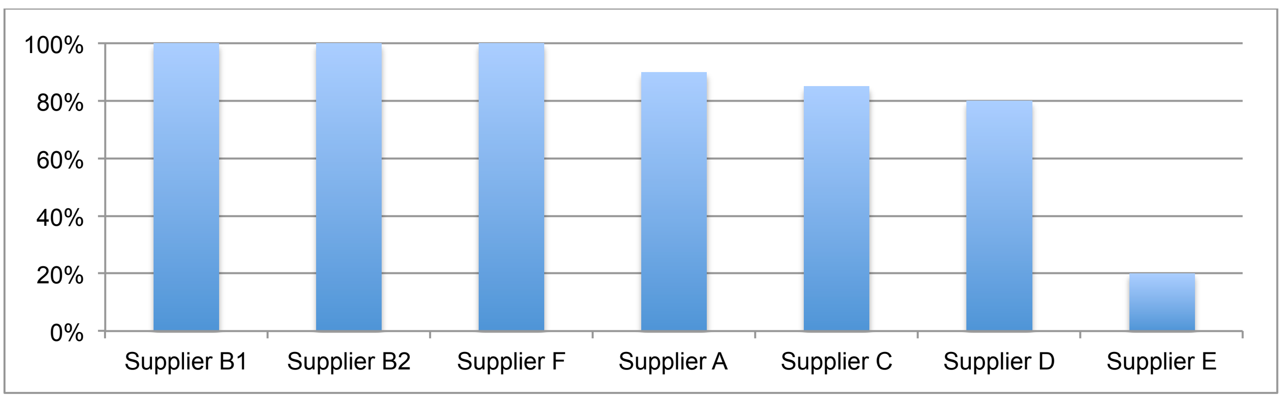

Figure 3. Percentage of RoHS parts procured by CubeSat suppliers.

Suppliers B1, B2, and F reported that 100% of the parts procured are RoHS compliant. As seen in Figure 2, Suppliers B1 and B2 also reported that they procure both space and military grade parts, which conflicts with the percentage of RoHS compliant parts procured. This discrepancy was addressed with the supplier, who reported that when industrial and COTS grade parts are procured they attempt to ensure they are RoHS compliant. A cogent correlation exists between Supplier F's responses to questions 2 and 3. As seen in Figure 2, this supplier reported that 100% of parts procured are industrial grade. As shown in Figure 3, Supplier F also reported that 100% of the parts are also RoHS compliant – a plausible scenario. A similar correlation exists for Supplier A – 90% of parts procured are industrial grade and 90% are RoHS compliant. The data suggests that each supplier is aware of whether they do or do not procure RoHS compliant parts as "I don't know" was not selected.

4.1.4 Question #4: EEE Suppliers

Each CubeSat supplier was asked to list all EEE part sources. The percentages in the table below represent the proportion of CubeSat suppliers who reported that they procure parts from a specific EEE part supplier. For example, it was reported on approximately 70% of the questionnaires that Arrow supplies parts to CubeSat suppliers.

Question #4: List all EEE suppliers you procure from.	
Arrow	71%
Avnet	71%
Digi-Key	71%
Mouser	71%
Newark	29%
EBV Electronik	14%
Alter Technology	14%
ES Components	14%
Exxelia	14%
Micross Components	14%
Eltek Semiconductors	14%
Farnell	14%
Elfa	14%
Flexitron	14%
RS Components	14%
VPT	14%
Aeroflex	14%
Microsemi	14%
Intersil	14%
Future Electronics	14%
Samtec	14%

Comments*:	
Supplier A	Some direct from OEM
Supplier B1	No comment provided.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	We only acquire parts from authorized distributors. In one instance we were not able to do so, we had them independently tested with an x-ray scan to verify authenticity.
Supplier E	(We) typically work directly with the OCM to procure parts to meet schedule in a timely manner. No independent distributers.
Supplier F	Some high volume parts that can be obtained from an authorized dealer or manufacturer than have e-stores have been obtained
Supplier G	See the question 2 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

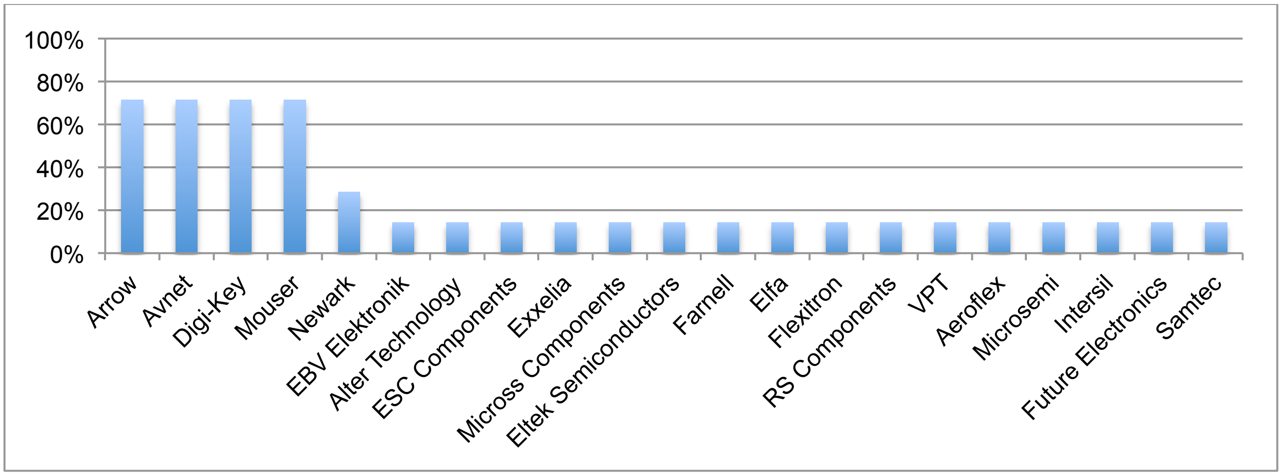

Figure 4. EEE part suppliers procured from as reported by CubeSat suppliers.

Some suppliers procure parts directly from the manufacturer but distributors are commonly used by the majority of CubeSat suppliers. The four EEE part suppliers most commonly procured from – Arrow, Avnet, Digi-Key, and Mouser – are all authorized distributors ((ECIA), 2015).

4.1.5 Question #5: Part Traceability

	Question #5: Do you verify part traceability to the: (Check all that apply.)							
	Part number	Manufacturer	Manufacturer's facility/line	Date code	Lot code	Wafer	I don't know	None of the above
Supplier A		X		X	X			
Supplier B1	X	X	X	X	X	X		
Supplier B2	X	X			X			
Supplier C			X					
Supplier D	X	X						
Supplier E	X	X		X	X	X		
Supplier F	X	X		X	X			

Comments*:	
Supplier A	No comment provided.
Supplier B1	When bare die is procured all this information above is used if it's available
Supplier B2	Lot code for actives only
Supplier C	No comment provided.
Supplier D	It's not worth the time and effort to go down this rabbit hole for COTS parts on our low cost programs. This would cost more than the program itself.
Supplier E	All of these are dependent on contractual requirements.
Supplier F	Date and Lot codes are checked when available
Supplier G	See the question 2 comment. (We) verify part number, manufacturer, and lot code (when applicable) for mechanical cubesat parts.

*Written verbatim from questionnaires received from CubeSat suppliers.

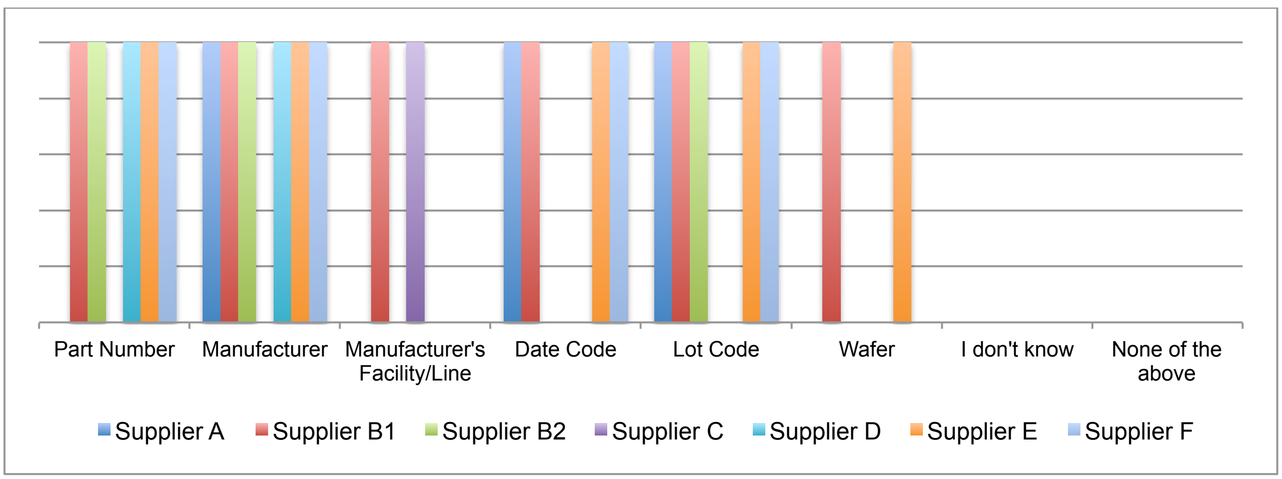

Figure 5. Part traceability practices by CubeSat suppliers.

All CubeSat suppliers verify either manufacturer or manufacturer facility/line information. The majority of suppliers also reported that they verify the part number and lot code. Supplier B1 reported that they verify all types of part traceability: part number, manufacturer, manufacturer's facility/line, date and lot codes, and wafer. Supplier C reported that they only verify the manufacturer's facility/line. The data suggests that each supplier is aware of their part verification practices and verifies part traceability as "I don't know" and "None of the above" were not selected.

4.1.6 *Question #6: Part Marking Verification*

	Question #6: Do you verify that the part markings (e.g., part number and die revision, date/lot code, etc.) match received documentation?		
	Yes	No	I don't know
Supplier A		X	
Supplier B1	X		
Supplier B2		X	
Supplier C		X	
Supplier D		X	
Supplier E	X		
Supplier F	X		

Comments*:	
Supplier A	No comment.
Supplier B1	No comment.
Supplier B2	The part markings are only checked on the package/documentation, not on components. We rely on our authorized supplier's routines.
Supplier C	No comment.
Supplier D	We perform board inspections upon reception of the assembled PCBs, and extensive functional checkouts at the PCB, and system level. All components are ultimately environmentally tested (except for radiation) at the system level.
Supplier E	No comment.
Supplier F	Only if documentation is available, some smaller parts (some capacitors, resistors, etc.) are too small for part markings. Checks are made after receiving, but additional documentation is not maintained
Supplier G	See the question 2 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

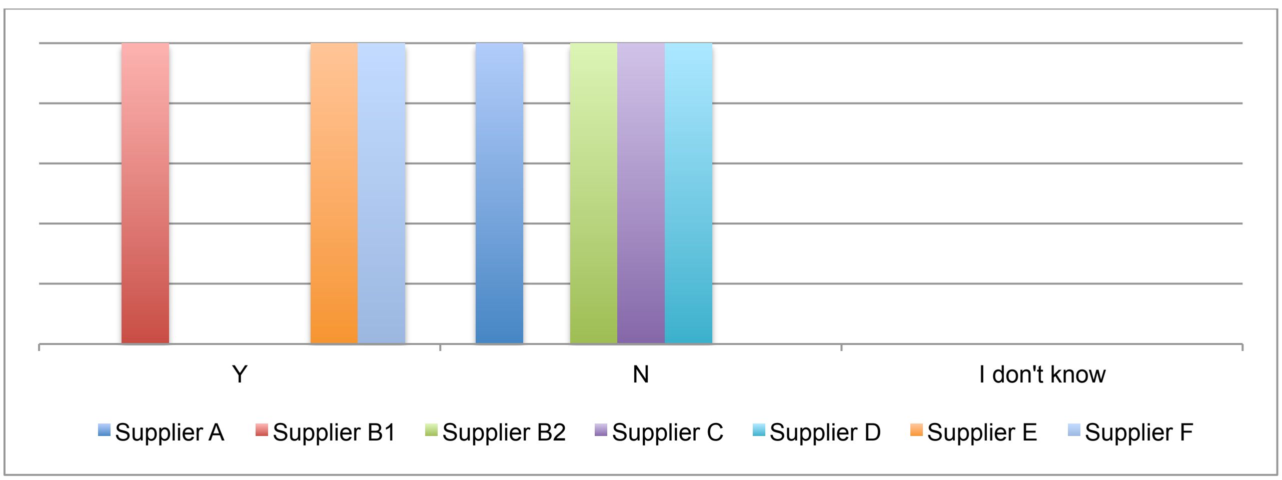

Figure 6. Part marking verification by CubeSat suppliers.

The data suggests that verification of part markings is not widely practiced by CubeSat suppliers. Supplier B1 – the same supplier as B2 – reported that they verify part markings for radiation-hardened product. However, for standard product, Supplier B2 does not verify part markings. The data suggests that each supplier is aware of whether verification of part markings is or is not performed as "I don't know" was not selected.

4.1.7 Question #7: Inspection for Authentic Parts

	Question #7: Do you inspect for authentic parts? If yes, what do you inspect? (Check all that apply.)							
	No	I don't know	Yes; I don't know	Yes; Other	Signs of prior use	Inconsistencies	Remarking	Package damage/ alteration
Supplier A	X							
Supplier B1				X				
Supplier B2	X							
Supplier C					X	X	X	X
Supplier D	X							
Supplier E					X	X	X	X
Supplier F					X	X		X

Comments*:	
Supplier A	No comment provided.
Supplier B1	The components used in the miniaturization are always bought thru secure and well known sources.
Supplier B2	We only use authorized distributors and trust their routines on this.
Supplier C	No comment provided.
Supplier D	We trust our suppliers to provide authentic parts from the manufactures.
Supplier E	Include GIDEP alert review.
Supplier F	Obvious signs for re-numbering/re-serialization or remarking are looked for, but no extensive process is used
Supplier G	See the question 2 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

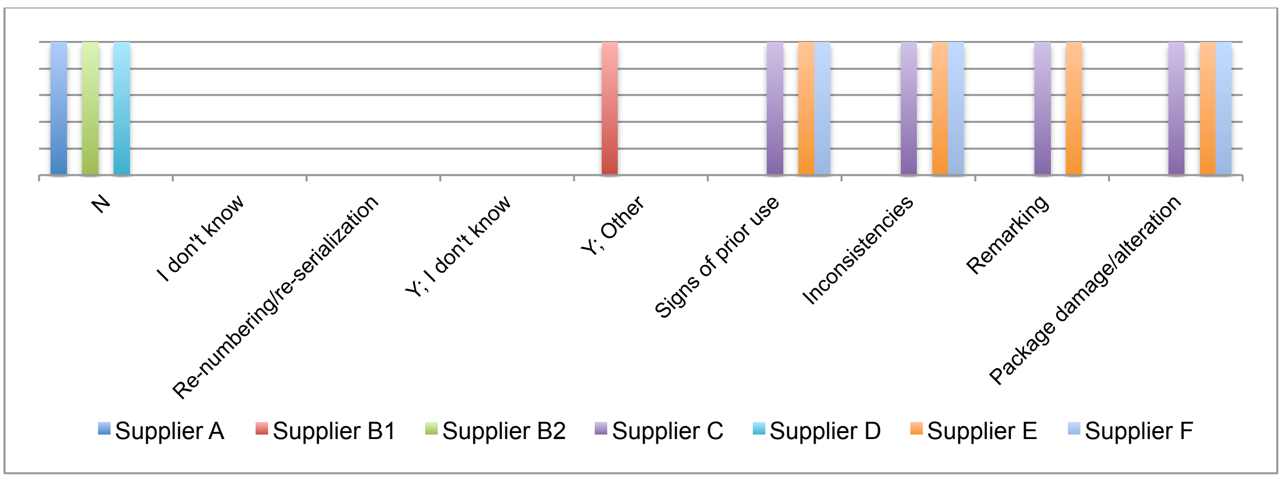

Figure 7. CubeSat suppliers' practices for inspecting for authentic parts.

The data suggests that inspection for authentic parts is not widely practiced by CubeSat suppliers. However, it also indicates that each supplier is aware of whether inspection for authentic parts is or is not performed as "I don't know" was not selected. Suppliers C, E, and F inspect for signs of prior use, inconsistencies, and package damage/alteration. Suppliers C and E also inspect for remarking. Analogous to verification of part markings, Suppliers' B1 and B2 inspection practices for authentic parts are dependent on the product's application. Supplier B1 inspects for authentic parts; Supplier B2 does not.

