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Telemetry and H-Gear Engineering Hardware Design and Delivery Standards

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ABSTRACT

Telemetry and H-Gear Engineering, Org. 8430, is frequently required to design, manufacture, test, and deliver products directly to flight tests and important ground tests. Due to schedule or budget constraints, these deliveries often cannot follow the full product acceptance process laid out in Sandia's Realize Product Processes. Telemetry and H-Gear Engineering therefore created tailored quality expectations and outputs for products that fall into this category. This document describes these quality requirements and the reasons they have been put in place.

ACKNOWLEDGEMENTS

The author wishes to thank Woodsy Owl, the feathery mascot of the U.S. Forest Service and a beacon of clarity for this effort. Woodsy is the model you, the reader, should channel as you consider hardware quality standards. While the pages that follow lay out reasonable, verifiable expectations, a qualifying prerequisite to delivering quality hardware is *GIVING A HOOT*. One must want their name associated with the product and be personally invested in the standards of excellence brought to bear in its design, qualification, and acceptance. The rest is just wrapping that personal accountability in a fortune cookie with which management can identify and validate.

CGP Grey also deserves a shout out for (unknowingly) allowing the author to steal his stick-figure awesomeness.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AEA	Atomic Energy Act (of 1947)
AM	Control Program (yep, AM = control program; this is not a typo – T030 rules!)
AT	Executable Program
BDR	Baseline Design Review
CD	Compatibility Document
CRR	Component Requirements Review
DER	Development Engineering Release
DPBPS	Defense Programs Business Process System
EA	Engineering Authorization
ES	Environmental Specification
ESD	Electrostatic Discharge
ETU	Environmental Test Units
HDP	Hardware Data Package
IC	Integrated Circuit
IER	Information Engineering Release
IPL	Integrated Product List
JTA	Joint Test Assembly
KCNSC	Kansas City National Security Campus (formerly KCP or Kansas City Plant)
MDM	Micro D-Subminiature (Connector)
ME	Mechanical Envelope
MP	Maintenance Procedure
NIST	National Institute of Standards and Technology
NW	Nuclear Weapon
PS	Product Specification
PSL	Primary Standards Lab
PWA	Printed Wiring Assembly
PWB	Printed Wiring Board
QER	Qualification Engineer Release
RPSS	Realize Product Sub System
RQ	Requirements Map
SD	Software Document
SNL	Sandia National Laboratory
SR	Software Requirements

Abbreviation	Definition
SS	Specific Use Specification
SXR	Special Exception Engineering Release
TBD	To-be-defined
TBR	To-be-resolved
TLDR	Too Long – Didn't Read
TK	Test Plan
WR	War Reserve

1. INTRODUCTION

Congratulations! You have [maybe] willingly accepted a role that will yield Telemetry or H-Gear hardware to a development flight test or important ground test. This role separates you, as Theodore Roosevelt once said, from the cold and timid souls who know neither victory nor defeat. Unfortunately, it also means the hardware you and your team will deliver requires some traceable rigor to [hopefully] ensure you realize more victory than defeat.

Figure 1: Thumbs up to you, hardware engineer. And remember, don't panic!

[Please read the following paragraph using the voice typically associated with legal copy that ends a pharmaceutical advert] Sandia has well-defined requirements on the rigor it brings to bear on nuclear weapons programs, and those requirements are meticulously codified by the RPSS and DPBPS documentation [1] [2]. Adherence to this standard is indeed the full expectation for our JTA and production H-Gear programs and to which our customers/management hold us accountable. However, for products that must deliver prior to the completion of the full process (e.g. development flight tests) and/or those where our SNL team is the production agency (e.g. non-JTA designs like ETUs), a tailored set of quality standards is both reasonable and necessary.

Management conceived this document with the lusty belief that it could collect our tailored set of expectations. Specifically, the document aims to:

- Identify the areas management feels each product team shall address prior to shipping a piece of hardware to a flight test or important ground test
- Present a standard in each of these areas that is achievable now given the resources available to 8430 personnel, common staffing levels for our products, and standard schedules/timeframes[1]
- Clarify to product teams why these quality steps enable successful product deliveries

If you happen to be a crusty, cynical veteran of product development like the author, you may have already rolled your eyes at the depth of the premise and the unlikely odds this document will succeed in changing your behavior. And your skepticism is justifiable as it was likely born from being force-fed other vague documents with similar intentions. Why will this document succeed in helping where others have failed? Two potential reasons are presented. The first is style. Even the newest- of new-hires has likely noticed through ~470 words that this document was written to both engage and entertain. The second, and likely more important, is that it will have stick figure drawings throughout reminding you, à la Douglass Adams, not to panic.

Now that your full faith and credit have been invested in reading more, let us discuss organization and scope. Several man-years were spent[2] developing the four rigor buckets [trademark pending[2]]

[1] Wow – you read footnotes too! You clearly have the type of attention to detail that will make you successful in a hardware role. Please note that the purpose of the standards laid out here is, if you happen not to have your own set of brilliant ideas on how to address a given area, to save you the mental real estate and time of developing one. Should you already be prancing down a fruitful field of excellence in any of the areas outlined, please continue and consider sharing your improved standards with everyone by amending this document. The author will not be offended – I promise!

[2] False statement included for humoristic intent (i.e., a joke)

enumerated in Figure 2 that will systematize this document. Let us now dive into each bucket individually.

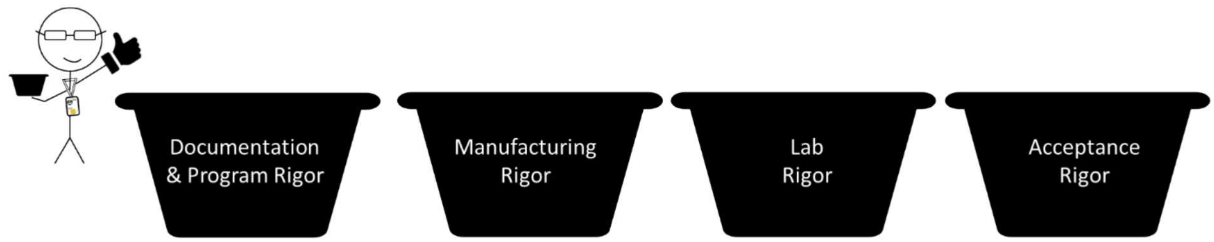

Figure 2: Rigor Buckets. A little panic may now be warranted.

