Cost Impacts of Upgrading Electronic Parts for Use in NASA Space Flight Systems

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1.0 Abstract

The work presented here provides a cost model to help mission designers and program managers both plan for and manage Electronic, Electrical and Electromechanical (EEE) parts program costs. The data shown below illuminates the “cost of ownership” for EEE parts used in space flight programs and highlights where costs saving strategies are best targeted. The use of post-procurement processing to increase part reliability assurance, or “upgrading”, is driven by the need for state-of-the-art parts with short lead times. This limited and selective use of upgrading will not greatly increase overall project costs. When upgrading is used broadly across the program however, the costs increase dramatically. Background is provided to show how upgrading costs impact projects within NASA’s multi-level parts assurance management system.

2.0 Definitions

NASA: National Aeronautics and Space Administration
EEE Part: Electronic, Electrical and Electromechanical device that is the lowest level of assembly in an electronic system.
EEE Parts Engineering: The engineering discipline associated with the selection, assurance and use of electronic parts in systems.
PPE: Project Parts Engineer. A parts engineer who is assigned to a specific project.
Qualification: The part of the Parts Assurance Program that ensures that a specific part will survive the application environmental and electrical conditions for the life of the mission.
Screening: The part of the Parts Assurance Program that establishes the acceptable performance of the parts and eliminates early life failures from the procurement or production lot. Some screening tests provide conditioning which stabilizes their electrical parameters.
Part Assurance Level: A number, 1, 2 or 3 with 1 being associated with the lowest risk, assigned to a particular EEE part which indicates the amount and type of assurance requirements levied upon it, prior to use in NASA hardware.
Military Class: A specification approach for procurement of high reliability electrical components. Different classes represent different reliability grades where assurance provisions include reliability requirements, in-process controls and monitoring, material inspections and testing.
Upgrading: A practice used to decrease the risk associated with an electronic part through the use of tests and inspections performed by the user or the manufacturer, imposed on the part following completion of all tests and inspections associated with standard processing for that part number.
Maximum Part Ratings: Guaranteed performance limits established by the manufacturer for an electrical part. Ratings define maximum use temperature, maximum bias conditions, timing parameters and other features that define the part’s functional limits.
Derating: Voluntary use of a part at some level lower than its maximum part rating in order to reduce the risk of failure and to prolong the part’s life. By using derated operating conditions an operational safety margin is realized.
Cost of Ownership: Total cost incurred by a project for a particular part. This cost includes screening, qualification, radiation assurance, handling and fall-out costs in addition to the procurement cost. This may be paid in one lump sum at procurement if all performance and assurance requirements are met by the part “off-the-shelf” or the cost is paid over time, after the part has been received, as its performance is being assured through analysis and test by the user.
COTS: Commercial-off-the-Shelf. The performance of COTS parts are guaranteed only against the contents of the vendor’s datasheet and not to a customer controlled specification. In general, COTS parts are intended for the commercial marketplace and terrestrial, non-high reliability applications. For these reasons, special NASA and Military assurance requirements such as lot traceability, lot-based destructive qualification testing and radiation testing are usually not met. *[The Federal Acquisition Regulation defines COTS as: Any item, other than real property, that is of a type customarily used by the general public or by*

non-governmental entities for purposes other than governmental purposes, and has been offered for sale, lease, or license to the general public. See FAR 2.101]

Radiation Effects: Electronic parts used in space flight applications must be verified to be tolerant of the penetration of high energy particles and the accumulation of charge, from the natural space environment. The type of tests used to simulate these effects and to validate a part's susceptibility to failure are called Total Ionizing Dose (TID) for accumulated charge and Single Event Effects (SEE) for particles. Both types of testing involve a variety of test conditions and are looking for more than one failure signature.

Radiation Testing and Hardness: Evaluation of a particular part type for susceptibility to failure and damage by energetic atomic particles of a particular charge and energy level and by accumulation of that charge in the part (the measure of which is the part's Radiation Hardness). Radiation test conditions can be set to observe the point of onset of degradation or failure (test to failure) or can be limited to demonstrate performance within a particular range of energies or accumulated charge, which is of interest to the user. Radiation hardness has been found to be strongly linked to device design and manufacturing processes, so must be established on a lot-by-lot basis for parts whose processing history is not highly controlled or the level of control is not known by the user. Parts which have undergone a significant process change might also need to be re-characterized for their Radiation Hardness.

Die Revision and Die Shrink: Design and fabrication of a semiconductor part that is parametrically identical to a pre-existing part, using a new electrical design, design rules or new materials (revision) or to occupy a smaller area of the wafer (shrink). The effect can be higher yields and faster and lower power performance. Die Revisions and Die Shrinks result in new and unique parts from a parts engineering perspective and usually require full screening, qualification and radiation testing before their risk is understood.