4.1.8 Question #8: Control of Non-conforming or Suspect Counterfeit Product

	Question #8: How do you control non-conforming or suspect counterfeit product? (Check all that apply.)				
	No controls	Segregate non-conforming product	Mitigate defects	Obtain authorization from customer/relevant personnel before using product	I don't know
Supplier A		X			
Supplier B1	No response selected.				
Supplier B2					X
Supplier C		X			
Supplier D		X			
Supplier E		X		X	
Supplier F		X			

Comments*:	
Supplier A	No comment provided.
Supplier B1	Within miniaturization there is not a problem with counterfeit products.
Supplier B2	This has not been needed yet so we have no routines around it.
Supplier C	No comment provided.
Supplier D	Non-conformal parts are found during board level or system level environmental testing. These units are segregated. An investigation will lead the cause of failure. 95% of the time, it's PCB assembly workmanship issues from the fabrication house.
Supplier E	Nonconforming materials are controlled based on Class I/Class II nonconforming product criteria. Suspected counterfeit parts are handled based on an internal procedure for counterfeit parts.
Supplier F	Non-conforming or suspect products have not been significant, usually dealt with EEE supliers
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

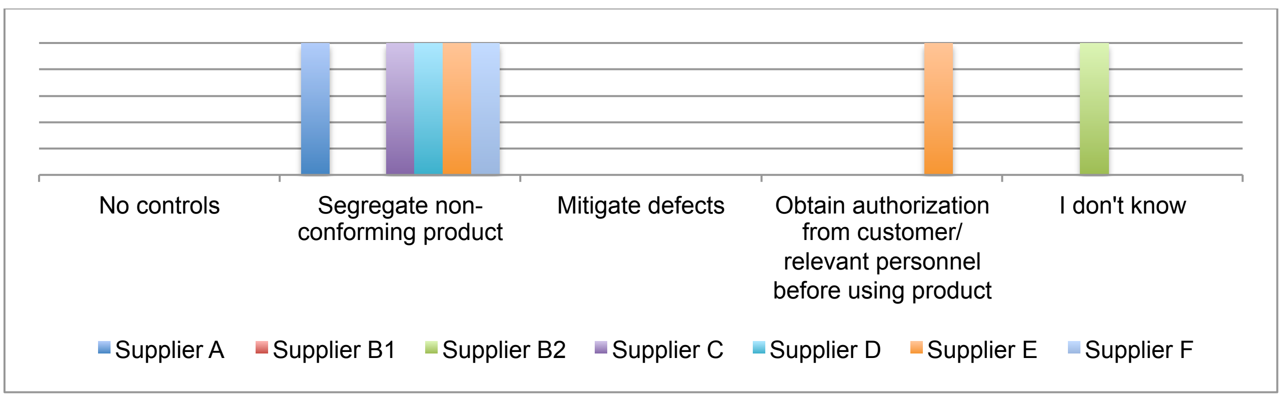

Figure 8. CubeSat suppliers' practices for controlling non-conforming or suspect counterfeit product.

All CubeSat suppliers, except Suppliers B1 and B2, reported that they segregate non-conforming product. Supplier E also obtains authorization before using the non-conforming or suspect counterfeit product. The data suggests that Supplier B2 is unaware of its processes to control non-conforming or suspect counterfeit product. Supplier B1 did not provide a response to this question.

4.1.9 Question #9: Verification of Electrical Properties

	Question #9: Do you verify part resistance, capacitance, and inductance?			
	I don't know	No	Yes; The equipment used is calibrated for testing	Yes; The equipment used is not calibrated for testing
Supplier A			X	
Supplier B1			X	
Supplier B2			X	
Supplier C		X		
Supplier D		X		
Supplier E			X	
Supplier F		X		

Comments*:	
Supplier A	No comment provided.
Supplier B1	Depending on the requirements. No controls are performed if it is considered unnecessary or if a control can harm the component
Supplier B2	We do not do this on each individual passive before we mount it, but each time the a new tape is inserted into the Pick-and-Place it does this test on the first component. Also, we cover the most critical component values during incoming inspection of the produced units.
Supplier C	No comment provided.
Supplier D	This is all verified with complete PCB and system functional checkouts.
Supplier E	Depends upon contractual requirements regarding piece part level, board level, or system level.
Supplier F	Some higher level parts are checked for size, footprint, etc. electrical checks are made at board level (first with proto-type, and then with fabricated boards for consistency)
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

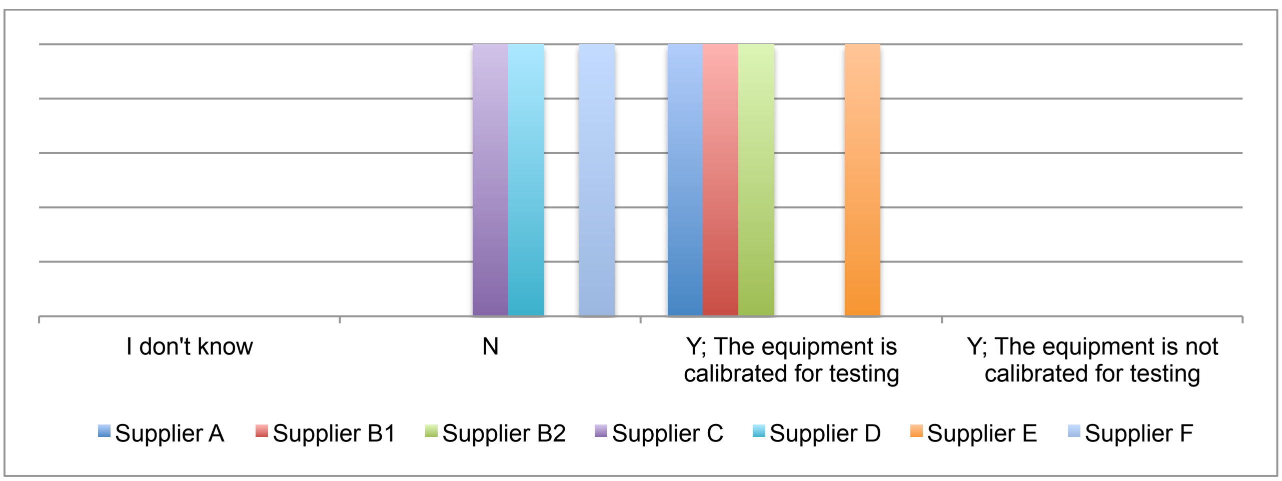

Figure 9. CubeSat suppliers' proclivity to verify electrical properties of received parts.

The data suggests that verification of electrical properties of received parts is not widely practiced by CubeSat suppliers. Suppliers A, B1, B2, and E, who reported that they verify electrical properties, also responded that calibrated equipment is used for testing properties. The data suggests that each supplier is aware of whether verification of electrical properties is or is not performed as "I don't know" was not selected.

4.1.10 Question #10: Part Qualification

	Question #10: What type of part qualification do you perform? (Check all that apply.)						
	None	I don't know	Acceptance testing (e.g., receiving inspection, visual examination, DPA, etc.)	Lot-specific testing	100% burn-in on flight devices	100% screening on flight devices (i.e., temperature cycling, electrical testing, etc.)	Initial product qualification
Supplier A							X
Supplier B1			X	X	X	X	X
Supplier B2			X		X		X
Supplier C					X		X
Supplier D			X		X	X	X
Supplier E			X	X	X	X	X
Supplier F			X	X	X		X

Comments*:	
Supplier A	No comment provided.
Supplier B1	The qualification tests performed on the miniaturized systems are to the standards set to the specific project.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	We go through qualification programs on new satellite designs to verify the design. Subsequent builds will go through acceptance testing. Some programs would use proto-flight levels. In either scenario, the components are stressed over temperature and in vacuum. When it comes to the flight unit integration, we perform enough risk reduction testing to have confidence the units will perform nominally during thermal vacuum.
Supplier E	Degree of part qualification depends upon contractual requirements. (We) have conducted all of these qualification measures.
Supplier F	Burn in-time is limited to 2-3 days of operations. Qualification tests are generally limited to vibration and performance, with some exceptions made for temperature.
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

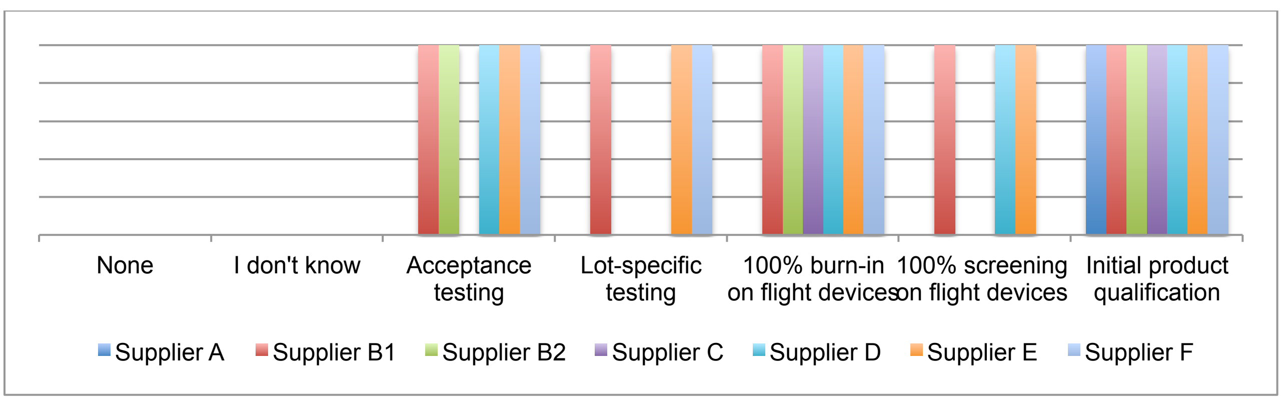

Figure 10. Type of part qualification performed by CubeSat suppliers.

All suppliers perform initial product qualification and a majority also perform acceptance testing and burn-in. Supplier B1 and E reported that they perform each type of qualification testing. The data suggests that each supplier is aware of whether part qualification is or is not performed as "I don't know" was not selected.

4.1.11 Question #11: Electrical Verification of Boards

	Question #11: What type of electrical verification of boards do you perform? (Select the answer that most applies.)						
	None	I don't know	Black box electrical testing	Electrical testing to verify individual component function	Electrical testing at extreme temperatures	Temperature cycling with electrical testing at extreme temperatures	Thermal vacuum testing
Supplier A						X	
Supplier B1			X		X	X	X
Supplier B2						X	X
Supplier C				X			
Supplier D			X	X			
Supplier E			X	X	X	X	X
Supplier F			X				

Comments*:	
Supplier A	Thermal vacuum testing also performed on first unit of each design type
Supplier B1	The verification tests performed on the miniaturized systems are to the standards set to the specific project.
Supplier B2	All Flight Model (FM) products are qualified according to our flight model routine, which include temperature cycling, humidity testing, Thermal Vacuum testing, Vibration/shock testing, EMC testing, TID testing, SEE testing & functional testing.
Supplier C	No comment provided.
Supplier D	Speaking specifically at the board level, we will do automated checkouts using on-boarding sensors along with external test hardware. This checks out the PCBs at the components level and flushes out workmanship issues. Prior to this, at the system level, the spacecraft will have gone through a qualification program over temperature, vacuum and vibration to verify the design. We have not seen enough part to part variability to justify aggressive environmental testing at the PCB level.
Supplier E	Again this is based upon contractual requirements.
Supplier F	No comment provided.
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

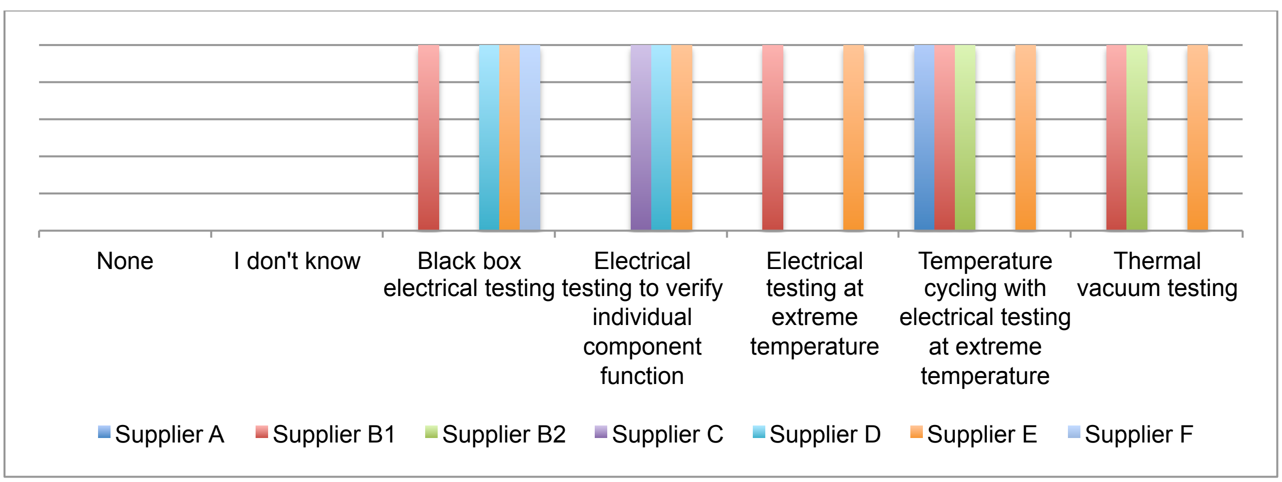

Figure 11. Type of board level electrical verification tests performed by CubeSat suppliers.

The data does not indicate the propensity to perform a specific type of electrical verification testing, however, each supplier reported that they perform electrical verification of boards. Supplier E reported that they perform each type of electrical verification testing. Supplier B2's responses indicate a bias towards thermal testing. The data suggests that each supplier is aware of whether electrical verification testing is or is not performed as "I don't know" was not selected.

4.1.12 Question #12: Board Level Radiation Testing

	Question #12: Do you perform board level testing for radiation? If yes, what type of testing do you perform?				
	No	I don't know	Yes; Proton board radiation testing	Yes; Gamma board radiation testing	Yes; Fault injection testing
Supplier A	Supplier reported that they perform TID with functional / fault testing concurrent.				
Supplier B1			X	X	X
Supplier B2			X	X	
Supplier C	X				
Supplier D			X		
Supplier E			X	X	X
Supplier F	X				

Comments*:	
Supplier A	Total Ionizing Dose with functional / fault testing concurrent
Supplier B1	The qualification tests performed on the miniaturized systems are to the standards set to the specific project.
Supplier B2	Heavy ions and neutrons are also possible to test for
Supplier C	No comment provided.
Supplier D	We have done basic testing with a Co-60 source for TID in one of our PCBs with a university partner. We are not particularly concerned with TID, and more concerned with latch-up and other SEU's. These issues we try to address at the system level. Testing of latch-up and SEU's can be quite expensive, and hasn't been necessary for our LEO applications. Going beyond LEO may require additional radiation testing.
Supplier E	No comment provided.
Supplier F	With rare exceptions rad hard parts are excessive for cost and long lead procurement. Effort is made to pick parts from manufacturers who provide rad hard parts and similar size/performance parts are desired
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

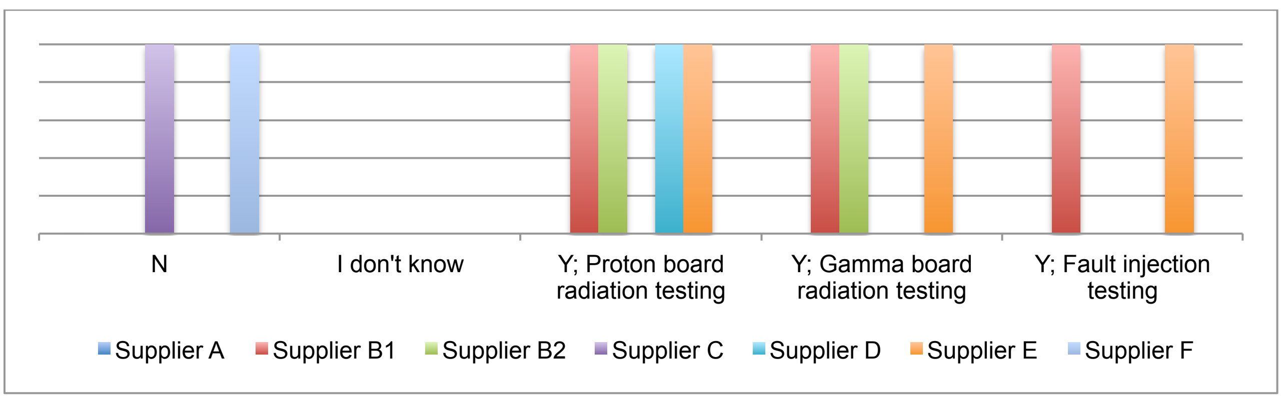

Figure 12. Types of board level radiation testing performed by CubeSat suppliers.