2. DOCUMENTATION AND PROGRAM RIGOR

Consider the following thought experiment: if someone handed you data, told you it was critical to the development or qualification of a nuclear weapon or NW component, and said you should trust it, would you? Of course not! You are an engineer, capable of inventing what-if scenarios even internet conspiracy theorists find thin. You'd first want to know all kinds of salient details about the data, most principally the nitty-gritties of the instrumentation system that collected the data. And when none of those details are documented, you'd conclude the data is as worthless and untrustworthy as the people who developed it. Given that completely non-hyperbolic scenario and the fact we make instrumentation systems for a living, documentation and some control over the process by which we developed the hardware seems a necessary element of any shippable system.

Maintaining our "things that hold water" metaphor, nestled inside the Documentation and Program Rigor bucket are four pails for comparison [the puns start now and, yes, they will get worse]: requirements, product definition, proof, and oversight.

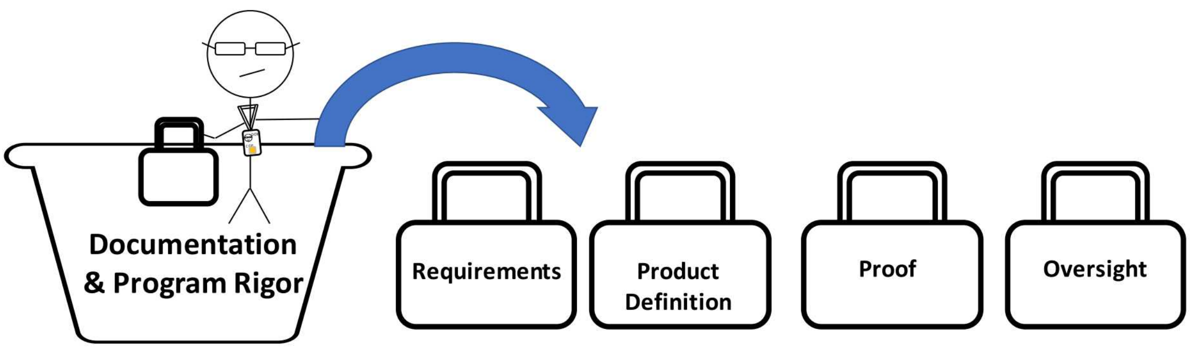

Figure 3: The Four Pails that hold the waters of Documentation and Program Rigor

2.1. Requirements

If requirements are the chicken, and the product is the egg, which came first? Most of our professional experience tells us the egg almost always comes first. And whether you started your development with thoughtful requirements or not, the first tailored expectation is that, prior to shipping product to a flight test or meaningful ground test, your requirements are WRITTEN DOWN AND RELEASED IN PRIME OR PDMLINK.

Why? Regardless of when you got your requirements relative to when you designed the hardware, the expected functions for the product must be documented in writing somewhere and be recorded before the product ships. Not doing so means you have nothing to document what the product is supposed to do nor any basis to show your testing sufficiently proved the product meets its intended function. Someone must write down the requirements that need to be verified and then publish them in a version-controlled, SNL archive so everyone can find them and know to which version the product was built. This is basic. Think Nike – Just Do It!

Reading every word in the CD, ME, and ES is an excellent way to evaluate your requirements; the author truly recommends it. But that's a lot to ask from your management and review panels [CDs aren't exactly paced like *The DaVinci Code*]. There needs to be some way of tracking the stability and thoroughness of the requirements over time and communicating that in an executive summary to management. The best we've come up with is to simply track the number of requirements and the number of TBDs/TBRs in the CD over time. The general time history shown in Figure 4 should be observed; requirements should increase and then stabilize near a reasonable limit as the TBDs/TBRs decrease.

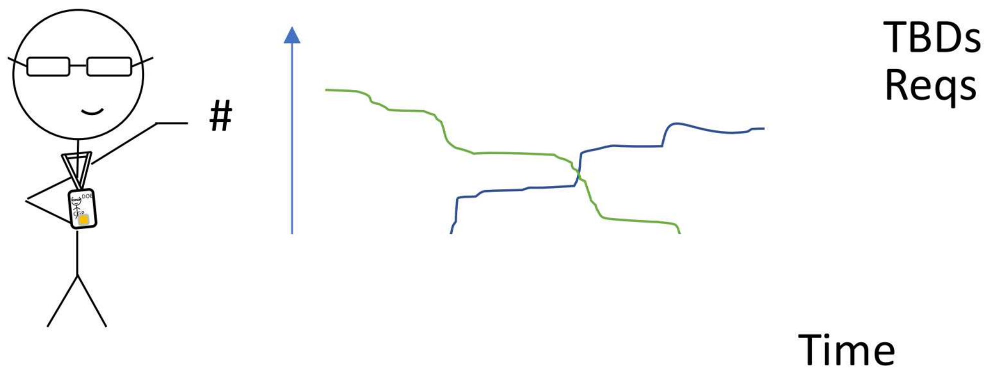

Figure 4: Expected Requirements and TBR/TBD Time History

Why? It is difficult to envision how a team could have a full handle on their requirements, to the point where they can deliver product to them, if they don't even know how many they have and how many are awaiting input (i.e. TBDs and TBRs). And, after several years of tracking the total number of requirements across our programs, we tend to find that JTA programs have between 125 and 200 requirements, and one-off TM programs have between 50-125 requirements. If your TM program has less than 50 requirements, expect a more thorough review of your CD because it's likely incomplete. If your program has over 200 requirements, you should be commended on your thoroughness but watch your schedule when you go to test, validate, and document all those requirements.

Tracking TBRs and TBDs should be a no-brainer as each TBR and TBD should have a burn-down plan that shows someone working the issue to come up with the missing information. While that is happening, each TBD/TBR should have the "as-worked-to" or "best-estimate" values, assumed by the product team, documented in the CD. If you have TBRs/TBDs and no one is working them, the requested graph will show the lack of TBR/TBD attention and management can respond.

In short, this is a cheap way of evaluating the state of the requirements with decent rules of thumb to determine if additional digging is required.

2.2. Product Definition

Product definition is tedious, time-consuming, and, yet, fundamental. A product is about to be shipped and used in a meaningful way – some set of documents should define every part that is in it and how it was put together. And that's the standard we should apply. Ask yourself the following question: could I give my drawing package, as archived in Prime or PDMLink, to another qualified Sandian and expect him or her to make an exact copy of the hardware I am shipping? If the answer is no, you fail! Visualize-management-drawing-a-big-red-"F"-on-your-term-paper fail! You don't want that, right?