3.0 Background

The National Aeronautics and Space Administration (NASA) continues to seek cost, schedule and performance efficiencies in their flight hardware builds that will enable them to continue providing platforms for scientific study within a fixed budget. These platforms give us data on all manner of knowledge-fronts from monitoring our Earth's ecological health and weather patterns, through gathering data on the origins of the universe. Electronic, Electrical, Electromechanical (EEE) Part management practices have a significant impact on mission success as they are a key part of the many interdependent science, engineering, quality and management processes that make up the larger NASA flight-hardware production process. The EEE part process dovetails with electrical design and subsystem Integration and Test (I&T) and can link quality organizations with production organizations. EEE Parts Engineers provide guidance to electrical designers for the selection, and risk reduction, of the EEE parts to be used based on quality and reliability goals provided by the project management and the quality team. Project Parts Engineers (PPE's) provide analysis and recommendations from the design phase through board qualification and any time after that, when a problem is linked to an electronic part.

3.1 Risk Management and EEE Part Assurance

When a flight project is started by NASA Headquarters the mission will have science goals, a flight profile and launch window, a spacecraft and the science instrument payload. The instruments may be built by the spacecraft provider or may be built by mission partners such as private aerospace companies, the NASA Centers, National and non-profit Research Centers and Universities. The proposals for the mission and the instruments that are generated by these organizations are selected on the basis of the viability of the scientific goals, the science and engineering approach, the management plan, schedule, and cost. The acceptance of a particular level of risk is generally not a key element of the proposal though the expected operating lifetime of the hardware is usually defined.

The concept of various levels of acceptable risk is often defined to payload manufacturers in terms of probabilities of success over 90%. Within this definition one can envision some number of gradations of risk between 10% risk of failure and 0% risk of failure. Within the EEE Parts management lexicon, risk level translates to part assurance Level. The NASA Electronic Parts Assurance Group (NEPAG) defines these assurance levels on their website [1/] and provides a matrix that gives specific examples of US military, European Space Agency, and Japanese Space Agency specified parts that map to the assurance levels.[2/] Level 1 parts are engineered for missions or applications with the lowest tolerance for risk (e.g. mission critical, life support, single-string), and Level 2 parts are engineered for some acceptance of risk. An example given in the website defines medium risk microcircuits as four times less reliable than low risk microcircuits and two times more reliable than high risk ones. The NASA Goddard Space Flight Center (GSFC) document 311 INST-001 "Instructions for EEE Parts Selection, Screening, Qualification and Derating" maps risk Level to specific EEE part assurance requirements. It lists the tests and conditions that must be imposed, on a post-procurement basis, when parts cannot be bought with the required assurance guaranteed. Prohibited materials and lessons learned are also included in the GSFC document and in the NASA Parts Selection List (NPSL, see http://nepp.nasa.gov/npsl/)

In-depth analysis of the 311-INST-001 document and the NEPAG Risk Assessment Matrix shows that there are standard tests used to assure EEE parts in rugged environments. Less obvious though is the use of a variety of approaches for demonstrating that the parts have long life and that the processes used to make them are understood by the manufacturers, are stable and are well controlled for high quality. These details show that there are assurance requirements that can and cannot be met purely through post-procurement testing. In the case of commercial-off-the-shelf (COTS) parts, the technology may not be understood or characterized well enough to allow parts engineers to produce an assurance plan that predictably fails only the weak individuals in the lot and demonstrates the longevity of the good ones, through accelerated aging tests.

Over the past few years NASA has built and flown hardware even more tolerant of risk than those which use Level 2 parts. Level 3 part assurance requirements have arisen to service these higher risk missions. Level 3, as treated in 311-INST-001, looks very much like a COTS part with a very modest amount of post-procurement testing. For clarity, the analysis herein ignores Level 3 and speaks only to Level 1, 2 and COTS grades of parts.

3.2 EEE Part Assurance and Cost Management Strategies

Standardized Level-to-risk language does not generally exist in the other engineering and manufacturing disciplines such as mechanical design, electrical design, propulsion, software production and integration and test. Practices may be used, such as the reduction of redundancy in the electrical design, when risk can be tolerated in the interest of some other advantage such as schedule, cost, weight or volume, however they are not part of the management documentation. The availability of the Level-based EEE part assurance plans allows a project manager, given some coarsely defined risk-tolerance, to instantly map that risk level to a well defined parts program which has well understood cost centers (parts and testing). With the 311-INST-001 tool, project managers can easily see where tests are added or subtracted to manage EEE part risk (up or down). This creates the impression that the EEE parts program can be an "opportunity" area for project cost management and cost reduction.

The purchase cost of EEE parts used in spacecraft can be very high while COTS parts are not so expensive. The cost of a flight model system can come as a shock when the prototype was breadboarded with commercial or industrial grade parts. The delivery lead-time difference can also be staggering. When the PPE converts a breadboard parts list into a flight parts list, the project may comprehend, for the first time, the more realistic costs and schedules associated with high reliability electronic systems. Project managers may only have planned for one or two specialty, high priced items such as detector arrays and laser diodes. The cost of the 300 to 1500 line item flight-grade parts inventory, where some line items cost $100 for 100 pieces while others cost $100,000 for 25 pieces, is far different than the $500 to $1000 spent on the breadboard parts. Design changes necessitated by program changes or system changes downstream can increase the number of parts needed and the associated costs. This may be the first point in the life of the project that the EEE parts costs are rigorously estimated. This is also a point well after the budget has been set.