All suppliers, except Suppliers C and F, reported that they perform at least one type of board level radiation testing. Suppliers B1 and E reported that they perform all types of radiation testing. The data suggests that each supplier is aware of whether radiation testing is or is not performed as "I don't know" was not selected.

4.1.13 Question #13: Analysis of Parts Under Various Thermal Conditions

	Question #13: Are the parts procured analyzed to survive within: (Select the answer that most applies.)				
	Parts are not analyzed.	I don't know.	Acceptable failure rates at room temperature?	Worst case junction temperatures?	Worst case operating temperatures still yielding acceptable failure rates for individual devices?
Supplier A					X
Supplier B1			X	X	X
Supplier B2	X				
Supplier C			X		
Supplier D	X				
Supplier E			X	X	X
Supplier F					X

Comments*:	
Supplier A	No comment provided.
Supplier B1	The analyses/tests performed on the miniaturized systems are to the standards set to the specific project.
Supplier B2	No MTBF/FIT reliability analysis are performed on std small satellite products, but we select components very carefully and use the ones that we have good radiation data. For rad-hard solution we do worst case and MTBF/FIT reliability analysis.
Supplier C	No comment provided.
Supplier D	The analysis is very basic, so I'm not calling it analyzing in the sense that JPL probably does it. We use smart rules of thumb for thermal design, and go through a lot of effort to provide thermal mass and routing where necessary. The benefit of COTS is these are much lower power, and thus the component level heating is a non-issue except for very specific instances.
Supplier E	No comment provided.
Supplier F	Note: suggested worst case operating temperatures for typical space vehicles are used, most customers do not perform thorough thermal analysis or flow thermal operating requirements
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

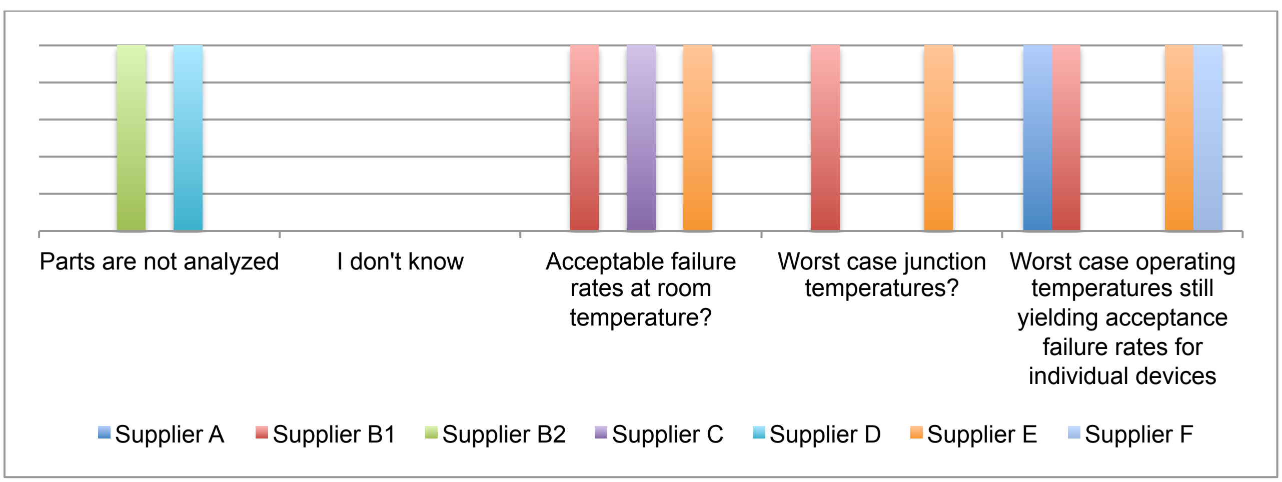

Figure 13. Part analysis performed by CubeSat suppliers.

All suppliers, except Suppliers B2 and D, reported that they perform at least one of the analysis types listed in the question. Supplier B1 and E reported that they perform each type of analysis. Suppliers A, C, and F reported that they perform only one type of analysis. The data suggests that each supplier is aware of whether analysis of part survival in certain thermal environments is or is not performed as “I don’t know” was not selected.

4.1.14 Question #14: Derating Practices

	Question #14: Are individual EEE components: (Select the answer that most applies.)					
	I don't know.	Verified to be used within datasheet limits for voltage, current, and power?	Application limits significantly lower than datasheet limits (ad hoc derating)?	Derated using established limits/factors?	Derated using established limits/factors and independent analysis proves worst case conditions meet those derating limits?	Derated using established limits/factors and independent analysis proves worst case conditions meet those derating limits with minimal violations?
Supplier A				X		
Supplier B1						X
Supplier B2				X		
Supplier C			X			
Supplier D		X	X			
Supplier E		X		X		
Supplier F		X				

Comments*:	
Supplier A	No comment provided.
Supplier B1	The design and analyses performed on the miniaturized systems are to the standards set to the specific project.
Supplier B2	ECSS derating with a few well defined exceptions.
Supplier C	No comment provided.
Supplier D	All parts are de-rated as conservatively as the application allows. In some instances, we don't have the luxury of broad stroke de-rating given some of the performance metrics we are required to hit.
Supplier E	Independent analysis of the engineer's WCA is conducted by the group leader. The analysis are available to the customer.
Supplier F	By design, not test. No attempt to use parts with derating is performed.
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

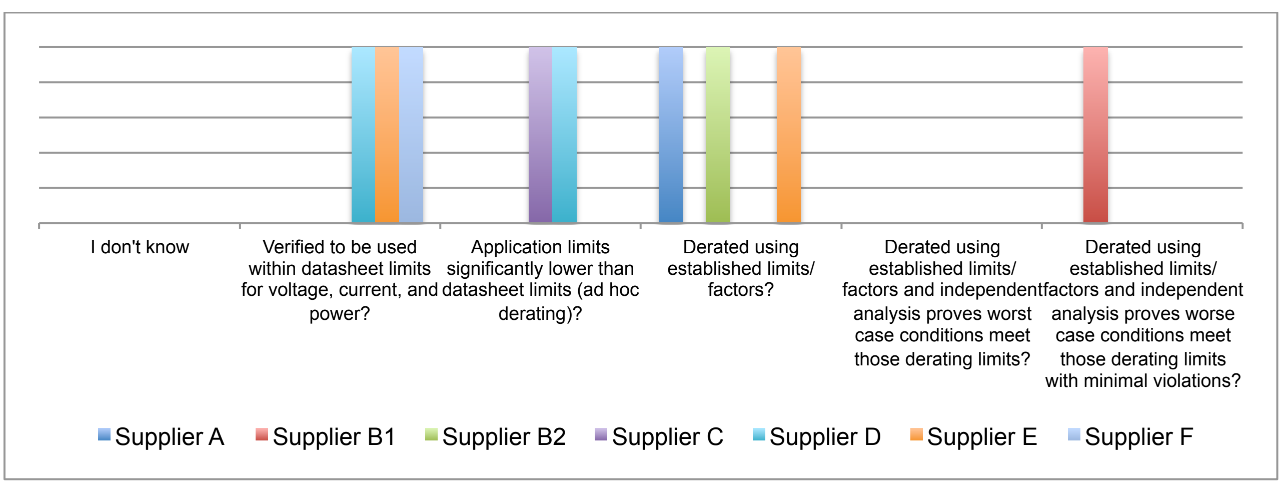

Figure 14. Practices employed by CubeSat suppliers to derate EEE components.

The data indicates that the majority of CubeSat suppliers verify EEE components will be used within the specified datasheet and application limits. Suppliers A, B1, B2, and E reported that EEE components are derated using established limits/factors. Supplier B1 also reported performing independent analysis to prove worse case conditions meet derating limits with minimal violation. The data suggests that each supplier is aware of whether derating is or is not performed as “I don’t know” was not selected.

4.1.15 Question #15: Operator Soldering Certification

	Question #15: Are operators certified to IPC J-STD-001 for soldering? If yes, are training records maintained?			
	No	I don't know	Yes; Training records are maintained	Yes; Training records are not maintained
Supplier A			X	
Supplier B1		X		
Supplier B2			X	
Supplier C	X			
Supplier D			X	
Supplier E			X	
Supplier F			X	
Supplier G			X	

Comments*:	
Supplier A	No comment provided.
Supplier B1	The assembly of miniaturized systems uses many different types of mounting techniques such as flipchip, underfill, gluing and wire bonding. Some operators for certain operations are certified and they have training records.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	We have one technician who was certified at his previous job. He solders flight hardware.
Supplier E	No comment provided.
Supplier F	Soldering certification to NASA Standard 8739.3 is held by our operators (last certification in 2014, required every 2 years). J-STD-001ES courses were not readily available at that time. Future training is anticipated to be for J-STD-001ES.
Supplier G	(We) utilize certified solder operators and inspectors that perform work on contract.

*Written verbatim from questionnaires received from CubeSat suppliers.

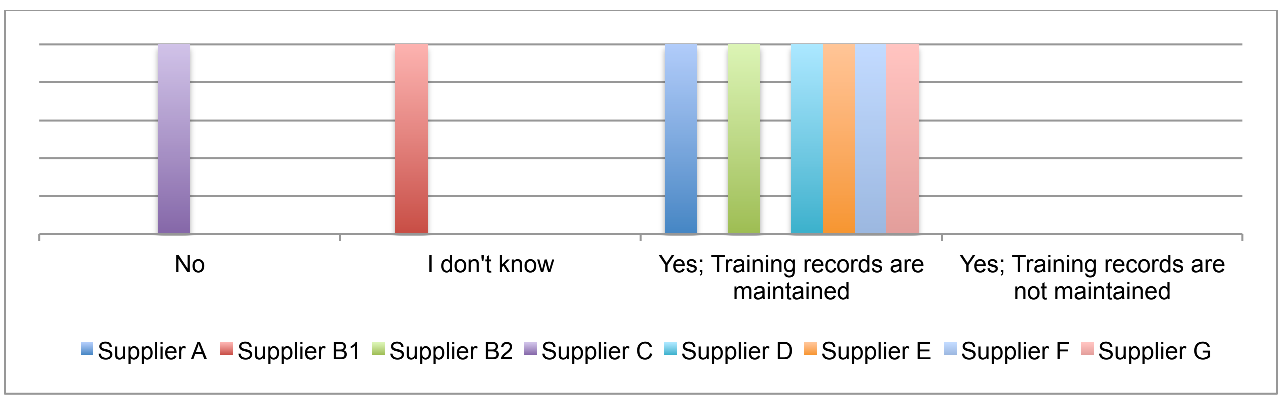

Figure 15. Operator certification to soldering standard, IPC J-STD-001.

The majority of CubeSat suppliers reported that their operators are certified to the soldering standard, IPC J-STD-001. Supplier C reported that their operators are not certified to this standard. Supplier B1 was unaware if their operators are certified to this standard; however, Supplier B2 – the same supplier as B1 – reported that their operators are certified. Supplier F reported that their operators are certified to NASA standard 8739.3; this standard was canceled in 2011 and NASA adopted IPC J-STD-001 as the standard by which operators are certified for soldering. (The NASA standard may still be applicable on some contracts as a valid document (NASA Electronic Parts and Packaging Program, 2011).)

4.1.16 Question #16: Quality of Delivered Boards

	Question #16: Are individual boards delivered with: (Select the answer that most applies.)					
	I don't know	Proto-type boards with haywires/cut traces?	Extensive rework and hand soldering?	An established build plan however no control/inspection over execution of assembly?	An established build instruction and reflowed components yet substantial rework is performed?	An established build instruction and reflowed components with minimal rework performed?
Supplier A						X
Supplier B1						X
Supplier B2						X
Supplier C						X
Supplier D						X
Supplier E						X
Supplier F						X

Comments*:	
Supplier A	No comment provided.
Supplier B1	No comment provided.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	We deliver design and assembly documentation to the fabrication houses. They deliver the boards, which we then inspect, and mark for rework as necessary. Simple fixes may be done in-house to save schedule. Under ideal conditions, no re-work is performed.
Supplier E	No comment provided.
Supplier F	No comment provided.
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

All CubeSat suppliers reported that boards are delivered with an established build instruction and reflowed components with minimal rework performed. The data suggests that each supplier is aware of quality of the boards delivered to their customers as "I don't know" was not selected.

4.1.17 Question #17: ESD Program

	Question #17: Which of the options below most closely describes your ESD program?					
	No controls	ESD mats and wrist straps	ESD equipment ionizers, benches, chairs, leg straps	Established ESD program; regular audits are not performed; personnel self-regulate	Established ESD program; regular audits are performed; low ESD limit	I don't know
Supplier A				X		
Supplier B1		X	X	X		
Supplier B2				X		
Supplier C		X				
Supplier D				X		
Supplier E		X	X		X	
Supplier F		X				
Supplier G		X				

Comments*:	
Supplier A	No comment provided.
Supplier B1	The tests are recorded in PCB production, but will also in the near future be recorded in the miniaturization lab environment, we have now the equipment to do test there.
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	All engineers go through ESD training, though no formal audits are performed. All work spaces include surface matts and ground mats with dedicated grounding wires to a grounding spike (not the building electrical). The engineers regulate themselves and others for best practices.
Supplier E	No comment provided.
Supplier F	No comment provided.
Supplier G	No comment provided.

*Written verbatim from questionnaires received from CubeSat suppliers.

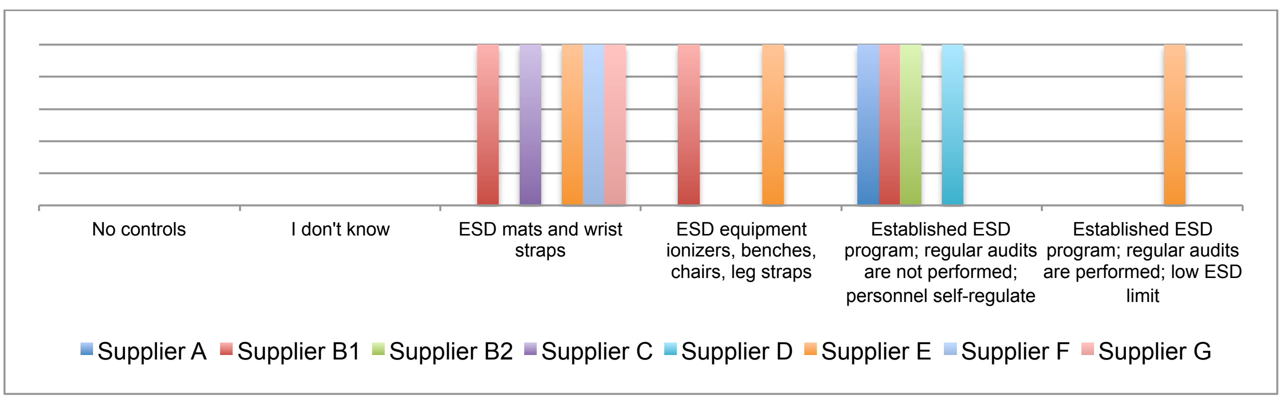

Figure 16. ESD precautions and programs instituted by CubeSat suppliers.

All CubeSat suppliers reported having equipment and/or established programs for ESD management. Suppliers A, B1, B2, D, and E reported that they have an established ESD program and Supplier E also reported that they perform regular audits. The data suggests that each supplier is aware of their internal ESD precautions and programs as "I don't know" and "No controls" were not selected.

4.1.18 Question #18: Utilization and Testing of Wrist Straps

	Question #18: If wrist straps are utilized, are they tested before use? If yes, is the test recorded?			
	No	I don't know	Yes; Test is recorded	Yes; Test is not recorded
Supplier A	X			
Supplier B1			X	
Supplier B2			X	
Supplier C	X			
Supplier D	X			
Supplier E			X	
Supplier F				X
Supplier G				X

Comments*:	
Supplier A	No comment provided.
Supplier B1	It's measured and in the area where it's needed it's also regulated.
Supplier B2	The tests are recorded in production, but will also in the near future be recorded in the lab environment, we have now the equipment to do test there.
Supplier C	No comment provided.
Supplier D	The benches have been tested, though day to day use it is not tested or recorded.
Supplier E	No comment provided.
Supplier F	Some initial testing is performed. Testing is not performed before each use. Straps showing significant wear are replaced.
Supplier G	No comment provided.

*Written verbatim from questionnaires received from CubeSat suppliers.