Now, most of us get the big stuff, like the schematic(s), documented exactly, but can your product definition answer yes to each of these questions?

- Are all drawing notes accurate (i.e. not just boilerplate that drafting threw on there from something Jill Wang wrote in 2016), and do the drawings faithfully represent how the product was built?
- Does the bill of materials on any PWA IPL include the exact electrical parts used, especially resistors, capacitors, the as-used temperature- or performance-grade of the ICs, etc.?
- Is the procedure used to assembly the product documented somewhere (like in an SS or inside the TK)? Does this include torque specs, Loctite application, potting or conformal coating specifications, etc.?
- Is all firmware (both the executable, AT, and the source code, AM) archived in Prime or PDMLink as well?
- Is there an HDP[3], DER, or IER that specifies the entire product definition (i.e. a list of all product drawings and support documents), and are all "redlines" or exceptions to the product definition built into the delivery unit(s) documented somewhere (e.g. a SXR or in the HDP)?

Expect management to use the questions above to probe the thoroughness of your product definition. Why? I'm not even going to write a why. You shouldn't have to ask.

2.3. Proof

Two things are required to prove the product definition you've taken great care to document meets the requirements you have painstakingly counted and tracked: TKs and RQ(s). Test plans and a requirements map are like peanut butter and chocolate – they are a SO MUCH BETTER together. Test plans without a requirements map mean you can't identify gaps or untested requirements; a requirements map without test plans is massively incomplete. Completed TKs and an RQ, released in PDMLink and Prime, is therefore a required element of our tailored quality rigor.

How will management evaluate the thoroughness of the TKs and RQ even if they can't read every word of them? [By the way – great question! I can tell you are recognizing patterns in the systematic chaos of this document now.] The first method is by a quantitative assessment of your RQ. The product team should create a pie chart, like the one in Figure 5, summarizing the number of requirements by verification method (e.g. test, analysis, inspection, verification/simulation, not met, etc.). Here again general rules of thumb can be applied based on historical reference. If 60-80% of your requirements are verified via testing, you have reasonably thorough test plans. If you have greater than 80% of your requirements verified via testing, you have very thorough test plans and must have paid careful attention to the way requirements were written (such that they could be tested); this is worthy of praise and, frankly, some healthy managerial skepticism that things were done correctly. And finally, if you have less than 60% of your requirements verified via testing, your

[3] What's an HDP? The Hardware Data Package is a non-EA/T030 document, typically formatted and distributed by your customer, that acts as both a CER/DER/IER and SXR. In other words, it documents exactly what you are delivering if the traditional documentation isn't ready yet. This includes to what drawings the delivery unit conforms, if there are any undocumented changes that have been made (e.g. white wires, rework, changed resistors values, different screws, etc.), and if any requirements are not met by the as-delivered design.

test plans and/or requirements should be reconsidered since that is, based on previous programs, less than adequate test coverage.

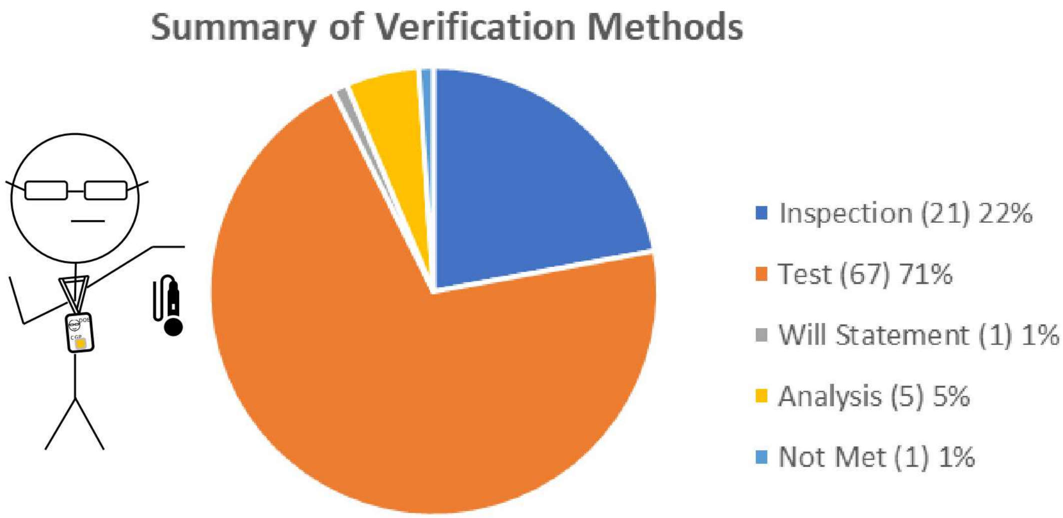

Figure 5: RQ Pie Chart Example. Drop the mic!

The second required step is that every test in the TK that verifies a requirement include the to-be-verified requirement number. And, for each requirement listed in the RQ as verified by test, the test number from the TK shall be listed. In other words, a casual observer could pick up the TK and search for a requirement number to find how it was tested. Or he or she could peruse the RQ and quickly find each test number used for verification. This map of TK-to-RQ and RQ-to-TK is so helpful, and confers so much thoroughness on the requirements verification process, that it has become a requirement of our tailored process.

Other important evaluations include:

- Are all analyses used to verify requirements documented and released?
- Are all simulations or verifications used to verify requirements documented and released?
- For all inspection-verified requirements, was the version of the document(s) inspected and the individual that performed the inspection recorded? Are those documents used for inspection still the current versions to which the program is working?
- Are all requirements not met documented an HDP (or SXR or memo or anything written down and shared) to ensure the customer understands the lack of capability?
- Are you certain it is okay that the requirement isn't met, and does your customer agree with your assessment? Why is it okay? If it is okay, why is it still a requirement?
- How and how well was your firmware tested?

Warning: that last question is more loaded than a farmers' market baked potato. There has been a long-standing debate as to the appropriate level of rigor to apply towards TM firmware. The conservative answer is that firmware should have its own QER, with each piece of firmware requiring a software requirements document (SR), full description of how the code works and how to compile the AT from the AM (SD+MP), and a unique TK to test/document all software requirements (TK) with results and a requirements map inside the TK. And that is a wonderful and thorough answer. However, most of our programs are unable to staff designers and firmware experts commensurate with the needs of full software quality rigor for each piece of firmware. Instead, we have top-level requirements that cover both hardware and firmware, and test to those requirements at the PWA or assembly levels. This is sufficient provided the team document how much of the code is covered by board or assembly level testing. If 90% or more of the firmware is covered by board or assembly testing, the firmware likely has adequate test coverage. Note that this 90% figure is ~~made up~~ engineering judgement; an even better standard is to quantify your code coverage, have a full understanding of what wasn't tested, and a description of why that is okay.

