AEROSPACE REPORT NO.
TOR-2010(8591)-20

Flight Unit Qualification Guidelines

June 30, 2010

John W. Welch

Vehicle Performance Subdivision
Vehicle Systems Division

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Space Systems Group

Developed in conjunction with Government and Industry contributions as part of the U.S. Space Programs Mission Assurance Improvement Workshop.

AEROSPACE REPORT NO.
TOR-2010(8591)-20

Flight Unit Qualification Guidelines

June 30, 2010

John W. Welch

Vehicle Performance Subdivision
Vehicle Systems Division

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Space Systems Group

Developed in conjunction with Government and Industry contributions as part of the U.S. Space Programs Mission Assurance Improvement Workshop.

AEROSPACE REPORT NO.
TOR-2010(8591)-20

Flight Unit Qualification Guidelines

June 30, 2010

John W. Welch

Vehicle Performance Subdivision
Vehicle Systems Division

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

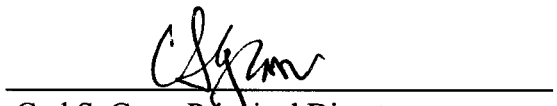
Contract No. FA8802-09-C-0001

Authorized by: Space Systems Group

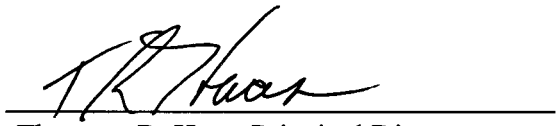
Developed in conjunction with Government and Industry contributions as part of the U.S. Space Programs Mission Assurance Improvement Workshop.

Flight Unit Qualification Guidelines

Approved by:



Carl S. Gran, Principal Director
Vehicle Performance Subdivision
Vehicle Systems Division
Engineering and Technology Group



Thurman R. Haas, Principal Director
Office of Mission Assurance and Program Execution
National Systems Group

Acknowledgements

This document has been produced as a collaborative effort of the Mission Assurance Improvement Workshop. The forum was organized to enhance Mission Assurance processes and supporting disciplines through collaboration between industry and government across the U.S. Space Program community utilizing an issues-based approach. The approach is to engage the appropriate subject matter experts to share best practices across the community in order to produce valuable Mission Assurance guidance documentation.

The document was created by multiple authors throughout the government and the aerospace industry. For their content contributions, we thank the following contributing authors for making this collaborative effort possible:

Chahriar Assad - Boeing
Steve Daudt - Ball Aerospace and Technologies Corporation
Alan R. Hoffman - Jet Propulsion Laboratory
Lt. Col. Stanton Hubbard - USAF
Rick Judt - Raytheon
Paul Kruszewski - Northrop Grumman Aerospace Systems
Abdel-Salam Niazy - Northrop Grumman Aerospace Systems
John Perazza - Lockheed Martin Space Systems Company
Dan Rodriguez - Applied Physics Laboratory
Michael Taylor - Jet Propulsion Laboratory
Y.C. Yiu - Lockheed Martin Space Systems Company

A special thank you for co-leading this team and efforts to ensure completeness and quality of this document goes to:

Ruth Braswell - Northrop Grumman
Mark Newell - Northrop Grumman
John Welch – The Aerospace Corporation

Abstract

The qualification of flight units must be appropriately planned and executed in order to ensure that design and/or manufacturing issues are identified early. This minimizes the potential for product delivery delays, increased cost due to flight unit rework, and at worst, anomalous system behavior or failure during testing at higher levels of assembly and/or on-orbit. Typical problems that result from inadequate qualification planning and/or execution are late or misinterpreted requirements, inadequate consideration of bounding conditions and performance parameters, failure to adequately qualify material, piece part or packaging technologies, and abbreviated testing which results in an inadequate understanding of variables or design margins. Other problems stem from faulty re-use assumptions for heritage hardware used in new applications or missions, configuration discrepancies between Development/Qualification models and flight production units, and changes to manufacturing processes without consideration for impact on the qualification baseline.

This Flight Unit Qualification reference guide has been generated from industry and government best practices in order to provide the qualification practitioner and review authorities with a qualification process and governance framework. The guide provides a recommended qualification process, including defining roles and responsibilities of key participants at design and hardware milestones. It also strongly endorses the establishment of independent Qualification Review Boards or equivalent independent review authorities that objectively audit the qualification process and ensure rigor and thoroughness. The guidelines include a practical set of tools for architecting comprehensive qualification plans, executing tests, and reviewing qualification results. It provides a treatment of commonly encountered qualification scenarios including the desire to leverage heritage hardware and the necessity to retest in the event of anomalies.

Executive Summary

While the terms “qualification” and “flight qualified” have been embedded in the space industry culture for decades, there exists no universally accepted definition or approach to achieving qualification on hardware intended for use in US Government (USG) agency space systems. As a result, the rigor applied to qualification planning and execution can vary considerably from company-to-company and government agency-to-government agency. A direct consequence of inadequate and/or incomplete planning and execution of unit level qualification is an increased risk of design and/or manufacturing escapes during the later stages of the hardware development cycle where both the cost and schedule impacts of such escapes are most severe.