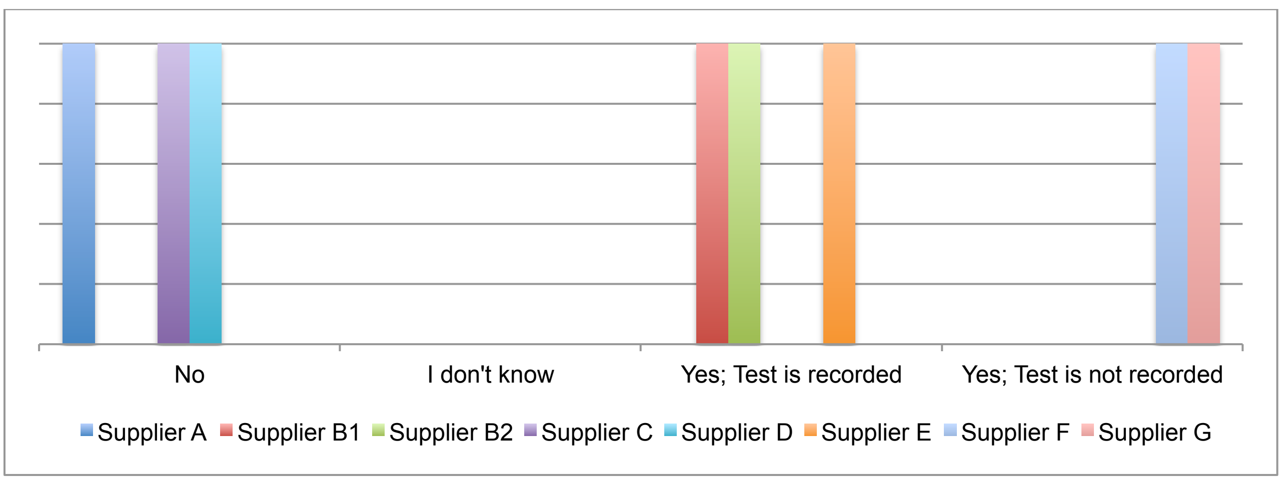

Figure 17. Wrist strap utilization and testing practices by CubeSat suppliers.

Responses to question 17 indicate that all CubeSat suppliers use ESD equipment, specifically wrist straps, however, not all suppliers test them before use. Suppliers B1, B2, and E reported that they test wrist straps and record results. Suppliers F and G reported that they test wrist straps but do not record results. The data suggests that each supplier is aware of whether wrist strap are utilized and tested as "I don't know" was not selected.

4.1.19 Question #19: Verification of Humidity Levels

	Question #19: Do you verify relative humidity? If yes, is this recorded?			
	No	I don't know	Yes; Humidity is recorded	Yes; Humidity is not recorded
Supplier A			X	
Supplier B1				X
Supplier B2				X
Supplier C	X			
Supplier D				X
Supplier E			X	
Supplier F				X
Supplier G				X

Comments*:	
Supplier A	Recorded only if out of specification
Supplier B1	No comment provided.
Supplier B2	We have equipment to keep certain humidity, but I don't know if we verify the relative humidity.
Supplier C	No comment provided.
Supplier D	We verify humidity in our clean room and lab. The unit has an alarm to indicate when there is insufficient humidity in the room.
Supplier E	No comment provided.
Supplier F	Spot checked, and only performed in clean room area. Only projects requiring full clean-room assembly would be verified to be fully assembled in this area.
Supplier G	No comment provided.

*Written verbatim from questionnaires received from CubeSat suppliers.

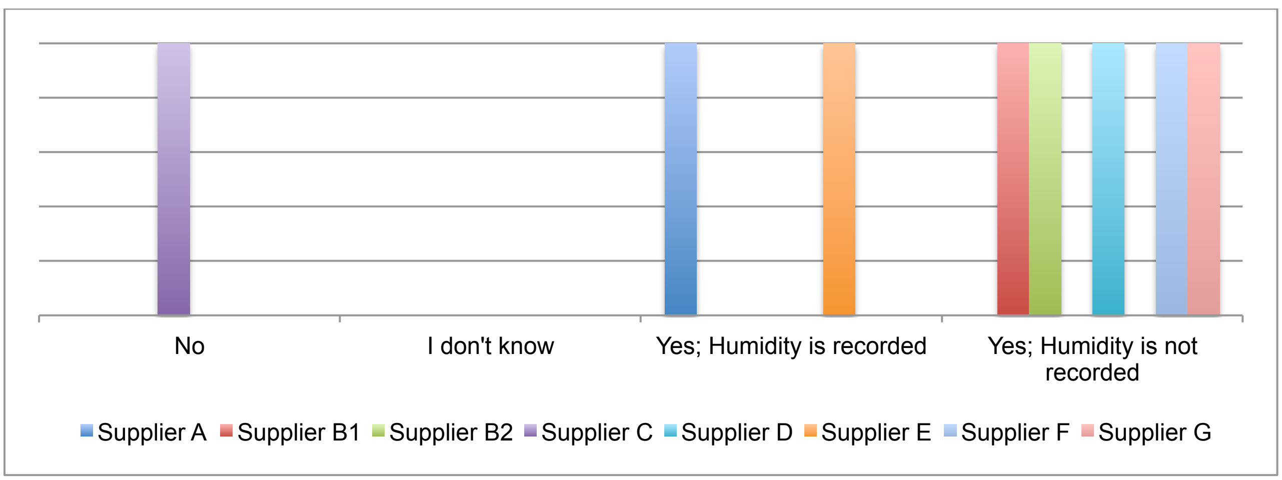

Figure 18. Humidity level verification and documentation practices by CubeSat suppliers.

All CubeSat suppliers, except Supplier C, reported verifying relative humidity. Of these suppliers, only Suppliers A and E reported that they record relative humidity. The data suggests that each supplier is aware of whether humidity levels are or are not verified and recorded as "I don't know" was not selected.

4.1.20 Question #20: EEE Part Storage

	Question #20: Which of the options below most closely describes your EEE part storage system?					
	No controls	I don't know	Parts are stored in original packaging without environmental controls	ESD precautions are observed	Humidity-controlled environment; ESD precautions are observed	Parts are stored in dry nitrogen; constant flow; ESD precautions are observed
Supplier A				X		
Supplier B1					X	X
Supplier B2			X	X		X
Supplier C			X			
Supplier D			X	X		
Supplier E			X	X		X
Supplier F				X		
Supplier G					X	

Comments*:	
Supplier A	No comment provided.
Supplier B1	No comment provided.
Supplier B2	This varies with part and sensitivity. Passives, connectors and PCB:s are usually stored in a ESD-controlled environment, but open. Actives are usually stored in the same environment adding their original packaging or being repackaged with vacuum and/or nitrogen in packaging similar to the original one. In some cases they have been stored in our dry nitrogen compartment. Rules are applied to how long the components are allowed to be stored before useage.
Supplier C	No comment provided.
Supplier D	We have a central parts inventory stored in original packaging and organized by type and part number. The bins are ESD safe.
Supplier E	Above "X" marks depend on control appropriate to the part. Part inventory is locked and controlled, ESD controlled, with standard climate controls.
Supplier F	No comment provided.
Supplier G	See the question 1 comment. Assemblies delivered by suppliers are stored in humidity controlled environment and ESD precautions are observed.

*Written verbatim from questionnaires received from CubeSat suppliers.

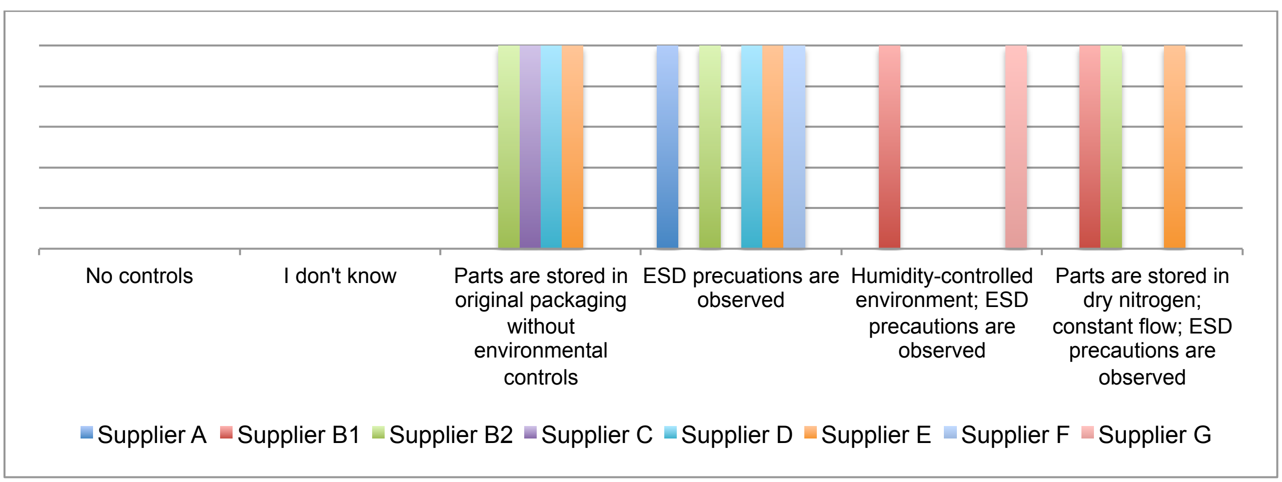

Figure 19. EEE part storage practices employed by CubeSat suppliers.

The data does not indicate a standard system for storing EEE parts, however, each supplier reported having controls in place. All suppliers, except Supplier C, reported observing ESD precautions when storing parts. Supplier B2 and E reported that they store parts in the original packaging without environmental controls and in dry nitrogen with constant flow. The data suggests that each supplier is aware of their EEE part storage systems as “I don’t know” and “No controls” were not selected.

4.1.21 Question #21: Failure Analysis

	Question #21: Do you perform failure analysis? If yes, which of the options below most closely describes the level to which you perform FA?				
	No	I don't know	Yes; I don't know	Yes; Failures are attributed to the root cause	Yes; Failure is attributed to the root cause; lessons learned are incorporated into a corrective action
Supplier A					X
Supplier B1					X
Supplier B2					X
Supplier C					X
Supplier D					X
Supplier E				X	
Supplier F					X

Comments*:	
Supplier A	No comment provided.
Supplier B1	No comment provided.
Supplier B2	Corrective action is taken when needed and in most cases included in upcoming releases, that is, not done as a hotfix.
Supplier C	No comment provided.
Supplier D	As a growing company, this is among the single more important things we do. We are in the process of integrating several extremely complicated flight vehicles. The engineers involved have struck a great balance between keeping a good pace, while being methodical with issue documentation and resolution. We use software tools for issue tracking that are transparent to the entire company, and require formal review and sign-offs on issue resolutions, and planned steps forward. We are proud of this process and the professionalism the team shows, which you don't always find in the nano-satellite community.
Supplier E	(We) are in process of bringing up a lessons learned process.
Supplier F	No comment provided.
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

All CubeSat suppliers reported that they perform failure analysis and all, except Supplier E, incorporate lessons learned into a corrective action. The data suggests that each supplier is aware of whether failure analysis is or is not performed as "I don't know" was not selected.

4.1.22 Question #22: PWA Suppliers

Question #22: List your PWA suppliers:		
	Supplier	I don't know
Supplier A	Spectrum Advanced Manufacturing Technologies	
Supplier B1	KOA, Frauenhofer, Pac-Tech, Ericsson	
Supplier B2	LEAB Uppsala	
Supplier C		X
Supplier D	Sierra Proto Express, Advanced Circuits, Largo	
Supplier E	ESMI	
Supplier F	Advanced Circuits, Screaming Circuits, Rush PCB, STI Electronics	

Comments*:	
Supplier A	No comment provided.
Supplier B1	(We) do most of the work in house but uses the sub suppliers suitable for the specific miniaturization project..
Supplier B2	No comment provided.
Supplier C	No comment provided.
Supplier D	We use a mix, and are always looking to improve and stream-line the assembly process. We have had successes and issues with all of them. This is common across industry.
Supplier E	No comment provided.
Supplier F	No comment provided.
Supplier G	See the question 1 comment.

*Written verbatim from questionnaires received from CubeSat suppliers.

Advanced Circuits is the only common PWA supplier between two CubeSat vendors – Suppliers D and F. Supplier B1 commented that it "does most of the work in-house but uses the sub suppliers suitable for the specific miniaturization project." Supplier C reported that it was unaware of their PWA suppliers.

4.1.23 Question #23: Contract Review

	Question #23: Do you perform contract reviews? If yes, are customer requirements flowed down to the supplier?			
	No	I don't know	Yes; Customer requirements are flowed down to the supplier	Yes; Customer requirements are not flowed down to the supplier
Supplier A			X	
Supplier B1			X	
Supplier B2			X	
Supplier C	X			
Supplier D			X	
Supplier E			X	
Supplier F				X
Supplier G			X	

Comments*:	
Supplier A	No comment provided.
Supplier B1	No comment provided.
Supplier B2	We do not perform formal contract reviews, but have looked at and discussed the production lines and storage facilities. And prices are also negotiated.
Supplier C	No comment provided.
Supplier D	As needed, yes we will flow requirements to all suppliers.
Supplier E	Flowed down as appropriate.
Supplier F	Contract reviews vary from program to program as to the detail performed, the majority of are at a level significantly less than a typical large spacecraft review. EEE requirements are not flowed to suppliers, parts are selected from available sources for existing parts.
Supplier G	No comment provided.

*Written verbatim from questionnaires received from CubeSat suppliers.

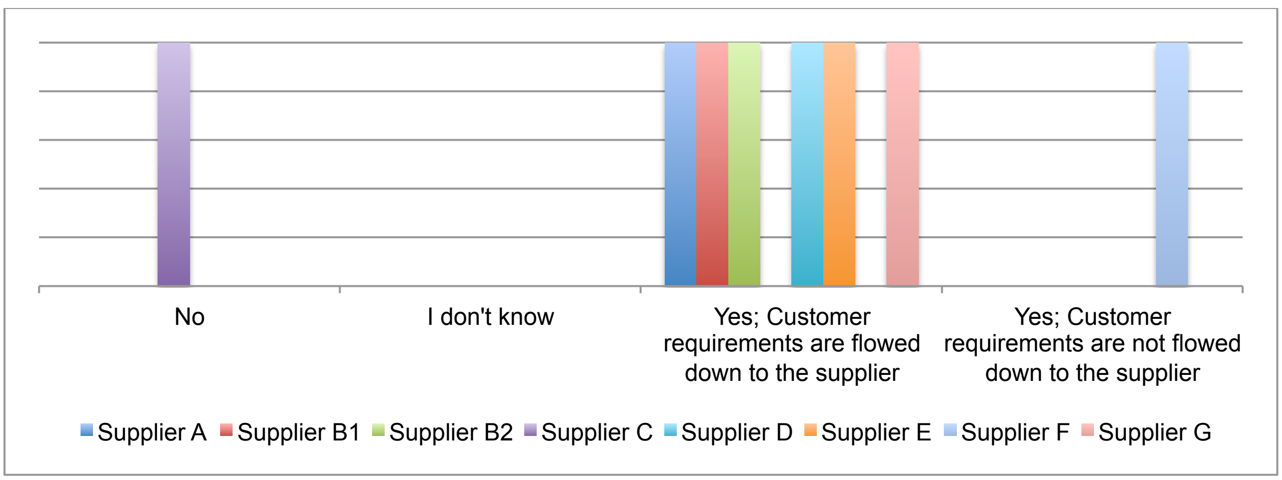

Figure 20. Contract review practices employed by CubeSat suppliers.

All CubeSat suppliers, except Supplier C, reported performing contract reviews. Aside from Supplier F, these suppliers also reported flowing down customer requirements to their supplier. The data suggests that each supplier is aware of whether they do or do not perform contract reviews as "I don't know" was not selected.

4.1.24 *Question #24: Furnishing BOMs for Boards*

	Question #24: Can you provide the customer with a BOM for flight boards? If no, can you provide a general parts list?			
	I don't know	Yes	Yes; A general parts list can be provided, too	No; A general parts list can be provided
Supplier A		X		
Supplier B1		X		
Supplier B2				X
Supplier C				X
Supplier D			X	
Supplier E		X		
Supplier F		X		

Comments*:	
Supplier A	No comment provided.
Supplier B1	Yes, the miniaturized products are developed for the customer and then we supply the full BOM and design.
Supplier B2	This is a very sensitive question. Under NDA we can provide you with a list of critical parts, but we don't want to give away the complete BOM.
Supplier C	No comment provided.
Supplier D	This is highly customer dependent. For pure commercial sales, no we do not provide a BOM. For large partnerships, we are very open with our designs in order to be success oriented.
Supplier E	No comment provided.
Supplier F	No comment provided.
Supplier G	Can be provided if the associated contract requires it. The BOM would come from the subcontracted board manufacturer.