Why? Many times, top-level requirements cover how to evaluate correct operations, but leave the non-operational state as an exercise for the designer to handle (i.e. a derived requirement). The firmware typically accommodates the non-operational case and has designed in some way to flag or identify the failure. Interface failures are very tricky to fully test; interface tests are usually performed with the real interface, and they tend to work. Thus, firmware functionality goes untested. That is the type of issue we want to uncover – are there pieces of your code that you haven't tested? And if you haven't tested them, why should we trust them? And if you don't need to trust them, can they be removed? An assessment of your code coverage gives management the confidence that enough of the code has been hit and your testing is complete, given that there are likely meaningful blocks of code that map to derived requirements not listed in the top-level CD (if the SR route is not exercised and/or the derived requirements are not documented). Is this a lot of work? It can be – but if it is a lot of work, doesn't that mean you didn't know how much of your code you were testing in the first place?

2.4. Oversight

Where will management engage to ensure you have rigorously approached rigor? Unless this is your first week on the job, you know the answer already – meetings. But not just a general status meeting. The rubber hits the road at Reviews. Reviews are the older, more established first cousin of the status meeting [you know, the cousin that got a scholarship to Brown and is now a writer for the *New Yorker*]. And you are responsible for organizing and holding at least three of them prior to shipping something important. Action items must be tracked formally and reported on at, and closed by, the subsequent review. Meeting attendance should be documented, and the review panel should produce written feedback post-review. Work with management to select the appropriate panel members, but most likely the 3-to-5-person panel will include independent peer staff member(s), management, and customer representatives.

2.4.1. Requirements Review

Ideally a review of the requirements is held prior to detailed design commencing. Akin to a CRR in SNL's formal process, this review will verify the state of the CD, ME, and ES using the entrance criteria outlined in section 2.1.

2.4.2. Design Peer Review

Best held after bench electrical testing and mechanical testing of the first prototype units, but before the design re-spin that will produce the delivery unit(s), the peer review lets more experienced staff feel important by nit-picking your careful work. This review is modeled after the BDR. Here the entrance criteria laid out in the Proof section (2.3) will be principally evaluated.

2.4.3. Flight- or Test-Readiness Review

Once everything is finished but the unit hasn't yet been delivered, the team can hold the flight- or test-readiness review such that management can verify everything was satisfactorily completed. Here the thoroughness of all four rigor buckets will be evaluated and management can give formal agreement to proceed with the delivery, akin to their signing of the QER.

2.4.4. Why Hold These Reviews?

Like sports, reviews don't build character, they reveal it. Staff must stand up and answer questions, and, surprisingly, the audience will remember the answers (especially when action items are formally tracked). Reviews are therefore accountability engines. Put yourself in the polished *Manolo Blanhik* shoes of management and you too will easily see why reviews are necessary. Plus, SNL reviews account for 23.4% of Donut Wheel's annual revenue[4]; support local small business and hold these reviews.

[4] Complete ~~engineering judgement~~ fabrication. But at least highly possible, right?

3. MANUFACTURING RIGOR

Why worry about manufacturing rigor? There are thousands of examples of poor manufacturing leading to failures and schedule delays. Planes have fallen, cars have crashed, batteries have burned, people have died sadly – very often due to flaws in minor manufacturing steps within complex systems. And while we have acceptance testing designed to catch major issues [wait, isn't that a rigor bucket too? Yep, it's coming], 8430's core competency is not manufacturing. Coupled with the high consequence of failure in our systems, the reasonable course of action is to have trusted, consistent manufacturing process to help us control quality. The following is hopefully a reasonable set of manufacturing controls that can be efficiently implemented.

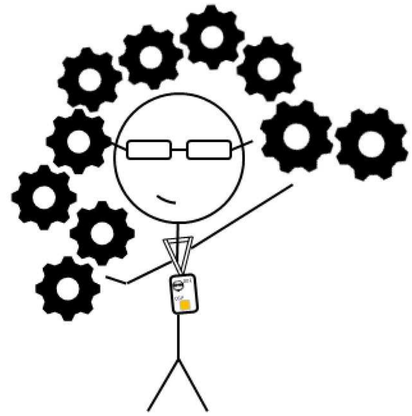

Figure 6: This machine does nothing. Your machine should work. Therefore you should follow reasonable manufacturing quality steps.

3.1. Mechanical Components and Hardware

Even brackets need manufacturing controls [inside joke, sorry]. All machined housings and mechanical sub-components should be ordered through the machine shop using this mildly-arcane order form [5]. The shop (a.k.a. Brian Cass) will take care of sourcing material that meets the drawing specification, selecting a qualified shop (including potentially our own shop), ensuring the shop can handle OUO/AEA drawings, and paying for the product. Make sure to request all inspection records and material certifications from the machine shop; if dimensions are critical, Sandia's inspection team can and should be used after receiving the parts.

Hardware (e.g. nuts, bolts, screws, etc.) should be purchased with certifications (i.e. lot info and proof of lot and material testing) in nearly all circumstances, and those certifications scanned and saved to a project folder for archival. While McMaster-Carr does offer some military specification hardware, it typically does not provide certifications. Therefore, for all significant hardware, use vendors like NorCal Supply in San Leandro, CA or Barnhill Bolt in Albuquerque, NM. Also note that the SNL test facilities do not carry certified hardware to bolt your fixtures to the test adapters on the shaker, centrifuge, etc., so remember key test hardware when ordering trusted hardware.

3.2. Electrical Components and Hardware

Sadly there is no handy machine shop order form for electrical hardware; the product team is left stranded to protect its electrical design from the manufacturing defect burglars like Macaulay Culkin in *Home Alone*. PWBs and their "stuffed" doppelgangers, PWAs, are a minefield of quality questions into which we shall now wade.