EEE part procurement is done approximately one third to one half of the way through the hardware delivery cycle. A considerable amount of money has been expended or committed by this time, perhaps through procurements for large items such as radiators, attitude control instruments, lasers and solar arrays. The one to two million dollars typically required for the EEE parts, for an average sized system, can seem a drastic hit to the project if it hasn't been properly planned for, even though this may be a fairly small portion of the overall budget. Program managers know that testing costs and minimum buys can drive up the overall parts costs and may seek ways to leverage their costs against monies spent by other projects to acquire the same parts. Given the right conditions this can be a big budget win, saving a program one or two hundred thousand dollars. Without the right conditions though, the attempts to leverage come up short, leaving the project with assurance issues that may be irresolvable. Examples of this are:

- The part was qualified or used in a very different way (temperature, function, radiation, data records) in the prior application,
- The part has undergone a die revision since its prior use and it is not sufficiently similar to the original with respect to radiation tolerance and functional reliability.

- The spare parts available to the new project from the prior project have become so old that they do not meet the current project's age restrictions.

In these examples the project should rescreen and possibly requalify the parts to mitigate the risks. This extra processing may negate any advantages of using the selected part.

Project managers trying to control costs are also heavily scrutinizing how radiation testing is managed. While radiation experts are finding new failure mechanisms that must be addressed by evaluation due to semiconductor technology changes, projects have a static or shrinking budget for radiation testing. Analysis and leveraging are being considered as alternatives for testing. Short flight project life cycles do not leave a lot of time to perform extensive analysis, followed by testing, with time remaining to start the process over to find an alternate for the "soft" part. This might result in implementation of a non-compliant part which cannot be replaced for schedule, cost or functionality reasons. For this reason, the NEPAG Part Assurance Matrix recommends radiation characterization for all part assurance levels.

Other cost drivers are associated with the state of the art and supply chain issues. Parts may not be available in space grades and electronic die revisions may require that radiation and qualification testing be repeated. The obsolescence of some technologies affects NASA though somewhat less than it does the military. Projects may have to turn to commercial grade parts to find the necessary functionality or use more programmable or application specific chips to work around part obsolescence.

Project managers may try to reduce the cost of parts by accepting more risk of part failure. In this case, the project moves away from Level 1 part programs and toward Level 3 part programs. Projects will define a Level 2+ program for example, where Level 1 parts are bought where they are affordable and available and Level 2 parts are used elsewhere. More problematic is when the same philosophy is used to define a 2- or a 3+ parts program. Unless the project manager is seeking to fulfill requirements for a very short (2 months or less) mission, this second approach can be a false economy.

4.0 NEPAG Cost Model

A model has been developed to quantify the cost of EEE parts as a guide for builders of instruments and spacecraft. Parts lists for hardware built at NASA were reviewed and a composite, representative, list was created as a basis for obtaining overall cost estimates. The costs for post-procurement testing, or “upgrading”, and radiation tests were added to the procurement costs to obtain a "cost of ownership". Three parts assurance Levels were considered: Level 1, Level 2 and COTS. Level 3 was not considered because it is so close to COTS that distinctions became confusing. Cost comparisons were made between the part commodities and the Levels and are shown in the graphs below. The composite parts list consists of components from the four dominant passive commodities and the two active commodities that are shown in Table 1.

Table 1. EEE Part Commodity Categories used in the NEPAG Cost Model

Passives	Actives
Capacitors Resistors Connectors Magnetics	Transistors and Diodes Monolithic and Hybrid Microcircuits

Spacecraft and Instruments use many similar EEE parts however some tend to be unique to Spacecraft; such as those used in the spacecraft power and communications systems. The model includes some of these parts but probably less than a typical Spacecraft would use. In this way, the list is somewhat smaller than a Spacecraft list and somewhat larger than an Instrument list.

Getting representative parts lists can be difficult. Many spacecraft subsystems, especially instruments associated with attitude control, are purchased as "boxes" and integrated into the spacecraft. Rarely are detailed parts lists provided for these, rather a statement of conformance to good flight hardware manufacturing practices is offered. The suppliers of these "off-the-shelf" boxes are not immune to the EEE part assurance and cost dilemmas described above, nor are the boxes immune to failed EEE parts. We do not have enough insight at this time to draw part usage and cost data from these instruments into the model.

4.1 Model Basis – Part Types, Variety of Part Numbers and Numbers of Piece Parts

Table 2 shows the part types chosen to represent the six broad commodity categories. A variety of resistors, capacitors, connectors and magnetic parts were chosen to represent the passive parts. Diodes, transistors, linear and digital microcircuits, and hybrid microcircuits were chosen to represent the active parts. We know that a part type (e.g. film resistor) can come in many different part numbers depending on the value of its performance parameters (e.g. resistance, wattage, temperature coefficient) and the package style. For the purposes of our model these many different part numbers are called "line items". For example, our research indicated that there typically would be 40 different thick film resistor part numbers on the list. This is not to say that there would only be 40 thick film resistors used in the hardware, but that only 40 *different types* would be used. The same has been done for the other commodities in our model.