*Written verbatim from questionnaires received from CubeSat suppliers.

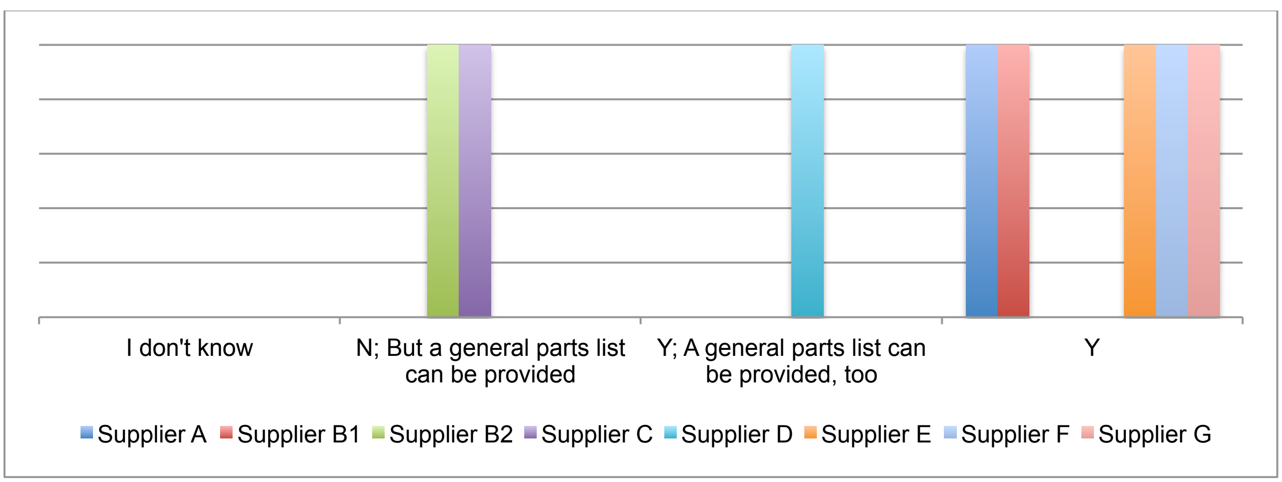

Figure 21. CubeSat suppliers' responses as to whether BOMs may be furnished.

All CubeSat suppliers, except Supplier B2 and C, are able to furnish BOMs for flight boards. Additionally, Supplier D reported that they are able to provide a general parts list, too. The data suggests that each supplier is aware of whether they are or are not able to furnish BOMs for flight boards as "I don't know" was not selected.

4.2 Data Analysis of NASA CubeSat EEE Parts Database

This section provides an analysis of part data supplied by NASA CubeSat projects for in-house board designs.

4.2.1 Percentage Breakdown of Total Parts

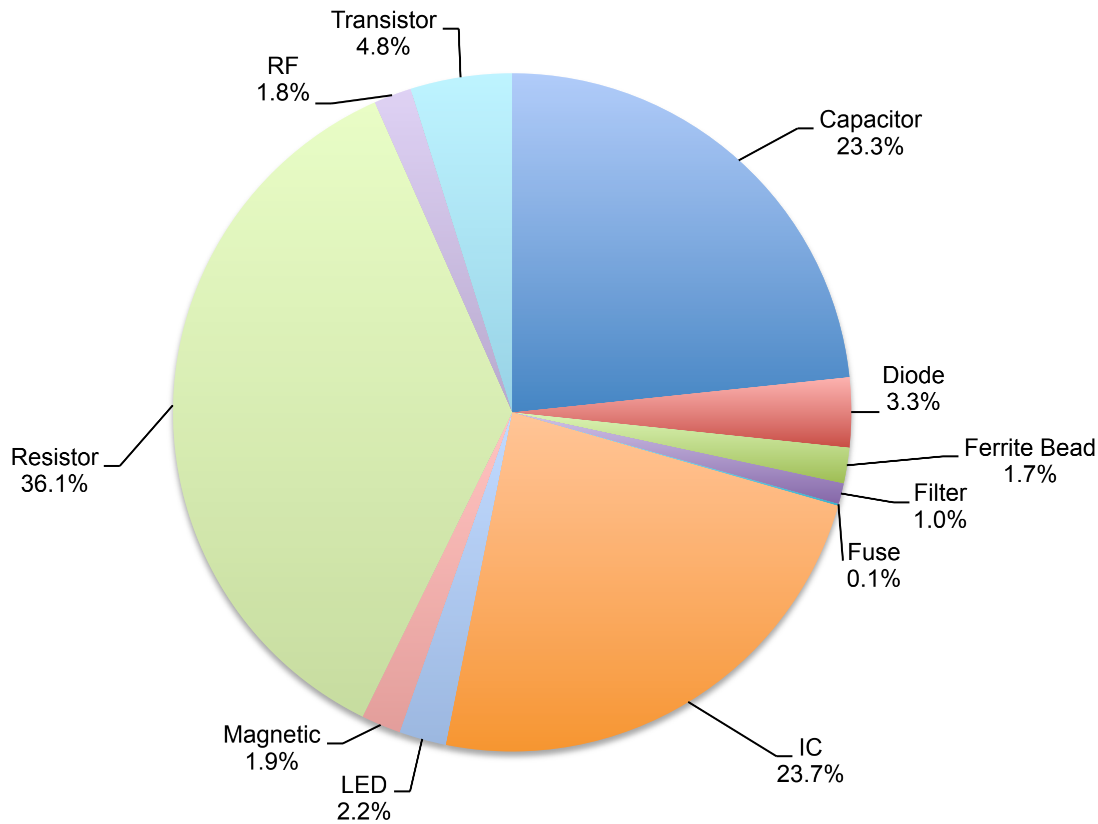

Figure 22. Percentage breakdown of the types of parts that comprise the database.

Passive components and ICs represent approximately 60% and 24%, respectively, of all parts in the database. Analogous proportions exist for standard board designs, indicating the dataset is a good representation of practical, real-world designs.

4.2.2 Percentage Breakdown of IC Components

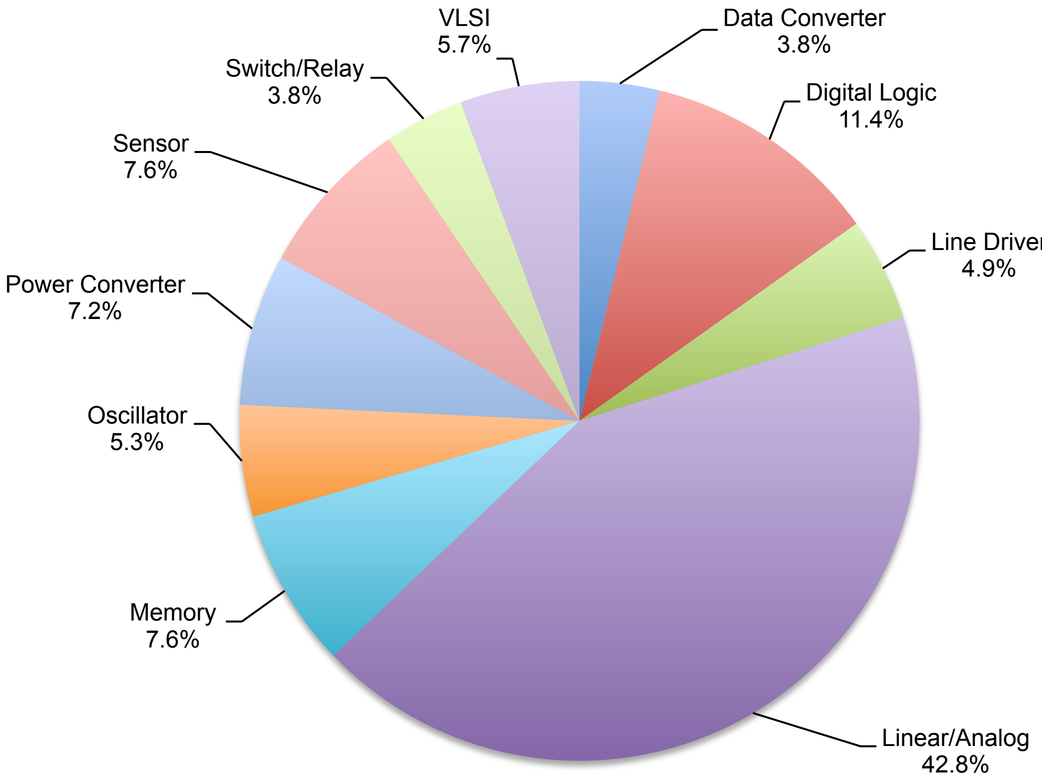

Figure 23. Percentage breakdown of IC components.

IC Subcategory	Subcategory Constituents
Data Converter	ADC/DAC
Digital Logic	Flip-Flop; MUX/DEMUX; Shift Register; Serializer/Deserializer; Logic Inverter; Inverter; Gate; Timekeeper/Timer; Counter
Linear/Analog	Amplifier; Charge Pump; Current Monitor; Driver; Multivibrator; Receiver; Supervisor; Voltage Regulator; Reference; Op-amp/Comparator
Line Driver	Buffer; Transceiver; GPIO
Memory	MRAM; PCM; Flash; PROM; EPROM/EEPROM; SRAM; SDRAM; MicroSD
Oscillator	Crystal; Oscillator; VCO
Power Converter	DC/DC
Sensor	-
Switch/Relay	-
VLSI	FPGA; ASIC; Complex Logic; Processor; Microprocessor; MCU

IC components represent approximately 24% of the total parts in the database. Subcategories were created to further define the type of IC components in the database. Linear/analog-type devices represent approximately 43% of all ICs.

4.2.3 IC Manufacturers

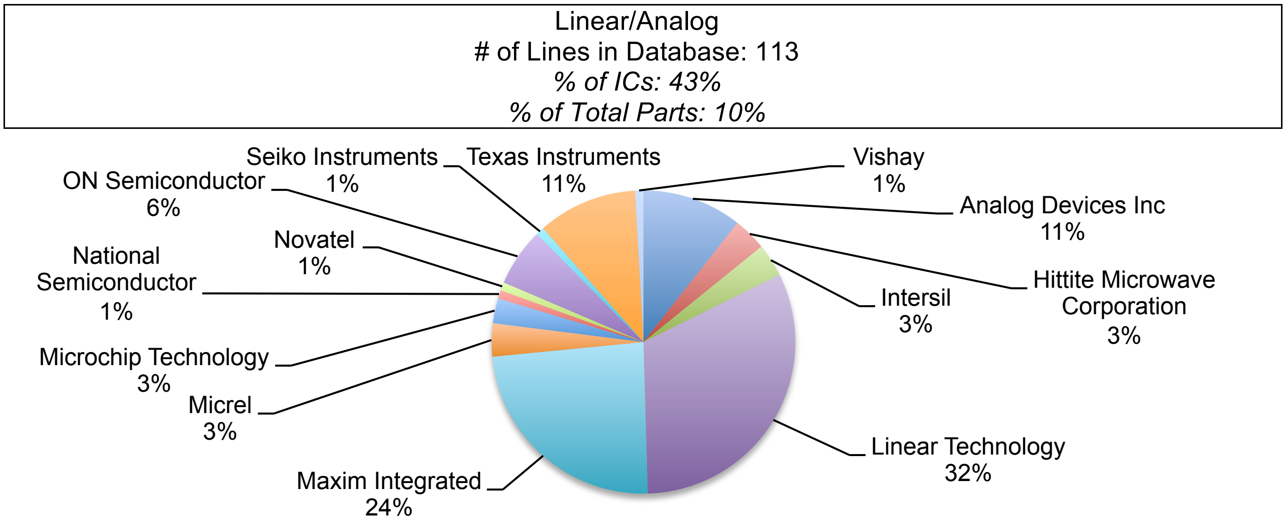

Figure 24. Manufacturers of linear/analog devices used to populate NASA CubeSat boards.

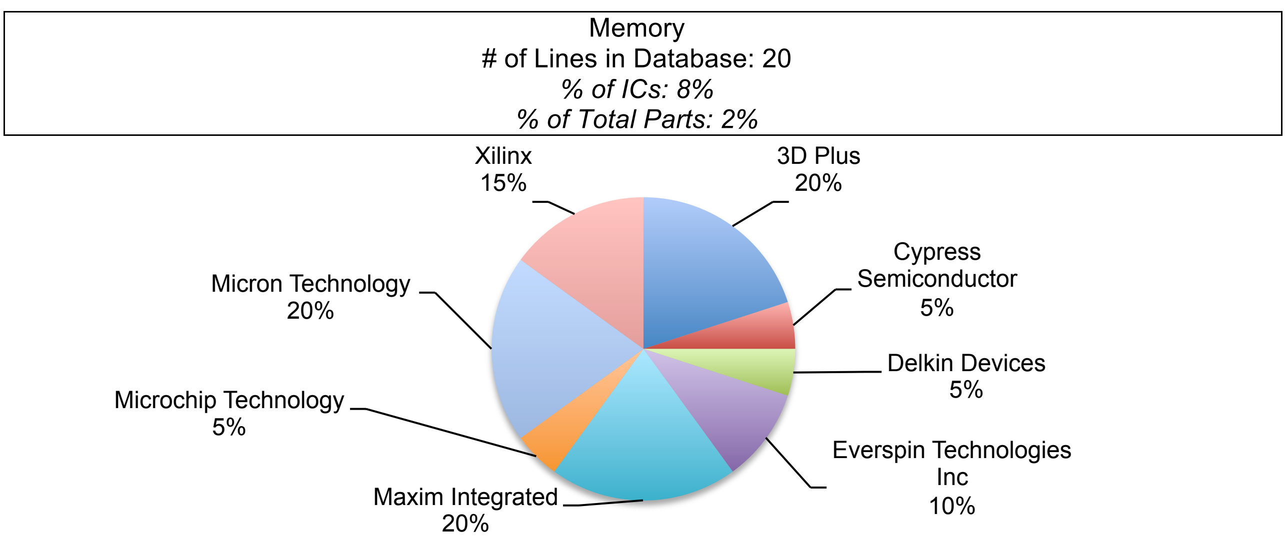

Figure 25. Manufacturers of memory devices used to populate NASA CubeSat boards.

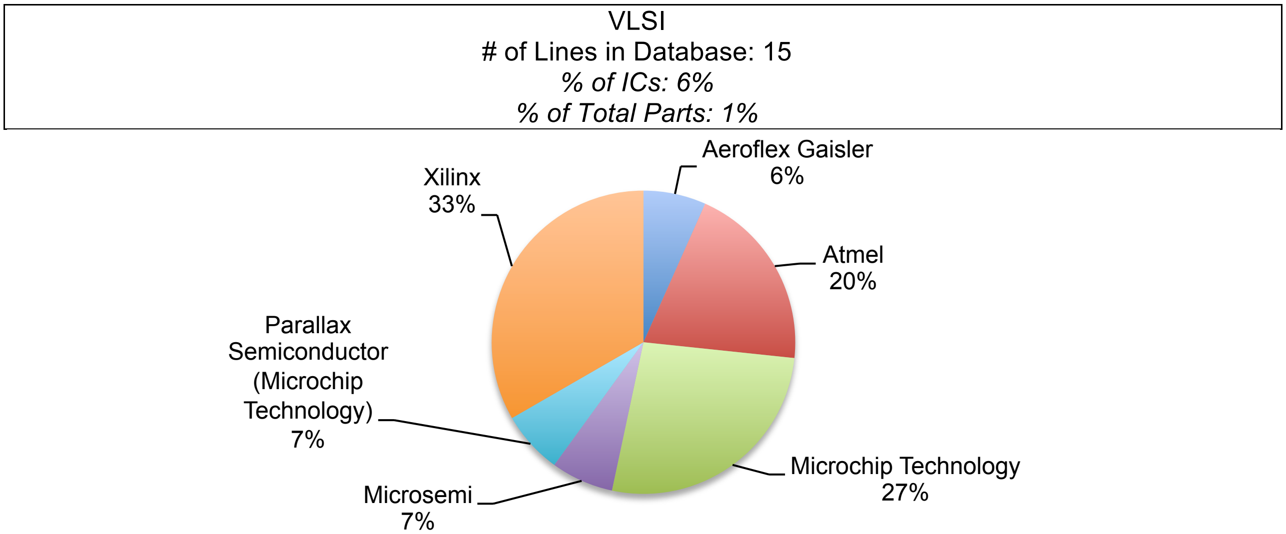

Figure 26. Manufacturers of VLSI devices used to populate NASA CubeSat boards.