3.2.1. PWBs

Basically a cake made of copper, dielectric, and adhesives, a PWB is intricate, small, and chock-full of critical manufacturing features. We control the fabrication quality of our PWBs through the selection of capable vendors and adherence to the requirements we place on the drawings. Our standard PWB drawing should call out the SNL 9928024 specification, which effectively enumerates MIL-PRF-55110H with clarifications and limited exclusions. Per this specification, three vendors – TTM Technologies, Murrietta Circuits, and Hughes Circuits – have been approved by KCNSC. Use of these three vendors to make the boards, to drawings that call out the 9928024 specification, does not require further investigation into vendor quality. Note that World International PCB will typically outsource fabrication orders to TTM Technologies if MIL-PRF-55110H is required, but confirm which fabrication facility it has quoted. If a different vendor is selected, seek proof that MIL-PRF-55110H (or whatever standard your drawing calls out) can be met and ensure that the MIL-PRF-55110H Group A and B testing is performed on conformance coupons. It is also staff's responsibility to ensure, if fabrication drawings are export controlled items (note that TM PWB drawings are typically not export controlled, but some can be so please pay attention here), that the vendor is on Sandia's AEA vendor list [6]; the three preferred vendors are on this list. All inspection results, such as certificates of conformances and stack-up, registration, impedance, and plating verifications should be requested, scanned, and archived.

Once PWBs are received, handling should be avoided as debris and contamination (like finger prints) can result in degradation of the plating (particularly if silver immersion is used). The boards should be maintained in air-tight packaging while awaiting loading.

Another best practice is to have the fabrication vendor mark a unique serial number on each PWB. That serial number can be used to reference the inspection documents and by the assembly house to track x-ray results, any required rework, solder profiles, or cleaning results. And a final best practice is to ensure a solder sample or a spare PWB is sent to the fabrication vendor to allow the reflow profile to be dialed in prior to starting reflow of the delivery units.

3.2.1.1. Implications of PWB Manufacturing on PWB Design

The ability to manufacturer PWBs to the 9928024 specification/MIL-PRF-55110H does put limitations on the design elements we can include in our PWBs. This results in limits on the density of connectors and BGAs/LGAs, trace width and spacing requirements, required surface finishes, minimum dielectric thicknesses, annular ring dimensions, etc. The KCNSC design guide [9], while not a requirement for SNL-/outside vendor-built products, is a helpful overview of conservative design rules that will enable manufacturing to 9928024; keeping your product consistent with these design rules is a best practice and should be attempted. Ultimately it is left to the individual board designer and their drafter to ensure the design rules employed on each PWB meet manufacturing requirements. An excellent best practice would be to have a thoughtful answer to the following: "What design-for-manufacturing rules did you enforce in your PWB layout and are any inconsistent with the KCNSC design guide?"

3.2.2. PWAs

PWAs incorporate the PWB (already discussed), large number of electrical components, and the assembly processes that holds them together. Grab an apron and let's start baking.

3.2.2.1. Electrical Components

A cake must be topped with delightful decorations if it is to be truly great. And if the PWB is the sponge in the cake, components are the sprinkles [yep, solder will be the frosting, but we will come to that next]. Our PWAs can routinely have 100+ unique components, ranging from the yeomen resistors and capacitors to complex ICs and stupid-expensive connectors. Each component can both be a purchasing/scheduling nightmare [why are there no caps in stock?!!!!] and a quality issue. We control the quality and reliability of the electrical components by choosing parts from reliable companies, purchasing through reputable vendors, and ensuring our assembly house verifies the meaningful elements of the parts.

Years of NW experience, KCNSC feedback, and review of datasheets recommend use of Kemet for all capacitors and Vishay/Dale for all resistors. Preferred ICs come from Linear Technologies/Analog Devices, Texas Instruments, and Maxim. Large-scale memory has preferentially been sourced from Micron and FPGAs from Microsemi (particularly if radiation tolerance is a requirement). However, the wide range of tasks memory or programmable logic perform make hard-and-fast rules about their selection tenuous; in other words, choice of programmable logic and memory should be a thoughtful design and qualification consideration on each program. We don't have preferred companies from which to source diodes, fuses, inductors, and magnetics – and while the TM/H-Gear engineer should consider the source of each component (i.e. attempt to use parts that have performed well in past programs if possible, source from stable, familiar companies, etc.), he or she will receive no guidance here. With all components, a best practice is to have a solid answer for "Why did you pick this part number and not some other, equivalent part?" and make sure that the manufacturer of the part and any previous experience is considered in that answer.

Connectors are yet another significant quality issue – both the mechanical and electrical functionality of our products depend on the robustness and quality of its connectors. Work done during the W76-1 development and recent TM work recommends Glenair as the preferred vendor for connectors and ITT Cannon as a second, acceptable source for MDM connectors [10]. Make sure to understand lead times for connectors early on as they can frequently be 10+ weeks (especially from Glenair). Connectors also routinely have sole-source implications – connector orders are prone to exceeding purchase card limits, forcing a purchase request, and once a design with a given manufacturer's connector is proven mechanically it becomes very risky and/or difficult to change – requiring longer purchase request handling times.

Table 1: Recommended Electrical Component Manufacturers

Component Type	Manufacturer
Resistors	Vishay Dale
Capacitors	Kemet
General ICs	Linear/Analog Devices, Texas Instruments, Maxim
Memory	Micron
Programmable Logic	Microsemi
Diodes/Inductors/Fuses/Magnetics	¯_(ツ)_/¯
Connectors	Glenair (heaven help your schedule)

The device package must also be considered in component selection. Pinned packages are more easily inspected, soldered, and reworked than BGAs/LGAs/QFNs and should be chosen preferentially as PWB space and component availability allows. BGAs and LGAs down to 0.8 mm ball spacings have been shown compliant with our MIL-PRF-55110H and 9913017 specifications, but tighter BGAs/LGAs should be avoided. Stacked capacitor packages should be avoided, especially if thermal cycle requirements exist (which they should). And please no 0201 packages – they are just too small.

Once the individual parts are selected, the team must purchase the parts. Controlling the origin of these parts is another element of our tailored quality approach. All electrical components shall preferentially come (a) directly from the company; (b) from distributors Digi-key, Mouser, Newark, Arrow, or Avnet; (c) from reseller Vyrian. Distributors Allied and Future electronics have been used in the past and can continue to be used but are not preferred as we have much less experience sourcing products through them. All certificates of conformance should be kept and scanned/archived. Any parts that are sourced outside of these trusted vendors should be brought to management and customer attention, and individual component testing or additional component scrutiny should be considered. The basic question should be "Why do you trust that the components you have on hand meet the datasheet specifications to which you designed?" Sourcing from the trusted sources listed and making sure to keep records is a fully sufficient answer.