Table 2. Types of Parts in Each Commodity Area Used to Build the Cost Model

Description	No. of Line Items in Spacecraft/ Instrument Model
Thick film, chip	40
Film, high stability, leaded	100
Film, leaded	50
Fixed, Wire wound	2
HV	3
Resistor network	5
Fixed Carbon	10
Resistor TOTAL	**210**
Capacitor, Tantalum, solid, leaded	10
Capacitor, Tantalum, wet, leaded	5
Capacitor, High Voltage	2
Capacitor, ceramic, chip	10
Capacitor, ceramic, leaded	33
Capacitor, tantalum, chip	6
Capacitor TOTAL	**66**
Connector, submini D	35
Connector, Micro-D	23
Connector, RF	4
Connector, HV	2
Connector, PC board	10
Connector, Circular	4
Connector TOTAL	**78**
Filter	2
Coil	15
MAGNETIC TOTAL	**17**
PASSIVE TOTAL	**371**

Description	No. of Line Items in Spacecraft/ Instrument Model
Switching, small signal	5
Power Rectifier	3
Transorb	1
Zener	8
Transistor, JFET, N-channel	3
Power P-CH Mosfet	2
Power N-CH Mosfet	2
PNP Transistor	5
NPN Transistor	5
Discrete Semiconductor	**34**
Prom-rad hard	1
SRAM- rad hard	1
Transceiver	1
Microcircuit, Voltage Reference, programmable	2
128Kx8 EEPROM	1
Quad Receiver/Driver	4
Dual Low Power Op Amp	10
4 Bit Up/Dn Counter (discrete logic)	10
DAC	1
ADC	1
Voltage reference	2
MUX	2
Microcontroller	1
Analog Switch	5
Charge sensitive preamplifier	1
DC/DC Converter	6
FPGA	1
MICROCIRCUIT TOTAL	**50**
ACTIVES TOTAL	**84**

Starting with the selected types of parts and number of line items in each part area, consideration was made regarding the number of pieces used in each commodity and subcategory. Figure 1 shows how many individual part numbers are in the model by commodity area and Figure 2 shows the number of piece parts by commodity. This model assumes 455 line items and 3136 individual parts (piece parts). The results show that of the total number of individual piece parts accounted for, 92% are passive and the remaining 8% are actives. Eighty percent of the line items are passives and 20% of the line items are actives. From a part count perspective, the passive parts bring far more risk to the system than the active parts do.

Figure 1. Number of Line Items (individual part numbers) by Commodity

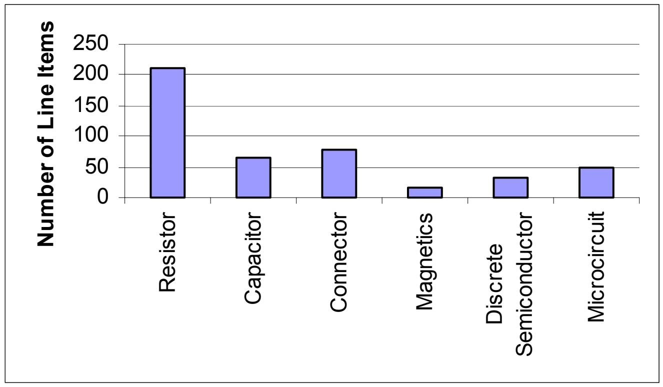
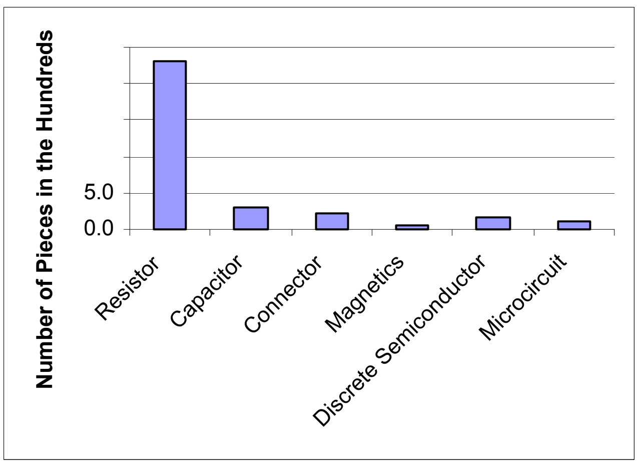
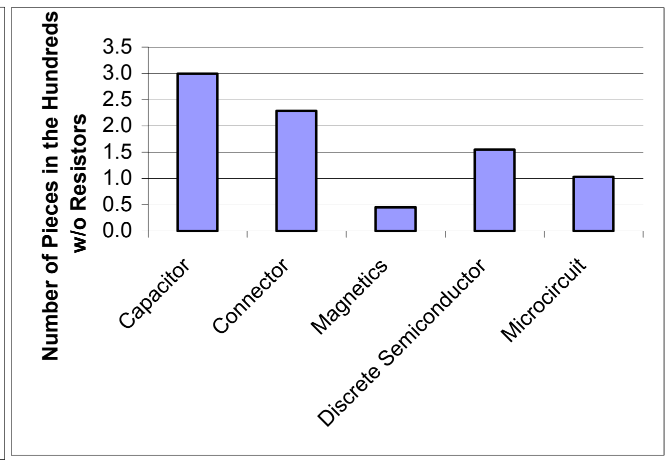