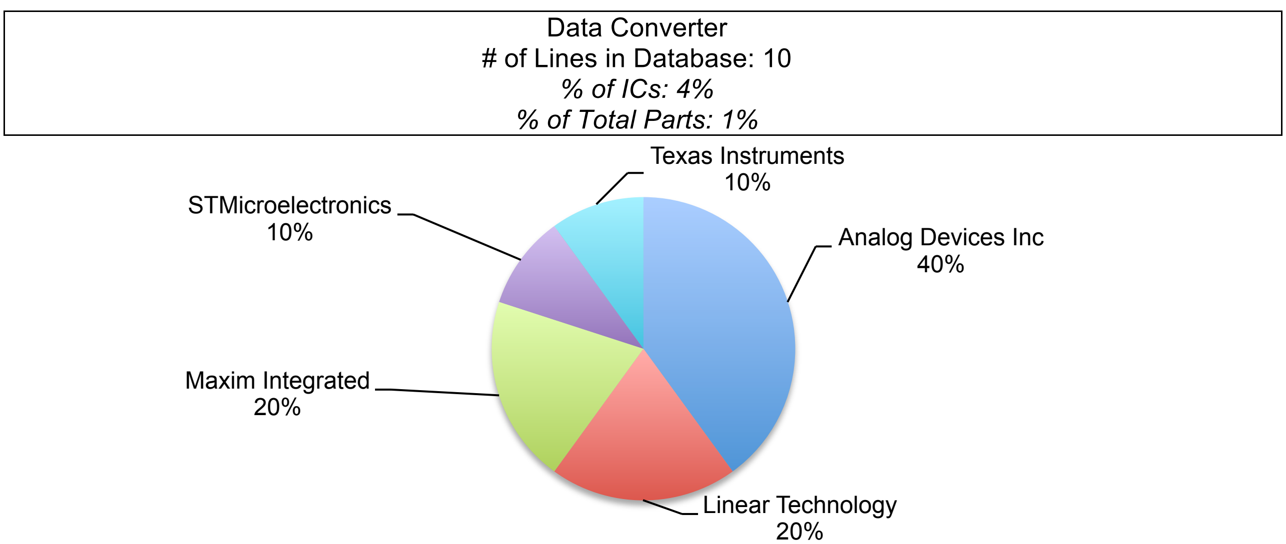

Figure 27. Manufacturers of data converter devices used to populate NASA CubeSat boards.

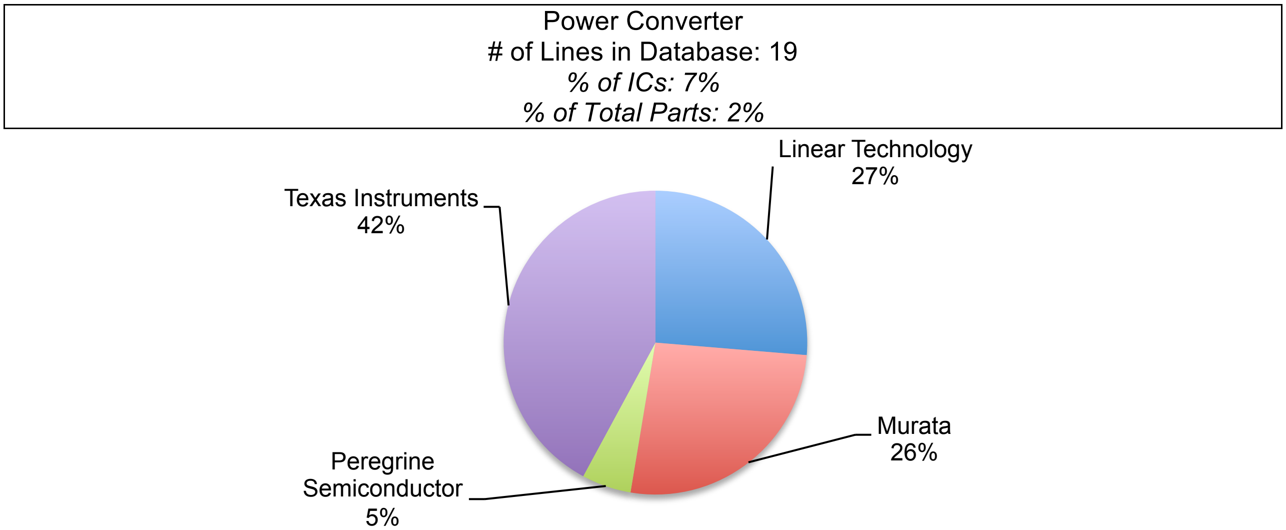

Figure 28. Manufacturers of power converter devices used to populate NASA CubeSat boards.

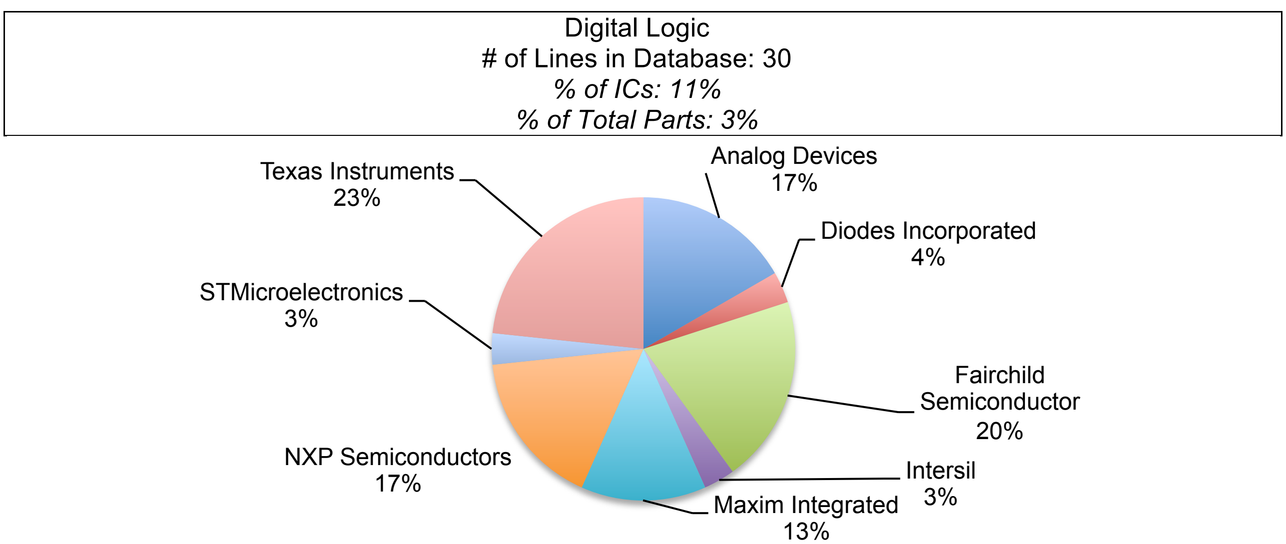

Figure 29. Manufacturers of digital logic devices used to populate NASA CubeSat boards.

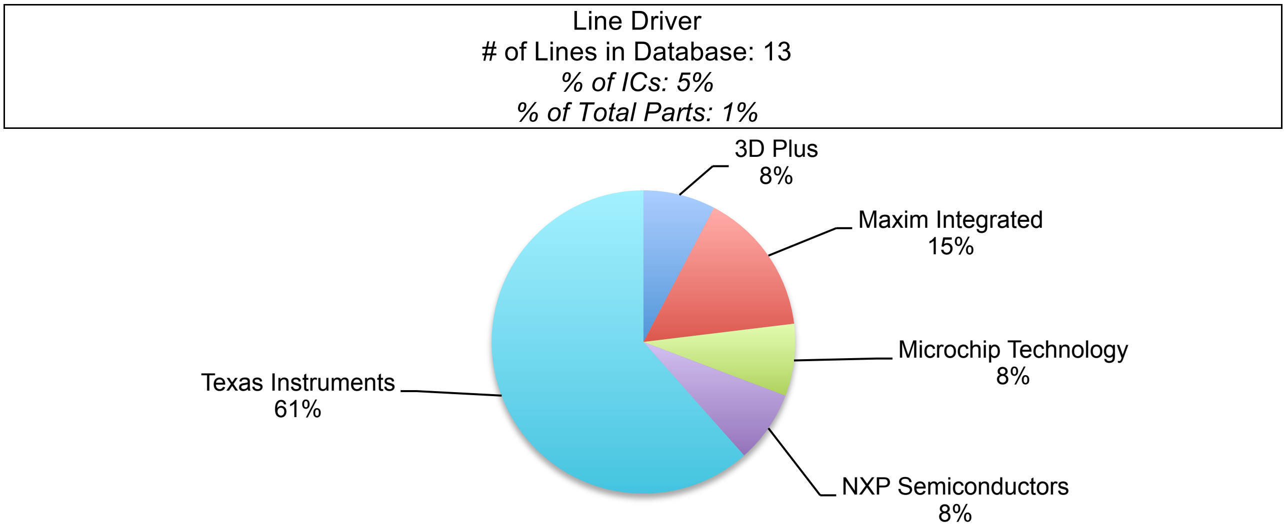

Figure 30. Manufacturers of line driver devices used to populate NASA CubeSat boards.

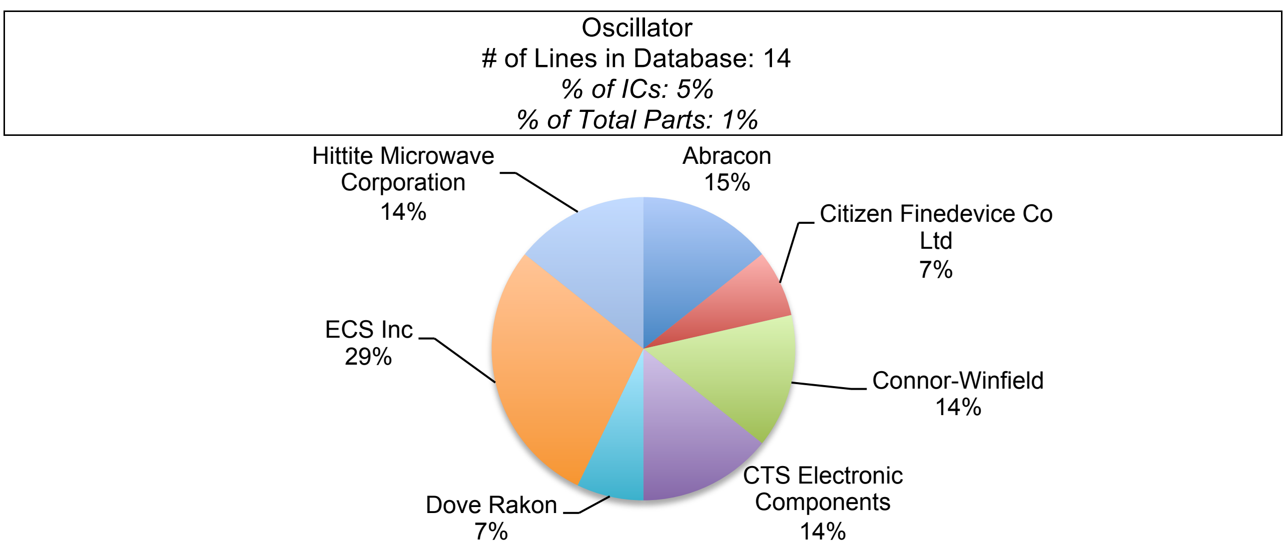

Figure 31. Manufacturers of oscillator devices used to populate NASA CubeSat boards.

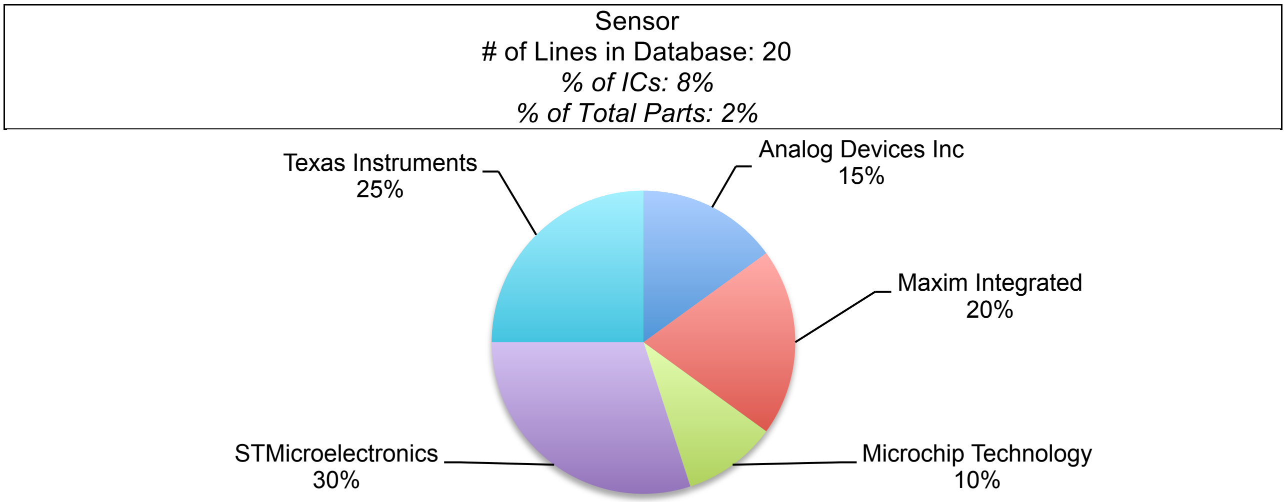

Figure 32. Manufacturers of sensor devices used to populate NASA CubeSat boards.

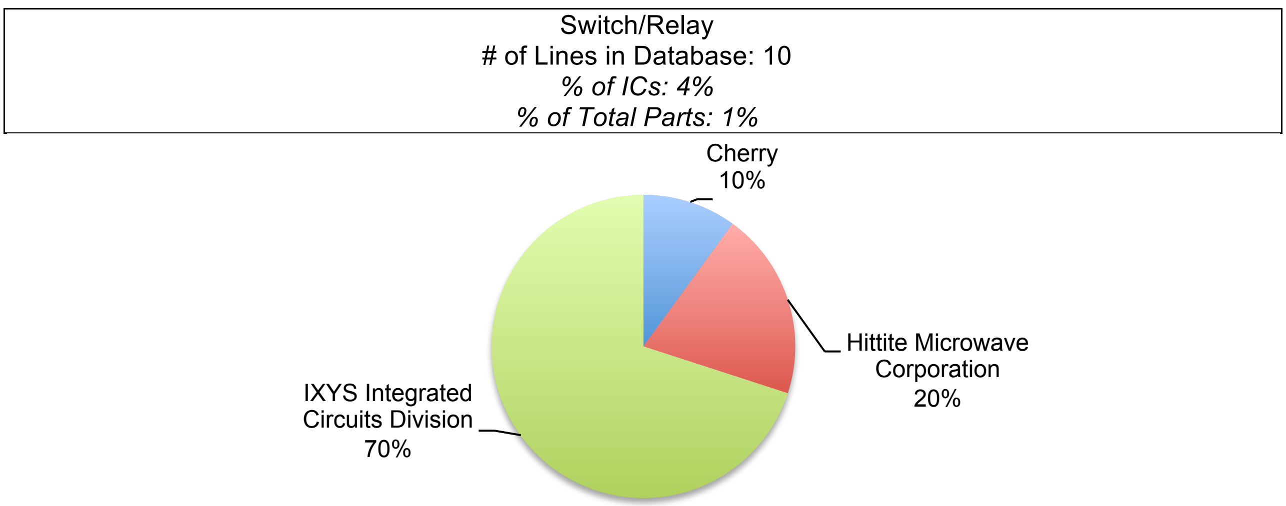

Figure 33. Manufacturers of switch/relay devices used to populate NASA CubeSat boards.

Figures 24-33 indicate that there are few manufacturers that supply the largest portion of devices in each IC subcategory. For example, for linear/analog devices, Linear Technology and Maxim Integrated manufacture the majority of components used to populate NASA CubeSat boards. In general, Linear Technology (16%), Maxim Integrated (16%), and Texas Instruments (15%) supply the largest percentage of IC components.