Even if high quality parts from reputable companies are selected, and those parts are purchased from trusted sources, mistakes happen: reels are mislabeled by the distributor, parts are incorrectly packaged by the company, etc. To prevent this, the assembly house selected to perform the reflow soldering shall at a minimum (a) verify the part marking of at least one piece of each IC per the part's datasheet; (b) verify the resistance of at least one piece of each resistor; (c) verify the capacitance of at least one piece of each capacitor; and (d) bake-out all humidity sensitive components prior to assembly unless they have been stored in climate-controlled environments. If all testable passives are of appropriate values, all parts are marked appropriately, parts were sourced appropriately, baked-out if necessary, and selected for the design with component quality in mind, you have fulfilled all tailored expectations for components.

3.2.2.1.1. Electrical Component Storage

Sadly, our tailored expectations about component quality break down as we have limited control of the components once they reach our lab. Our current best practice is to store the components on reels or in static bags within static-dissipative reel bins inside standard cabinetry. Limited to no humidity or climate control is available for component storage. This is a gap that has been identified and will be improved upon in the future. One final best practice is, if possible, to keep part kits intact through the end of the service life of the delivered product. If failures do occur and component quality called into question, knowing exactly which reel and lot from which the component(s) came is very useful. A much more sophisticated component-to-PWA-to-unit tracking system is desired but is a long way from being implemented.

3.2.2.2. Assembly

All carefully selected components and manufactured PWBs must come together electrically with the help of the frosting on our cake: a lead-tin amalgam (or silver/copper/bismuth+tin for the environmentally conscious). Our products are assembled by a non-SNL assembly house, whether it is KCNSC for production hardware or contract assembly houses. The performance of this assembly house is another critical element of the quality of our electronics assembly. Our tailored process requires the use of audited and trusted assembly houses that can meet our 9913017 specification, automated optical inspection to verify conformance, and archival of quality records.

Specification 9913017 points primarily to IPC-A-610D class 3 with exclusions and clarifications. Two assembly houses have proven they can perform to this standard. Murrietta Circuits has been verified by KCNSC as meeting this standard and Megaforce Corporation has been audited by SNL Org. 9400 and shown to meet this standard [4]. Use of these two assembly houses, along with drawings that call out the 9913017/ IPC-A-610D class 3 standard is sufficient to meet our tailored quality standards. If a different assembly house is chosen, some form of engineering evaluation or quality audit should be required to prove they can perform to the standards called out on your drawings. That evaluation should be documented and presented to management and/or the customer. And again, if an assembly house other than the two listed above are used, staff must verify the vendor is listed on the AEA supplier list [6] if your assembly drawings are export controlled (note that most TM PWA drawings ARE export controlled).

Post-reflow of the PWAs, our tailored process requires that that our contract assembly houses use automatic optical inspection machines to evaluate the results of the surface mount process. This machine ensures parts are properly aligned, solder is present in all places it is expected, component leads are wetted, all parts that should be loaded are present in the finished product, and much more; it essentially verifies IPC-A-610D class 3 soldering standards with greater accuracy and speed than a human inspector. It is a phenomenal tool for ensuring a quality build – if you haven't seen one in action, ask your assembly house for a tour. After you see what it can do, you'll always want your product run through one.

The team should also pay the assembly house for the full records from the assembly processes, including reflow thermal profiles, x-ray results, BGA/LGA void fraction calculations, cleaning records, optical inspection records, and any rework. This information, provided the assembly house is following the 9913017 specification, should be recorded and traceable by PWA serial number such that it could be referenced later.

4. LAB RIGOR

You've followed, or are on track to follow, all responsible document and program rigor steps and you've built product to a standard commensurate with flight testing. Well done! Now you have hardware in hand and need to handle and test it. That's where the Lab Rigor bucket comes in. There needs to be some standard for how you treat meaningful hardware given the common set of things we tend to do with it. In no particular order, those include the following.

4.1. ESD

Electrons make most of our hardware work. Sadly, rogue electrons can also make most of our hardware not work. Mitigating ESD is a basic quality tenet, particularly because ESD damage can be latent, eluding acceptance testing designed to catch failures prior to shipment. Your team should be committed to following best practices when handling or testing ESD-sensitive electronics outside of protective bags or when unprotected conductors are exposed.

Figure 7: ESD is bad. Let's avoid it.

1. Perform work in labs that utilize dissipative flooring that meets (1) ASTM F 150 with 100 V applied voltage, flooring shall have an average resistance to ground, and an average resistance between electrodes placed three feet apart, of 1×10^6 minimum to 1×10^9 ohms maximum; (2) 5,000 volts to 500 volts in less than 0.25 seconds per Federal Test Method FED-STD-101C/4046.1. The labs in 910/110 and 911/134 have this flooring.
2. Use dissipative, grounded lab benches or mats. All Eaton workbenches in the 910/110 and 911/134 labs, including the solder station benches, meet this standard.
3. Staff shall wear ESD smocks grounded to the lab bench/mat through a 1Mohm resistance. Contact Cindy Alvine to procure a smock that meets this requirement, or just head to 911 and steal the author's smock [he won't mind]. A wrist strap with identical grounding can be substituted but is not preferred.
4. Whenever possible, ionizing fans shall be used for additional ESD protection.
5. Stand while testing or handling products as nearly all chairs in the labs are not dissipative.

Is your product ESD sensitive? Almost assuredly yes if your product has any electronics within it. But how sensitive? Most, but not all, of our COTS electronics are internally protected to at least a 1kV human body model. And the best practices above are consistent with protections outlined in 9957024, Control of Static Sensitive Devices, for products safe to human body model withstand voltages above 250V (Class B). However, if you have selected components susceptible to ESD below 250V human body model (here again is yet another reason to carefully read all component datasheets), your products may need additional protection, or you may need to pick different components. And if your products do require special handling above the standard here, you should include a drawing note that calls out the required protections (again see 9957024 for more details).

Also pay acute attention to products with unprotected JTAG and USB traces as past designs have shown those functions particularly susceptible to ESD. During hardware transit and shipping, ensure ESD-safe bags and packing materials are used.