Figure 2. The Number of Piece Parts by Commodity





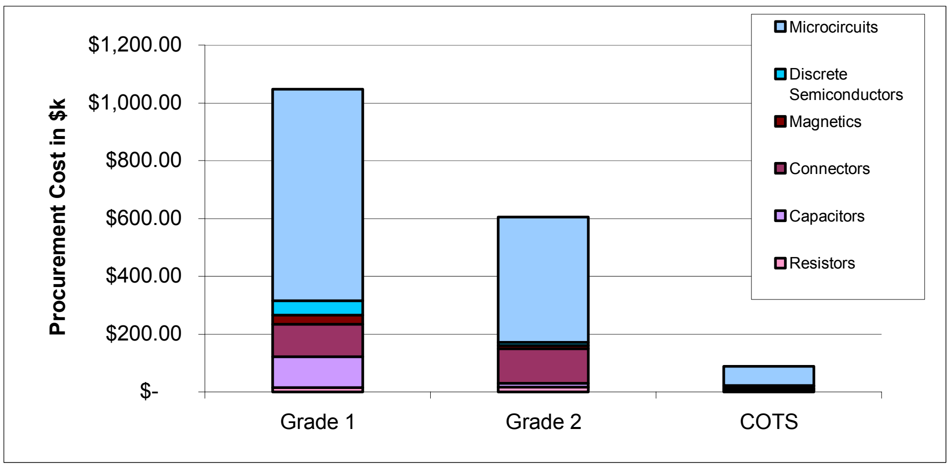
4.2 Procurement Costs

The cost of the parts in the model was researched by reliability grade. The cost of the part might be determined by the cost of one piece multiplied by the number of pieces needed, however this generally does not occur in real procurement situations. A minimum purchase is often required. Also, quantities are usually required for multiple builds (engineering model, flight model), for spares and for test and evaluation samples. The minimum buy quantity will depend on the part type, its complexity, existing stock, how often the part is manufactured, the size of the production runs, the anticipated market and so on.

Minimum buys vary by part type and grade; 100 pieces for resistors and 25 pieces for microcircuits, for example. This model used a minimum buy of 10 for parts that are sold individually and used the vendor's minimum buy quantity when one was quoted that was higher than 10 pieces. In some cases, lower reliability parts were found to cost more than higher reliability parts because the minimum buys were much higher for the commercial parts; tens of pieces versus hundreds or thousands of pieces.

The results of the procurement cost analysis for Grade 1, Grade 2 and COTS parts are shown below in Figure 3 in thousands of dollars. The model shows that while the number of line items is dominated by the passives, the cost is driven more by the actives, specifically the microcircuits. Measured by procurement cost, the actives account for ~75% of the total regardless of the assurance Level. When broken down within the actives to the commodity level, it can be seen that the majority of the cost is coming from the microcircuits. This suggests that cost/reliability trade-offs should be focused on the fewer, cost driving line items; the microcircuits.

Figure 3. Cost of Procurement by Part Level



4.3 Upgrading Costs

The research showed, though not detailed here, that there is a large and relatively ready supply of Grade 1 and Grade 2 passives on the market. This is especially applicable to capacitors and resistors and less so for connectors and magnetic devices. Where Grade 1 and Grade 2 product is not available "off-the-shelf", post processing or additional testing must be done on lower Level parts. It can be performed by the manufacturer in accordance with the customer's specification or by the customers themselves. In either case this additional processing adds a substantial layer of cost to the procurement figures shown above. This post processing, called upgrading, can include management planning, engineering of test plans, test fixture development and manufacturing, test execution, data reduction and inventory management. The types of testing included in upgrading are electrical verification measurements, environmental stress screening, sample-based qualification testing, long-term aging or life testing and destructive physical analysis (DPA). Radiation hardness testing is also part of upgrading but is treated here as a separate cost factor because so many of the actives are no longer available as radiation hard devices "off-the-shelf". Radiation testing costs are considered not to apply to passive parts at all. Upgrading costs have been named by original equipment manufacturers as the most expensive part of the space EEE part budget.

Table 3 shows the cost elements of upgrading that are considered in the model. The costs in this table are *per production lot* and are based on estimates provided by a NASA in-house test facility and quotes received from private test laboratories. The commodities are each tested in different ways due to many factors including their critical electrical parameters, the physics of their operation and failure modes, and their packaging design and materials. Non-recurring engineering costs (NRE), which include sockets, test boards, travelers, and software programs, are generally higher for microcircuits than for the passive part types. This is because microcircuit technology is changing very rapidly, expanding the need for unique test hardware and test vectors (software). The NRE charges shown in the table below should be considered estimates of the minimum that would apply. NRE charges of $100,000 per lot have been quoted to NASA for complex microcircuits. An American Competitiveness Institute study reports NRE's between $2,750 and $770,000 per part lot for microcircuits[3/]. Additional procurement costs result from the need to plan for screening fallout.