In order to reduce risk and drive consistency into the industry, a Flight Unit Qualification reference guide has been generated that delineates a systematic approach to successful qualification and which can be readily incorporated by organizations throughout the space community.

Specifically, this guide contains:

- A qualification process and gated review flow
- Guidelines for establishing an *independent* Qualification Review Board (QRB) or equivalent Independent Review Authority
- Best practices for ensuring that environmental requirements, qualification plans, qualification hardware pedigree, requirements compliance verification methods and testing are properly reviewed and approved
- Checklist and template tools for preparing and executing qualification plans
- Criteria for Qualification by Similarity as a qualification methodology
- Criteria for Retest of qualified hardware due to redesign, change in manufacturing processes or environments, test discrepancies, rework or refurbishment

Following these guiding practices will result in the technical risks being mitigated as early as possible in the design/development process of flight units, thereby reducing costly downstream escapes and helping ensure mission success.

The scope of this guideline has been limited to the unit, product, or configured item level under the assumption that it is a key building block for the majority of space systems. In addition, this document is nominally written for a Class A space flight program as described in MIL-HDBK-343 [1]. However, the basic principles contained herein can be tailored as appropriate for Class B, C, or D programs with reduced lifetime requirements and/or higher risk tolerance.

Contents

List of Tables

List of Figures

List of Appendixes

1. Introduction

Qualification activities, including analyses, demonstrations, inspections and tests, are conducted to prove hardware and software meet specification requirements with adequate margin. In addition, qualification testing validates the acceptance program by demonstrating acceptable test techniques, procedures, equipment, instrumentation and software. Completion of a full qualification program ensures that subsequent hardware production units will be capable of surviving multiple acceptance tests and test cycles that may be necessary because of failures and rework, while still maintaining flightworthiness. Accordingly, qualification testing should be completed and consequential design improvements incorporated prior to the initiation of flight hardware acceptance testing.

The most common USG agency verification and reliability specifications all contain qualification terminology, test parameters and approaches intended to ensure mission success. There are however, differences in the terms and approaches used to achieve "qualification" within the industry depending on the cultural norms, experiential knowledgebase and mission specific charters of the various USG agencies and government contractors. In addition, the space community as a whole continues to accumulate valuable operational data and gain detailed knowledge of our space systems which continues to improve "qualification" approaches.

In spite of the differences in terminologies, methods, and approaches, all successful qualifications adhere to fundamental "***tenets of qualification"***:

- Tests, analyses, and inspections, as required, are conducted on the product to demonstrate satisfaction of design requirements ***with margin***.
- Tests, analyses, and inspections, as required, are conducted on the product to demonstrate robustness ***in the intended environment and application***.
- Qualification articles are ***sufficiently representative*** of the flight design.

The guiding practices set forth in this document are intended to aid the space community in adhering to the above qualification tenets while allowing for cultural, programmatic, and contractual influences which often preclude universally prescriptive approaches. Toward that end, the authors have deliberately adopted a Qualification Process and Independent Review model as the overarching framework in which to conduct qualification activities with an emphasis on focused oversight at key process gates. This approach will ensure that all stakeholders for a given activity have formally collaborated and concurred on plans, methods, and results in order to achieve a "flight qualified" consensus.

1.1 Background

Unit level (or product) qualification is a key element of the verification and validation process for all space-borne hardware. However, a recent survey of industry practices has identified that qualification planning is often incomplete and/or the execution is inadequate often resulting in the late discovery of design and manufacturing issues. Examples of actual qualification escapes are provided in Appendix E. Typical qualification escapes include:

- Late or misinterpreted requirements
- Inadequate consideration of bounding conditions, performance parameters, and operational modes (i.e., failure to Test Like You Fly)
- Failure to appropriately integrate material, piece part, and packaging technology qualifications resulting in faulty assumptions on product robustness and integrity

- Failure to appropriately verify proper interactions of the equipment in an integrated environment
- Abbreviated testing or faulty assumptions resulting in inadequate understanding of variables or design margins
- Discrepancies between Development/Qualification models and flight production units
- Faulty re-use assumptions for heritage hardware in new applications or missions
- Manufacturing process changes without consideration for impact on the qualification baseline

As a result, there is a need for a reference guide that captures and centralizes all of the necessary elements required to achieve a successful Flight Unit Level Qualification.

1.2 Purpose

While qualification activities are typically a normal part of any given program, approaches within the industry in many cases have proven to be ad-hoc in nature, often inconsistent, and deficient in structure. The purpose of this document is to delineate a general systematic approach that can be readily incorporated by organizations throughout the space community for successfully achieving flight unit qualification. Elements covered include a framework for the qualification process, a structure for the qualification oversight board, and a practical set of tools for architecting comprehensive qualification plans, executing tests and reviewing qualification results. Recommended approaches are defined for the treatment of commonly encountered qualification scenarios including the desire to leverage heritage hardware or the need to define retesting requirements in the event of anomalies. By following these guiding practices technical risks will be mitigated as early as possible in the design/development process of flight units, thereby reducing costly downstream escapes and helping ensure mission success.