4.2. Calibrated Lab Equipment

Sandia rightly dictates that all measurements (e.g. torques, weights, voltages, currents, etc.) taken for acceptance or requirements verification (which I'll call "important" measurements going forward) must be done with equipment that has been calibrated with traceability to NIST. To us, this means all important measurements are taken using equipment with a valid (i.e. unexpired) SNL calibration sticker (per the PSL/Sandia's calibration program) and 6-digit tracking number. Think torque wrenches, scales, multimeters, oscilloscopes, thermometers, and more. The TK/TD shall include the 6-digit number of each piece of equipment used to take every important measurement and the date it was taken (or the date the TK was executed). Why? Any measurement is circumspect until the equipment that took the measurement is shown inside of calibration limits AFTER the important measurement was made; recording the 6-digit equipment calibration number and date in the TK/TD allows you to identify measurements that must be reconsidered in case the next calibration of the equipment in question fails (and, sadly, sometimes this happens).

In certain tests, using a calibrated input (e.g. a voltage input from a power supply), and thereby forgoing the need to measure the input using a calibrated measurement tool (e.g. measuring the voltage input using a calibrated multimeter) is acceptable. The same rules apply however – the input device must be calibrated per the PSL/Sandia' calibration program and the TK/TD must record the equipment's 6-digit tracking number. Note that doing this likely has accuracy implications as measurement equipment is typically more accurate than stimulus-generating equipment.

4.3. Rework

Thankfully no TM or H-Gear program has ever had to perform rework on any of its products, ever; they have all been perfect by design from day one[5]. But just in case something drastic happens and one of your products does require rework, the individual performing the rework should be trained, only clean and trusted equipment used, and the product returned to the assembly clean of flux or oils due to handling. Specifically:

1. Soldering of components and inspection shall be done by trained staff having completed IPC 7711/7721 Rework and Repair of Electronic Assemblies certification at a minimum. The preferred method is to return the hardware to the assembly house for professional rework and inspection. If schedule prevents that, the next best option is to employ 8640 staff to perform the rework. In no circumstances should the author of this document perform the rework.
2. Rework of BGAs, LGAs, and QFN-packaged components should be avoided at all costs. It is exceptionally difficult for even the best trained assembly houses with the most advanced equipment to do this well. And, in the process of removing the previously offending BGA/LGA/QFN, the plating and flatness of the PWB is typically materially affected. If a product must be flown/tested with a reworked BGA/LGA/QFN, a risk should be brought to management and the customer's attention.
3. The 910/110 and 911/134 lab space does not currently control the type of work performed on its solder benches. Thus contaminant like low melt desolder wire or other products used in the rework of previous product are likely present on the bench or on the solder iron tips. Care shall be taken to avoid cross contamination until a quality-significant rework station

[5] Another humor-motivated linguistic device (i.e. still just a joke)

can be brought online. This again is reason to preferentially perform rework at a professional assembly house or in 8640's lab.

4. Most rework is performed while sitting, and again almost all chairs in the lab are not dissipative. Care shall be taken to protect against ESD events while performing rework, with personnel wearing grounded smocks at a minimum and use of an ionizing fan wherever possible.
5. Prior to using or conformal coating the reworked hardware, the product shall be cleaned by either an alcohol bath or via plasma cleaning. Contact April Nissen/Org. 8344 to discuss plasma cleaning [this capability is coming online as of Winter 2018].

4.4. Cables

Cables are fickle lovers – trust me when I say they will burn your house to the ground given the slightest provocation. Often overlooked, unscheduled, and rushed, cables and cable quality are the root cause of an extraordinary percentage of our failures. The author experienced this the hard way during the very first B61 JTA Modernization Flight Test Qualification Unit One. A single conductor in a cable that had been tested on the bench numerous times failed when assembled into the system (when it was stretched to fit). Later analysis showed the backshell potting had large bubbles, leaving this conductor unsupported. That conductor carried the thermal battery fire current and its failure resulted in a complete loss of data during a multimillion-dollar flight test. In summary, if a diode doesn't take out your product, I'll bet a donut it will be a cable. Most cables we require are test cables, meaning they are not delivered to your customer. Nevertheless, cable quality is important – like I said, a silly cable will destroy your test the first chance it gets – and should not be overlooked.

1. Save yourself from a world of hurt, sciatica, and managerial second-guessing by employing 2636, 8640, Glenair, or BetaTron (http://www.betatronelectronics.com/) to build your cable(s). They know how to get twisted pairs to match the length of their untwisted brethren in the same bundle, strip wires correctly, pot backshells soundly, they always remember sheathing and shrink wrap before it's too late, and otherwise do all the tedious stuff most of us don't do (and then subsequently regret). This likely means you'll have to produce a drawing for outside personnel to tell them how to build the cable. Doing so is but a bonus to this method since cable drawings are very helpful indeed.
2. For the love of all that is holy, perform a continuity test on your cable BEFORE PLUGGING IT IN TO YOUR HIGH-QUALITY HARDWARE. Tim Kostka went out of his way to build an automated way to do this that takes mere seconds; even the author was able to figure it out, that's how simple this thing is to use. See reference [4] for all the details.

5. ACCEPTANCE RIGOR

And now, the end is near; And so I face the final curtain; My friend, I'll say it clear; I'll state my case, of which I'm certain [8]: Acceptance testing is important. It's the final verification step of our quality process. Often this step is rushed as [while this has never, ever, ever happened to the author] design and manufacturing has pushed schedule. Push back against the dark forces of delivery dates and schedule pressure to ensure these steps are performed. The adage that there is never enough time to do the job right, just enough time to do the job again, should be heeded wisdom.

5.1. Serialize and Take Pictures of Everything

I know this sounds very, very basic. However, simple stuff often gets overlooked. Every unit shipped shall have a unique serial number. A professional twist on this is to follow the SNL/WR serialization standard 9919100 [which is probably called out in your drawing notes anyway – go ahead, I'll wait while you look at your drawings]. This callout recommends a serial number in the form: [Manufacturer's Code: SBJ in our case] – [Serial Number] – [Date Code Type IA]. An example would be SBJ-1001-L18, or unit 1001, made by SNL, in December of 2018. Serialization enables tracking, which enables feedback and understanding in the event of failures. Please serialize everything.

Another simple, very helpful step is to take pictures of everything – all of the PWAs prior to assembly, the full assembly, any custom steps or wet-mount processes (like epoxy on cables), etc. Both the 910 and 911 labs have Keyence digital microscopes that can take wonderful images of our PWAs. While this is not a required step, it is a very useful quality element and, time permitting, should always be done.