Table 3. Cost Elements for Upgrading (Per Part Lot)

	Electrical	Environmental	DPA	Other direct costs (NRE)	Total Cost for COTS --> 2	Total Cost for Grade 2 --> 2+
Resistors	$1,875	$2,250	$1,125	$2,000	$7,250	$5,000
Capacitors	$1,875	$2,250	$1,125	$2,000	$7,250	$5,000
Magnetics	$3,000	$3,000	$1,875	$2,000	$9,875	$6,875
Connectors	$600	$600	$900	$2,000	$4,100	$3,500
Discrete Semiconductors	$2,250	$1,500	$1,800	$3,000	$8,550	$7,050
Microcircuits	$3,000	$1,500	$2,700	$6,000	$13,200	$11,700

The model assumes that the Environmental tests (large numbers of thermal cycles, moisture, vibration, shock, etc.) are not needed for upgrading Level 2 parts for Level 1 missions. It is more useful to characterize the electrical distribution of the Level 2 part lot and to look at the quality through DPA. All tests would be necessary for COTS-to-Level 2 upgrading because the manufacturer generally does not perform lot-based electrical and environmental testing. Level 2 parts upgraded for use in Level 1 missions are called Level 2+ parts because Level 1 parts achieve their high reliability through stringent raw material control, manufacturing process controls, wafer-level and pre-encapsulation inspections and life testing with statistics-based sample sizes that correlate to failure rate levels of 0.001 parts per million. This type of reliability cannot be achieved through upgrading.

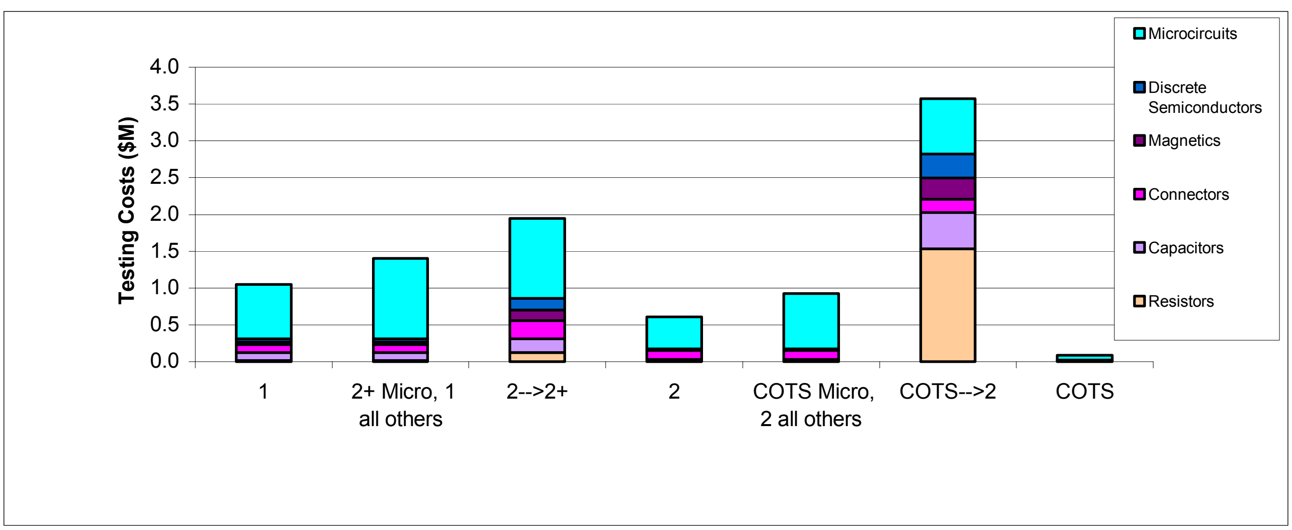
The testing costs model assumes that when using COTS parts, *all* of the part types would need upgrading to be used in a Level 2 program while less than 100% of Level 2 line items would need upgrade testing when they are processed for use in Level 1 missions. This is because in practice some line items are simultaneously Level 1 and Level 2-ready and are not sold as only one or the other. Table 4 shows the percentages of line items in our model that would need Level 2- to- Level 2+ upgrade testing for use in a Level 1 program.

Table 4. Percentage of Line Items That Would Be Tested When Upgrading

		2-->2+	COTS-->2
		No. of Line Items Needing Testing for Upgrading	
	Number of Line Items	Electrical and DPA	Electrical, Environmental and DPA
Resistors	210	10%	100%
Capacitors	66	50%	100%
Connectors	78	50%	100%
Magnetics	17	90%	100%
Discrete Semiconductors	34	50%	100%
Microcircuits	50	60%	100%

Figure 4 shows the cost of ownership (initial procurement + procurement for destruct samples and screening fallout + upgrading testing) for COTS parts upgraded for use in a Level 2 program, compared to their original cost and compared to the cost of the Level 2 equivalents. It also shows the cost of the Level 2 parts upgraded for Level 1 use compared to their Level 1 equivalents. The effect of the upgrading testing is an increase in cost over the cost of the Level of part that is needed. It is 1.8 times more expensive to upgrade Level 2 parts for Level 1 (2+) applications and 5.9 times more expensive to upgrade COTS parts for Level 2 use, rather than buying the Level-ready parts. This increase translates to $900,000 for the Level 2 to 2+ scenario and $3.7 million for the COTS to Level 2 scenario.