4.2.4 Operating Temperature Ranges

Datasheets were collected from multiple sources, including distributor and manufacturer websites. Operating temperature ranges reported on the manufacturers' datasheets were recorded in the database. (This is the reported temperature at which the IC is qualified to operate.) Seventeen unique temperature ranges were recorded:

0°C to +70°C	-40°C to TBD
-10°C to +70°C	-45°C to +85°C
-20°C to +70°C	-45°C to +125°C
-25°C to +85°C	-50°C to +150°C
-40°C to +85°C	-55°C to +125°C
-40°C to +100°C	-55°C to +130°C
-40°C to +105°C	-55°C to +150°C
-40°C to +125°C	Industrial
-40°C to +150°C	

Part grades are designated by their operating temperature (ALTERA, 2015) (Maxim Integrated, 2015):

1. Commercial: 0°C to +70°C
2. Industrial: -40°C to +85°C
3. Extended Industrial: -40°C to +100°C
4. Automotive: -40°C to +125°C
5. Military/Space: -55°C to +125°C

These temperature ranges are generally accepted in industry. Minor variations (+/- 5°C to 25°C) exist between accepted temperature ranges and those that were reported on manufacturers' datasheets. In Figures 34-44, the part grade will be displayed in lieu of the numerical value. Temperature ranges will only be displayed numerically if they cannot be designated by a part grade.

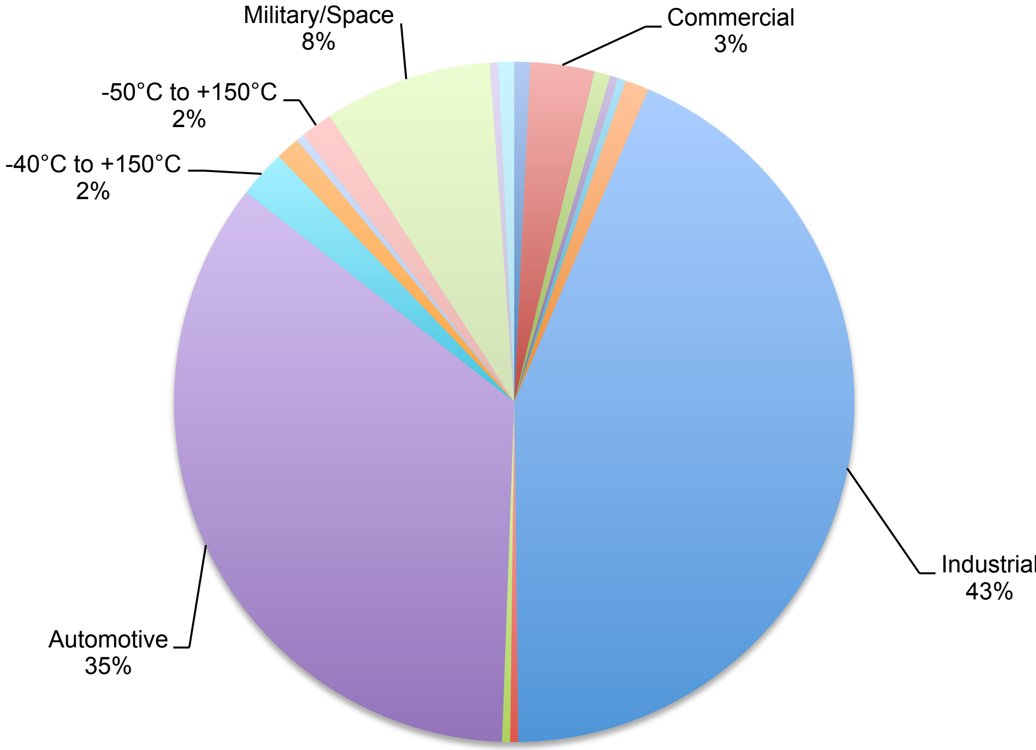

Figure 34. Manufacturers' reported operating temperature ranges for IC parts.

Figure 34 shows the percentage breakdown of operating temperature ranges reported for ICs. For readability, only those temperature ranges that represent >1% are displayed. The three temperature ranges with the greatest representation are: Industrial (43%), Automotive (35%), and Military/Space (8%).

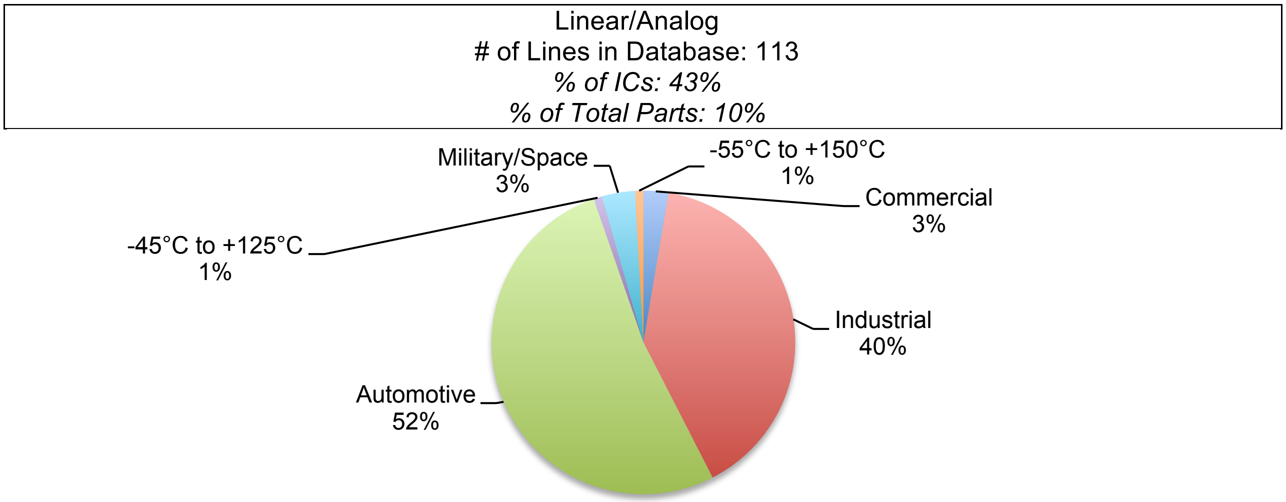

Figure 35. Qualified operating temperature ranges for linear/analog devices (as reported by the manufacturers).

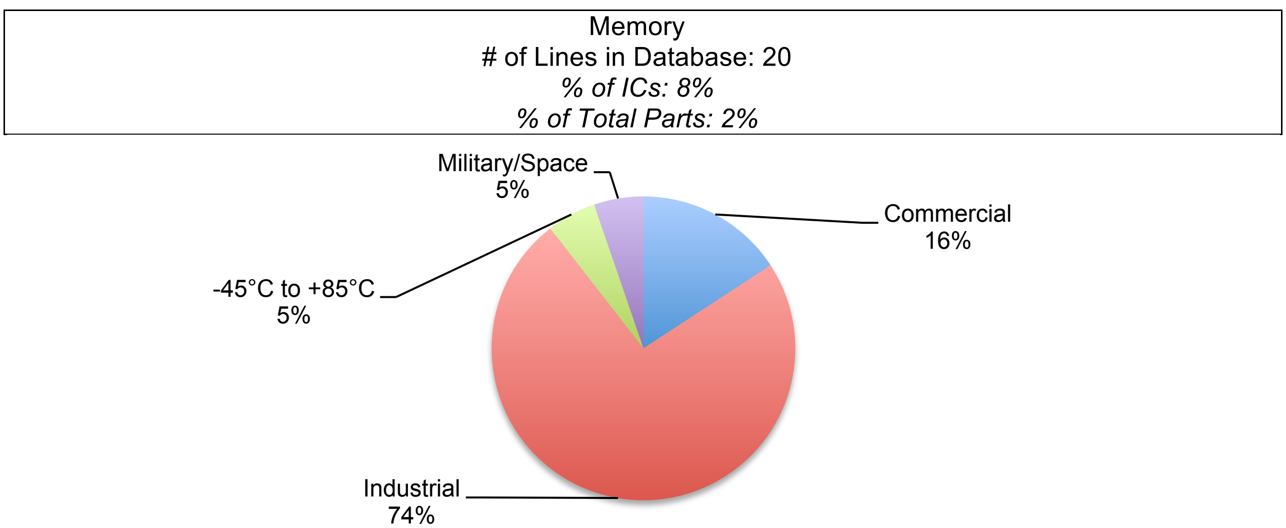

Figure 36. Qualified operating temperature ranges for memory devices (as reported by the manufacturers).

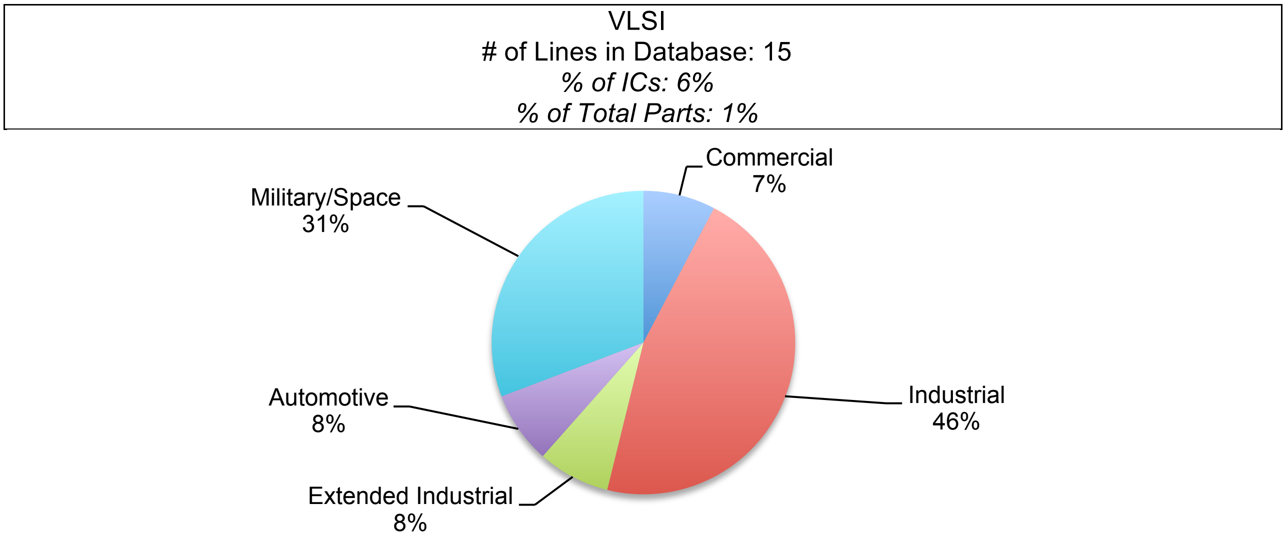

Figure 37. Qualified operating temperature ranges for VLSI devices (as reported by the manufacturers.)

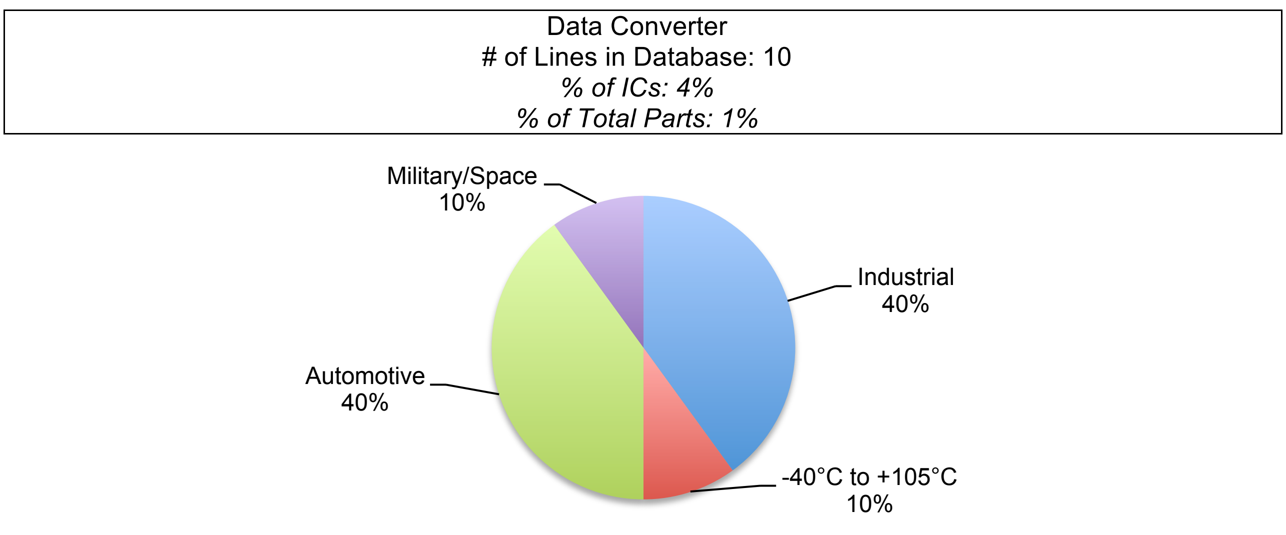

Figure 38. Qualified operating temperature ranges for data converter devices (as reported by the manufacturers).

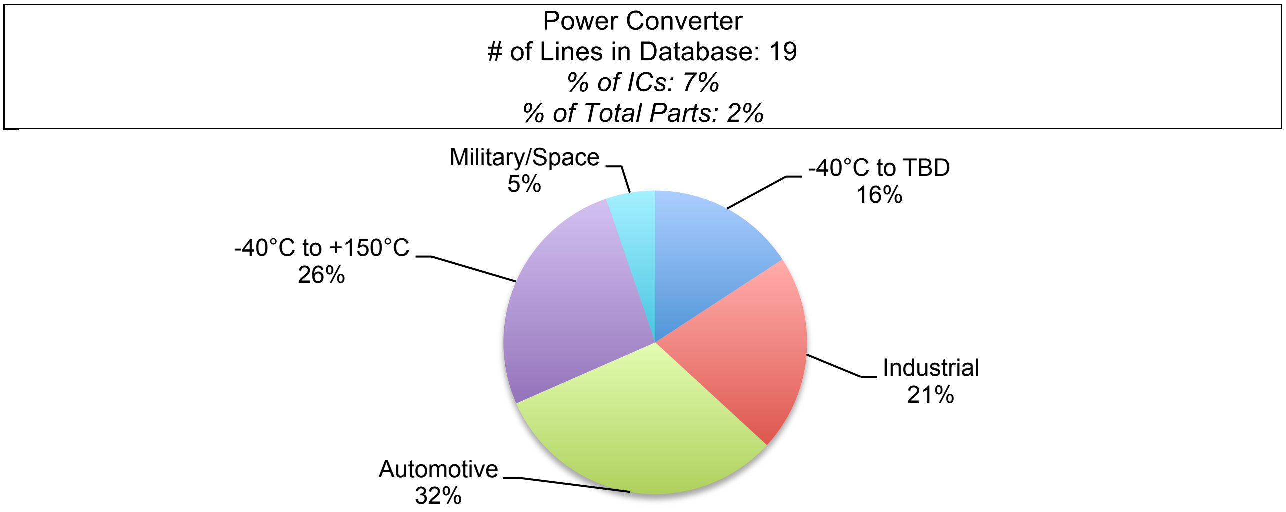

Figure 39. Qualified operating temperature ranges for power converter devices (as reported by the manufacturers).

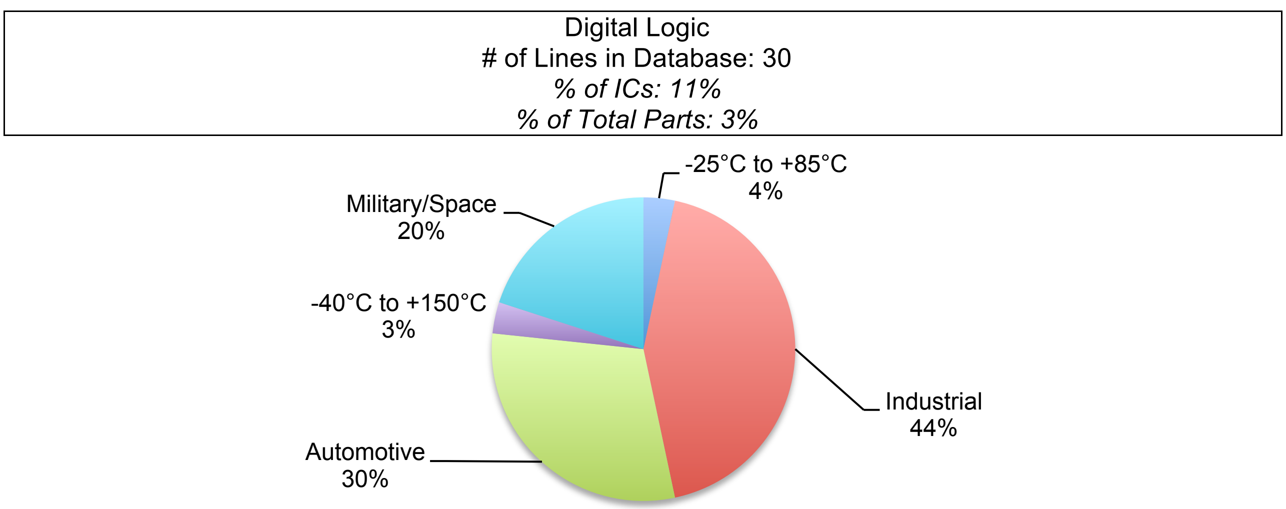

Figure 40. Qualified operating temperature ranges for digital logic devices (as reported by the manufacturers).