5.2. Acceptance Bench Testing per a PS or TK

Every product shipped shall have a written PS or TK that describes how that individual unit's functionality was verified on the bench. Every requirement need not be verified during TK/PS bench acceptance testing – most notably, requirements that are handled by firmware do not need to be reverified if covered during qualification testing. However, every requirement fulfilled by hardware must be tested, especially interface requirements, pinouts, and power. If not, how will you know that specific unit will work in the final assembly or flight? A best practice is to have pre-defined limits for all acceptance tests in the TK/PS such that someone other than the product designer could evaluate if the test was successful (e.g. current draw can be 0.1+/-0.05A at 28V). Results of TK/PS testing shall be recorded by unit serial number and archived.

5.3. Acceptance Environmental Testing per a PS or TK

A longstanding WR tradition is to test every product mechanically to an acceptance limit that is much lower than the qualification testing performed on the development unit/lot, the theory being that manufacturing defects will reveal themselves during low-level testing without fatiguing the delivery products. And while the author has never seen data showing a connection between likelihood of identifying failures and acceptance test levels, rules of thumb and best practices have been developed onto which our tailored quality standard has glommed.

At a minimum, every delivered unit shall undergo one thermal cycle to the product's required temperature limits with operational tests at the two temperature extremes. This is a must for any product with firmware where timing can be contingent on the individual IC's performance. Additional thermal cycles maybe negotiated as requirements, but one is a quality requirement.

Acceptance random vibration testing at ambient temperature, known familiarly as a "solder shake", is required for unpotted assemblies and recommended for potted assemblies in our tailored quality process. Our customers have the right to define custom acceptance vibration levels for their products. In lieu of defined requirements, recommended test levels are 6dB below qualification levels for the full qualification duration at ambient temperature only. If your customer requires combined temperature and vibration acceptance testing, make sure to add significant additional time to accomplish the acceptance testing. And while it is strongly recommended to fully stimulate the hardware during acceptance vibration testing, the unit shall be powered at a minimum. Note that if the hardware isn't stimulated during vibration such that you cannot fully assess the state of the hardware upon completion of vibration, bench electrical testing per the PS/TK should be repeated after vibration. For this reason, it is typically more efficient to perform the PS/TK bench electrical testing after acceptance vibration testing.

5.4. Digitizer Calibration

Most of our products digitize sensor or other analog inputs. Each digitizer in our systems must be calibrated to produce a linear gain and offset that can convert the raw ADC output to engineering units (volts, amps, G's, parsecs, etc.). That calibration process must stimulate the inputs at 3-5 points across at least 10-90% of the full-scale range of the channel (e.g. inputting 0.5V, 2.5V, and 4.5V for a 0-5V input or -4V, 0V and 4V for a -5 to 5V channel). Inputs used for this calibration must be applied with a calibrated source or measured with a calibrated device. The resulting counts vs. engineering unit best-fit line and the calibration factors (i.e. gain and offset of that best-fit line) must be archived and eventually transmitted to our customer when the data is viewed/used.

6. CONCLUSION

The author truly appreciates and respects your willingness to read to the end. Hopefully this document has held your attention long enough to make you think about the need to systematically approach quality in our 8430-made delivery units. No product is perfect [except for those delivered by the author, of course] and, while the expectations laid out here are (hopefully) reasonable, it is highly unlikely all recommendations/requirements will be followed. Deviations or exceptions to this standard are (likely) fine, provided they come after honest conversations with your customer and your management about what was done and why [documenting those conversations and decisions would be even better]. Your customer's trust and respect are worth almost as much as your own pride in your product – focusing on, and having thorough documentation of, the types of issues presented in this document have typically gone a long, long way toward building and strengthening that trust. In short, strive valiantly, remember there is no effort without error, know great enthusiasms in a worthy cause, and make sure to enjoy the triumph of high achievement [again, completely stolen verbiage from Teddy Roosevelt – that guy could sure write].

Figure 8: Who's Awesome? You (and Teddy Roosevelt) are awesome!

APPENDIX A. CHECKLIST (DOCUMENT TLDR)

By popular demand, here is a summary list of the required quality elements in our tailored process for hardware manufactured and delivered by 8430 to flight tests or major ground tests. Reference the "learn more" section for background, additional best practices, and recommendations.

Quality Element	Learn More in Section
Requirements documented and released into Prime or PDMLink	2.1
Complete product definition, such that any qualified Sandian (other than the product designer) could remake the exact product, released into Prime or PMDLink	2.2
Mapped Test Plan(s) and Requirements Map released into Prime or PDMLink	2.3
Analysis, simulations, and inspections used to verify requirements are documented	2.3
Written documentation of unmet requirements or product definition exceptions	2.2 and 2.3
Firmware test coverage documented with any untested firmware evaluated	2.3
Requirements Review, Peer Design Review, and Flight/Test Readiness Reviews held with action items tracked and closed	2.4
Mechanical parts machined or purchased through reputable vendors as recommended or selected by SNL machine shop	3.1
Mechanical hardware (nuts, bolts, screws, etc.) purchased with certifications and certifications archived	3.1
PWBs manufactured by fabrication houses qualified to specification called out on fabrication drawing	3.2.1
Quality of manufacturer of all electrical components considered with preferred manufacturers and previously tested components preferentially selected	3.2.2.1
Electrical component package size and type considered for quality and rework	3.2.2.1
Vendor of all electrical component purchases considered, with preferred vendors used wherever possible	3.2.2.1
Assembly house verified passive values, IC part markings, and baked out all humidity-sensitive components	3.2.2.1
Assembly house verified to meet specification called out on PWA drawing	3.2.2.2
Assembly house used automated optical inspection to inspect assembly	3.2.2.2
Assembly house provided all inspection records and those are archived	3.2.2.2
ESD controls followed during test and assembly of hardware	4.1
All requirement-verifying measurements made with calibrated devices with sufficient records to track the measurement to the calibrated device that took it	4.2
Rework performed by qualified staff on reworkable components with the product left sufficiently clean post-rework	4.3
Cables manufacturing quality considered, and cables are at least tested for correct continuity prior to use	4.4
Products serialized	5.1
Acceptance testing per a TK or PS performed to verify all requirements fulfilled by	5.2

Quality Element	Learn More in Section
hardware	
One operational acceptance thermal cycle, plus any customer-required additional thermal cycles, performed on each delivery unit	5.3
Acceptance vibration testing performed on non-potted products or any potted products required to perform acceptance vibration testing per customer	5.3
Calibrated all digitizers with a 3-5 point linear calibrations	5.4

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