Figure 4. Cost of Parts with Upgrading Testing Costs Added to the Procurement Costs



Earlier it was shown that the passive parts do not account for the majority of the procurement cost and are generally widely available as Level 1 and 2 parts. When only the microcircuits are upgraded and all of the other parts are bought “Level-ready”, the total costs come significantly closer to the costs of the target Level and are more affordable than for upgrading all of the parts. In no case are upgraded parts less expensive than “Level-ready” parts. Upgrading should only be done when lead-time and functionality preclude buying the “Level-ready” equivalent. This shows that buying “Level-ready” parts where available and using upgrading judiciously, the PPE can better align the part program practices with the assurance, cost, schedule and technology needs of the program. Efforts which increase ready access to “Level-ready” material should be supported (mass buys, new technology qualifications, vendor inspections) to help reduce part costs.

4.4 Radiation Cost Factors

Radiation testing requirements are very closely tied to the mission environment, which is related to the orbit (or mission path for deep space missions), the galactic calendar, the solar cycle, the mission duration, the shielding provided by the spacecraft design, and the spacecraft propulsion system. Further, the technology and design of the device may require more or less radiation testing. For the purposes of this model a single cost was assigned, , for testing a lot of parts for Total Ionizing Dose (TID) hardness and for Single Event Effects (SEE), though several tests apply to the SEE category. These costs, shown in Table 5, are per lot and were estimated based on NASA project experience using an in-house engineering group and in-house and out-of-house facilities. These numbers were determined to be reasonable estimates for the purposes of this analysis, by NASA radiation effects specialists though another source estimates a much higher cost for SEE testing ($47,000 to $77,000 per lot)[3/]. There is no difference between the costs assumed for radiation testing of Grade 1, Grade 2 or COTS parts, although, the greater functionality and complexity inherent in most COTS active parts are likely to make them more expensive to test.

Table 5. Costs for Radiation Testing Used in the Model

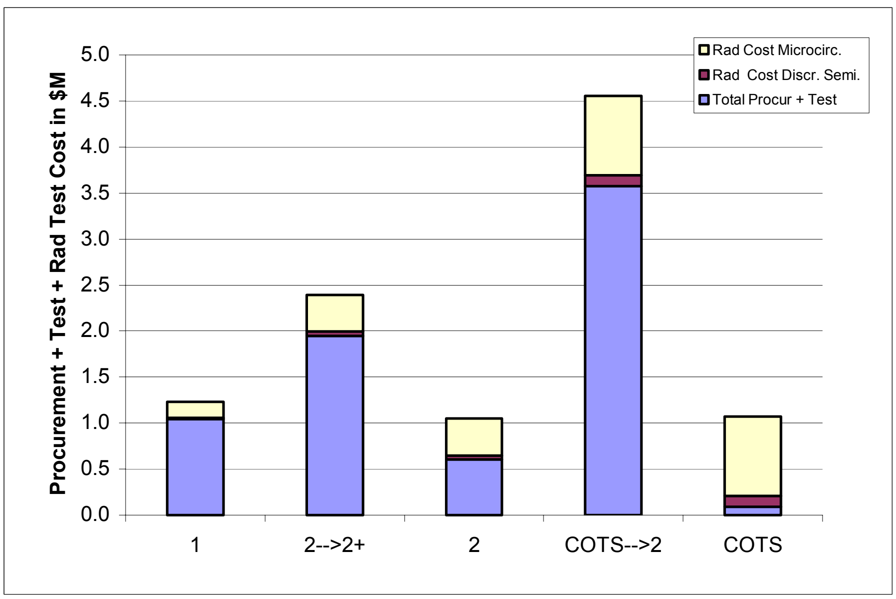
	Cost of TID Testing	Cost of SEE Testing
Discrete Semiconductors	$5,000.00	$15,000.00
Microcircuits	$10,000.00	$35,000.00

Radiation testing only applies to the active components, which are the discrete semiconductors and microcircuits. Not every active part needs to be radiation tested. Some parts do not need testing because the semiconductor technology is well understood and characterized through prior testing and use. This knowledge may indicate that the part is radiation tolerant enough for the application or that its degradation mechanism is tolerable in the circuit. This prior knowledge will not apply to COTS parts to the same degree, as they are generally considered to be very dynamic from a design, process and production lot standpoint; all key factors which affect radiation tolerance. Estimates were made for the percentage of the total number of line items that would need single event effects and total ionizing dose testing and are shown as percentages in Table 6. Figure 5 shows the costs of the radiation testing added to the procurement costs and the upgrading costs. Figure 5 represents the full cost of ownership of the parts.