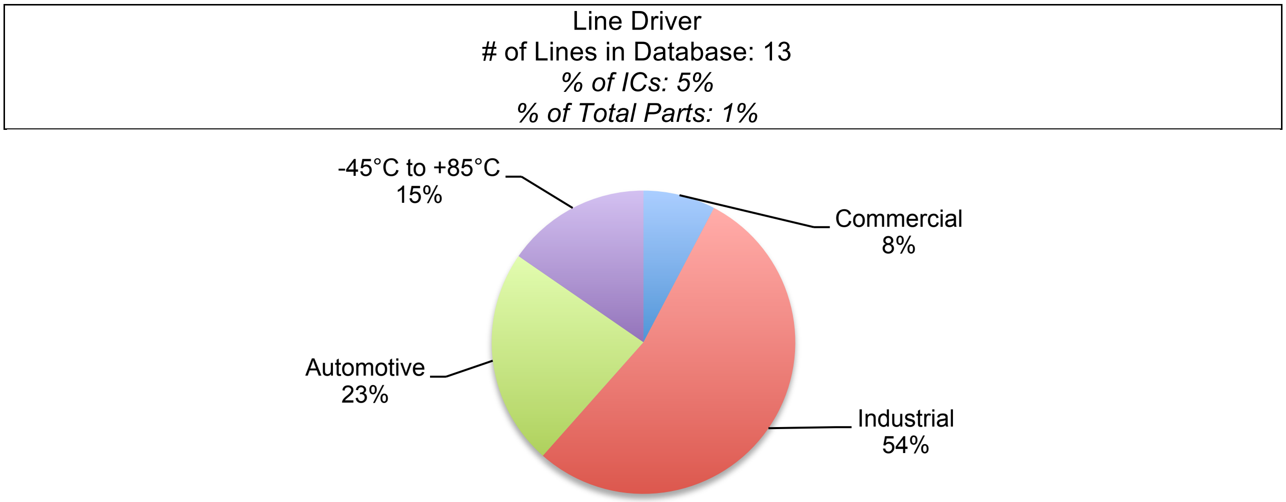

Figure 41. Qualified operating temperature ranges for line driver devices (as reported by the manufacturers).

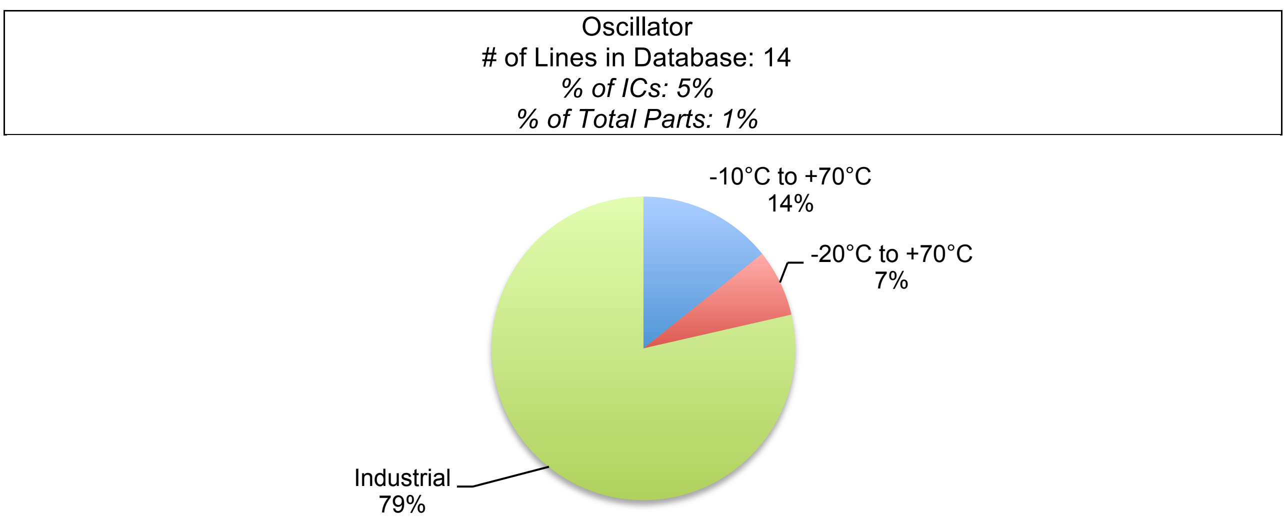

Figure 42. Qualified operating temperature ranges for oscillator devices (as reported by the manufacturers).

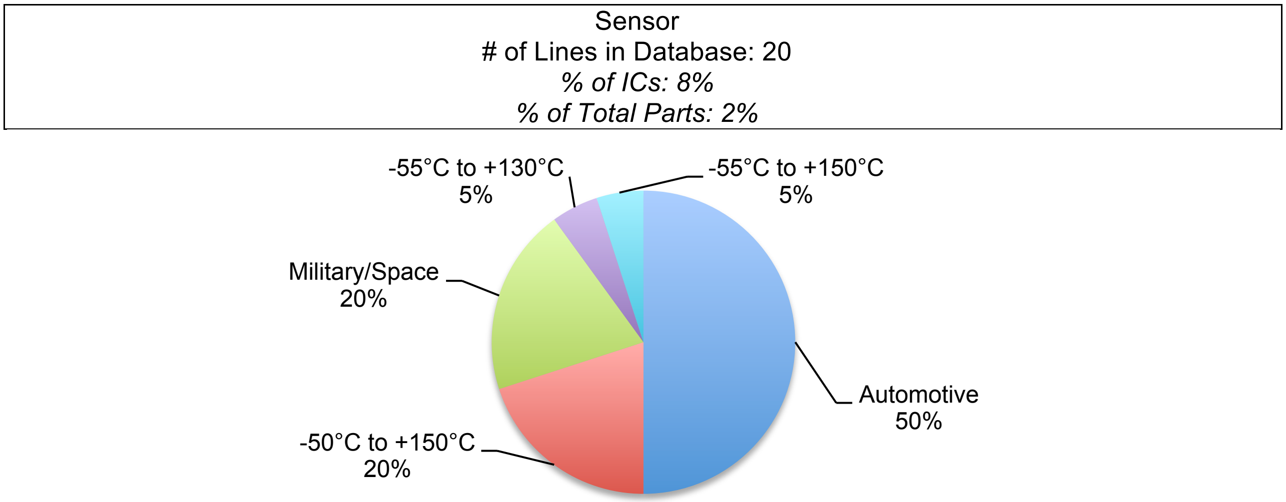

Figure 43. Qualified operating temperature ranges for sensor devices (as reported by the manufacturers).

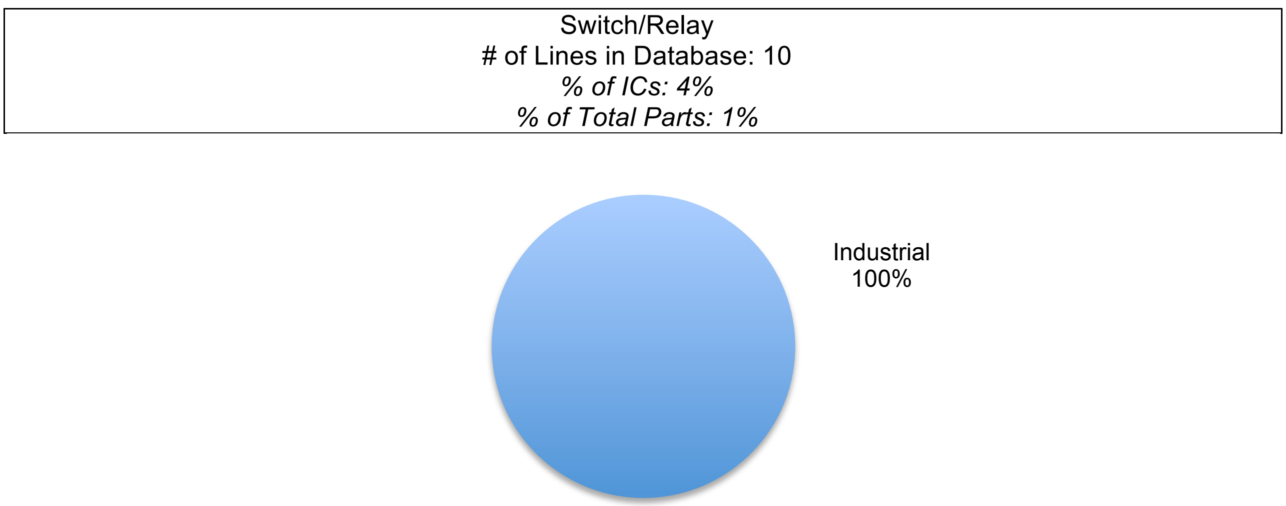

Figure 44. Qualified operating temperature ranges for switch/relay devices (as reported by the manufacturer).

Figures 35-44 indicate that Industrial, Automotive, and Military/Space grade parts represent the majority in each IC subcategory. These graphs also reveal the nuances (+/- 5°C to 25°C) between accepted (i.e., Commercial, Industrial, Extended Industrial, Automotive, Military/Space) and customized temperature ranges.

5. CONCLUSIONS

1. CubeSat suppliers reported that the majority of parts procured are industrial/automotive or commercial grade; a small percentage are space grade. See Figure 2. The NASA CubeSat parts database indicates the majority of parts procured are industrial or automotive grade; a small percentage are military/space grade. See Figure 34.

2. CubeSat suppliers reported procuring a large percentage of parts from distributors. Both CubeSat suppliers and NASA CubeSat projects reported procuring parts from similar distributors, including Arrow, Avnet, Digi-Key, and Mouser. These distributors are large organizations serving global markets.
    a. Arrow and Avnet reported annual sales >$20 billion (Arrow Electronics, 2015) (Avnet, 2015); Digi-Key reported annual sales upward of $1 billion (Digi-Key Electronics, 2015). Mouser Electronics, a subsidiary of Berkshire Hathaway, did not report annual sales on their website.

3. Some CubeSat suppliers reported that they do not inspect for authentic parts, however, many procure from authorized distributors who follow counterfeit part mitigation practices ((ECIA), 2015). Several NASA CubeSat projects also reported that parts are not inspected by a designated inspection group upon receipt. (See Section 3.2 NASA CubeSats: Part and Board/Assembly Procurement Practices.)

4. The degree to which qualification and testing practices are implemented by CubeSat suppliers varies.
    a. All suppliers reported that they perform initial product qualification and many also perform acceptance testing and burn-in.
    b. All suppliers reported that they perform electrical verification of boards, but the data does not indicate the propensity to perform a specific type of testing.
    c. The majority of CubeSat suppliers reported that they perform at least one type of board level radiation testing and one type of analysis to verify part functionality.
    d. The majority of CubeSat suppliers verify EEE components will be used within the specified datasheet and application limits.

5. The data suggests that Supplier B1 and E perform the most extensive suite of tests – both reported that they execute each type of qualification and radiation testing and analysis to verify part functionality. Supplier E was the only supplier that reported performing each type of electrical verification test listed in the question. Supplier B1 was the only supplier that reported performing the most extensive part derating practices where independent analysis is exercised to prove worse case conditions meet derating limits with minimal violation.

6. Suppliers B1 and B2 are the same supplier and furnished two separate questionnaires to reflect their approach towards customers requiring radiation-hardened (e.g., NASA/ESA) versus standard (e.g., small satellite) products. There were several differences observed between Suppliers B1 and B2 with regards to their parts management practices:

a. Supplier B1 reported that they verify all types of part traceability, but Supplier B2 only verifies part number, manufacturer, and lot code. (See 4.1.5 Question #5: Part Traceability.)
b. Supplier B1 verifies that the part markings match received documentation, but Supplier B2 does not perform this verification. (See 4.1.6 Question #6: Part Marking Verification.)
c. Supplier B1 reported that they inspect for authentic parts; Supplier B2 does not perform the inspection. (See 4.1.7 Question #7: Inspection for Authentic Parts.)
d. Supplier B1 reported that they perform each type of qualification testing listed in the question. Supplier B2 responded that they only perform acceptance testing, 100% burn-in on flight devices, and initial product qualification. (See 4.1.10 Question #10: Part Qualification.)
e. Supplier B1 reported that they perform a more extensive suite of electrical verification tests relative to Supplier B2. They perform black box electrical testing, testing at extreme temperatures, temperature cycling with electrical testing at extreme temperatures, and thermal vacuum testing. Supplier B2 reported that they only perform temperature cycling with electrical testing at extreme temperatures and thermal vacuum testing. (See 4.1.11 Question #11: Electrical Verification of Boards.)
f. Supplier B1 reported that they perform all types of board level radiation testing. Supplier B2 only performs proton board testing. (See 4.1.12 Question #12: Board Level Radiation Testing.)
g. Supplier B1 reported that they perform each type of part analysis listed in the question. Supplier B2 reported that they do not analyze parts. (See 4.1.13 Question #13: Analysis of Parts Under Various Thermal Conditions.)
h. Supplier B2 reported that operators are certified to IPC J-STD-001 and the records are maintained. Supplier B1 was unaware if their operators are certified to this standard. (See 4.1.15 Question #15: Operator Soldering Certification.)
i. Supplier B1 reported that BOMs can be furnished to a customer procuring flight boards. Supplier B2 reported that they cannot furnish BOMs for flight boards, but can provide a general parts list. (See 4.1.24 Question #24: Furnishing BOMs for Boards.)

Generally, Supplier B1 appears to perform more tests and take more precautions than Supplier B2. Despite these differences, similarities in Suppliers' B1 and B2 ESD programs/practices were identified. Both suppliers have an established ESD program, test and record wrist strap functionality, and verify relative humidity.

7. The number of "I don't know" responses reported was minimal. This indicates that CubeSat suppliers are aware of their internal practices.

8. Resistors (36%), capacitors (23%), and ICs (24%) represent the majority of component types in the NASA CubeSat parts database. A few manufacturers represent a large percentage of parts in each IC subcategory. In general, Linear Technology (16%), Maxim Integrated (16%), and Texas Instruments (15%) supply the largest percentage of IC components.

9. Operating temperature ranges, as reported on the manufacturers' datasheets, were recorded and seventeen unique ranges were identified. Minor variations (+/- 5°C to 25°C) between accepted temperature ranges and those reported on manufacturers' datasheets were observed. The three grades with greatest representation are Industrial (43%), Automotive (35%), and Military/Space (8%).

6. ACRONYMS AND ABBREVIATIONS

ADC/DAC	Analog to Digital Converter/Digital to Analog Converter
ADCS	Attitude Determination and Control
ASIC	Application-Specific Integrated Circuit
BOM	Bill of Material
C&DH	Command and Data Handling
COTS	Commercial Off-the-shelf
DC	Direct Current
EEE	Electronic, Electrical and Electromechanical
EPROM/EEPROM	Erasable Programmable Read-Only Memory/Electrically Erasable Programmable Read-Only Memory
EPS	Electrical Power System
ESA	European Space Agency
ESD	Electrostatic Discharge
FA	Failure Analysis
FPGA	Field Programmable Gate Array
GPIO	General Purpose Input/Output
GPS	Global Positioning System
IC	Integrated Circuit
IPC J-STD-001	Requirements for Soldered Electrical and Electronic Assemblies
JPL	Jet Propulsion Laboratory
LED	Light-Emitting Diode
MarCO	Mars Cube One
MCU	Microcontroller
MRAM	Magnetoresistive Random-Access Memory
MUX/DEMUX	Multiplexer/Demultiplexer
NASA	National Aeronautics and Space Administration
NEPP	NASA Electronic Parts and Packaging Program
PCM	Power Converter Module
PROM	Programmable Read-Only Memory
PWA	Printed Wiring Assembly
RF	Radio Frequency
RoHS	Restriction of Hazardous Substances
SDRAM	Synchronous Dynamic Random-Access Memory
SRAM	Static Random Access Memory
VCO	Voltage Controlled Oscillator
VLSI	Very Large Scale Integrated Circuit

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Datasheets were collected primarily from EEE part distributor websites, including Digi-Key (www.digikey.com) and Mouser Electronics (www.mouser.com).