Table 6. Percentage of Parts Needing Radiation Testing

	Grade 1		2-->2+		Grade 2		COTS-->2		COTS	
	TID	SEE	TID	SEE	TID	SEE	TID	SEE	TID	SEE
Discrete Semiconductors	0%	2%	5%	7%	5%	7%	10%	20%	10%	20%
Microcircuits	0%	10%	10%	20%	10%	20%	50%	35%	50%	35%

Figure 5. Added Costs of Radiation Testing on Top of Procurement and Upgrading Costs



5.0 Summary

EEE Parts Engineering provides critical functions to NASA's flight hardware production process. A unique aspect of this engineering discipline is that there are defined parts program practices that map to programmatic-level risk acceptance. These practices define distinct levels of risk; very low for screened, qualified, radiation tested, and user specified parts to very high or unknown for unscreened, unqualified and non radiation characterized COTS parts. The cost and availability of the parts varies widely among the assurance Levels and the part types, making cost management strategies difficult to identify. Aspects such as part technology, maturity, commercial marketability and assurance pedigree will impact the procurement costs. Minimum buy restrictions can have significant impacts on overall procurement spending.

Attempts to improve part availability (performance features and lead time) have project managers to turning to the use of upgrade testing on parts with a lower assurance Level rather than waiting to get the higher assurance part, paying high procurement costs for the higher assurance parts, or designing around the part with more advanced performance but with lower assurance. Upgrading testing consists of screening and qualification testing that is done on a lot basis after part procurement. Radiation testing is always required where data does not already exist and can be independent of an upgrading effort. The procurement cost, the upgrading costs and the radiation costs represent the full "cost of ownership" for the part lot.

A model was put together to show the cost impacts associated with upgrading and radiation testing and to illuminate areas where upgrading may be most beneficial. Six commodity areas were chosen to represent the typical mix of parts on a flight instrument or spacecraft parts list. Research of real parts lists were used to build the model with 455 unique part numbers (spread over the 6 commodities) representing 3136 individual piece parts. The breakdown reflected a 80% to 20% passives to actives distribution by unique part number (91% to 8% by piece part) while about 75% of the overall procurement costs are for the active parts, specifically the microcircuits. This is independent of assurance Level. Though the model does not address it, the research indicated that in general, the passive parts are readily available at the highest assurance level further reducing the motivation to apply upgrading to the passive parts.

Upgrade testing and its associated cost, varies by part type and assurance level. Upgrading to assurance Level 1 cannot be achieved however assurance of Level 2 parts can be raised through testing to enable their use in Level 1 applications. Technology knowledge may limit the ability to upgrade COTS parts. The model defines upgrading costs by commodity, and with respect to the starting and ending assurance level. Not every lot will need the upgrading testing or radiation testing. The model shows that upgrading costs $900,000 for the Level 2 to 2+ scenario and $3.7 million for the COTS to Level 2 scenario. This is 1.5 times more expensive than buying Level 1-ready parts and 5.8 times more expensive than buying Level 2-ready parts, respectively. When only the microcircuits are upgraded (Level 2 procurement cost and 2-→ 2+ testing costs), the total costs look very similar to the costs of buying all of the parts at the target assurance Level. The costs are never less than the "Level-ready" part when upgrading is used to achieve a better assurance level.

Radiation analysis and testing is a post-procurement cost and part of the total "cost of ownership". Prior technology and part knowledge will reduce the need to do some radiation testing on Level 1 and Level 2 parts but will not be applicable to COTS parts. The need for radiation testing is generally independent of assurance Level. Radiation testing can increase the cost of ownership by 17% (Level 1) to 1100% (COTS).

For our cost model developed here, the parts program will cost between $1.0M and $1.5M when all of the parts can be bought "Level-ready" and the needed radiation testing is done. Where upgrading is required, the costs can climb toward $4.5M.

It should be noted that this paper has discussed the cost of upgrading. This is frequently confused with uprating which is the process to enable the use of a part outside its rating envelope. Uprating is out of scope for this paper.

6.0 Conclusions

The parts program is a critical part of the production process for space flight hardware. When planning for the associated costs, **it is important to calculate the Total Cost of Ownership** of the parts, which consists of the procurement cost and the costs associated with upgrading. The cost of upgrading is weighted by commodity type, the cost of testing, (and associated NRE and labor costs), and the cost of part fallout.

When considered by part count only, the passive parts can be considered the higher risk commodity from a system perspective. From a cost perspective, their availability in high reliability styles, with no need for upgrading, reduces their effect on the overall assurance cost to the parts program. There is **little cost or assurance benefit to procuring passive parts with low assurance and using upgrading to increase their assurance level. This applies to discrete semiconductors** as well.

Upgrading is costly. Upgrading should only be done when lead-time and functionality preclude buying the "Level-ready" equivalent. **Cost benefits typically associated with COTS can only be realized if they do not require upgrading or radiation characterization. Cost leveraging is generally not available for COTS because radiation testing and qualification tests are performed on a Lot-by-Lot basis for COTS.** Efforts which increase ready access to "Level-ready" material should be supported (mass buys, new technology qualifications, vendor inspections).

We do not propose ignoring the great potential offered by new technology and COTS, though a "wise-use" strategy is necessary. **For routine circuit functions, Level 1 and 2 ready parts should be used.** Where those functions are critical, Level 1 parts should be selected. **COTS should be used where their state-of-the-art size, weight, speed, memory and other performance characteristics are essential to the mission or when critical schedules drive their use.**

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