1.3 Applicability

This document is intended for use by all personnel involved in performing, reviewing, and/or approving flight unit qualifications for space applications, including internal/external customers, prime contractors, subcontractors, program review authorities, program managers, safety and mission assurance functions, responsible system and design engineers, test engineers, and independent review authorities.

It is recognized that qualification occurs at multiple levels within the integration chain beginning with devices or piece parts and proceeding up through space vehicle and integrated space and ground systems segments. The focus of this guideline has been limited to the unit, product, or configured item level under the assumption that it is a key building block for the majority of space systems. Contractual performance and other requirements including qualification are also typically set at the unit level and flowed to government contractors beginning with the prime contractor and proceeding down through the supply chain to subcontractors.

This document is nominally written for a Class A space flight program as described in MIL-HDBK-343 [1]. However, the basic principles herein can be tailored as appropriate for Class B, C, or D programs with reduced lifetime requirements and/or higher risk tolerance. Tailoring of the basic processes and oversight principles is appropriate when there is agreement among all stakeholders, including at a minimum, the flight unit provider, prime contractor, and internal/external customers, that a higher level of risk can be tolerated due to reduced lifetime requirements, and/or high hardware maturity levels with low system complexity, and/or experimental/technology demonstration nature of the program.

1.4 Scope and Content

This document provides a comprehensive best practice reference guide for flight unit qualification for space applications.

Specifically, this guide contains:

- A qualification process and gated review flow
- Guidelines for establishing an *independent* Qualification Review Board (QRB) or equivalent Independent Review Authority
- Best practices for ensuring that environmental requirements, qualification plans, qualification hardware pedigree, requirements compliance verification methods and testing are properly reviewed and approved
- Checklist and template tools for preparing and executing qualification plans
- Criteria for Qualification by Similarity as a qualification methodology
- Criteria for Retest of qualified hardware due to redesign, changes in manufacturing processes or environments, test discrepancies, rework or refurbishment

There are many topics related to flight unit qualification which the authors have not treated in any significant detail in the interest of containing the scope of the document to baseline hardware qualification practices. In many cases, these topics are covered in greater detail elsewhere and are thus only referenced to illustrate the connection to flight unit qualification. Such topics include:

- Software qualification (embedded software, firmware, test software, etc.)
- Parts, materials and processes (PMP) and sub-assembly qualification
- Test Like You Fly (TLYF) verification methodology

2. Reference Documents

The following documents are generally acknowledged to play an important role in shaping the specification of contractual qualification requirements or contain useful information that will aid the qualification practitioner:

1. "Design, Construction, and Testing Requirements for One of a Kind Space Equipment," DOD-HDBK-343 (USAF), 1 February 1986.

2. Perl, E., "Test Requirements for Launch, Upper-Stage and Space Vehicles," (MIL-STD-1540E), Aerospace Report No. TR-2004(8583)-1, Rev. A, 6 September 2006.

3. "Test Requirements for Launch, Upper-Stage and Space Vehicles," Volumes I and II, MIL-HDBK-340A, 01 April 1999.

4. NASA Goddard Space Flight Center, "General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects," GSFC-STD-7000, April 2005.

5. NASA Systems Engineering Handbook, NASA/SP-2007-6105, Rev. 1, December 2007.

6. "Rules for the Design, Development, Verification and Operation of Flight Systems," Goddard Technical Standard GSFC-STD-1000E, 13 July 2009.

7. Hannifen, D. W., Peterson, A. J. and Tosney, W. F. (editors), "Space Vehicle Test and Evaluation Handbook," Aerospace Report No. TOR-2006(8546)-4591, 6 November 2006.

8. Englehart, W. C. (editor), "Space Vehicle Engineering Handbook," Aerospace Report No. TOR-2006(8506)-4494, 30 November 2005.

9. Guarro, S. B. and Tosney, W. F. (editors), "Mission Assurance Handbook," Aerospace Report No. TOR-2007(8546)-6018, 1 July 2007.

10. Cheng, P. G., "100 Questions for Technical Reviews," Aerospace Report No. TOR-2005(8617)-4204, 30 September 2005.

11. Fink, R., Griese, R., Hoang, B., Nagano, S., Shaw, B., and Sobetski, J., "Guideline for Space System Late Changes Verification Management," Aerospace Report No. TOR-2008(8506)-8377, 30 June 2008.

12. Speece, D. J., "Objective Criteria for Heritage Hardware Reuse," Aerospace TOR to be released as part of the 2010 Mission Assurance Improvement Workshop.

13. NASA Lessons Learned website, http://llis.nasa.gov/offices/oce/llis/home/index.html.

14. Knight, F. L, "Space Vehicle Checklist For Assuring Adherence to "Test Like You Fly" Principles," Aerospace TOR-2009(8591)-15, 2009 Mission Assurance Improvement Workshop, 2009.

3. Flight Unit Qualification Process

3.1 Overview

Flight unit qualification is the formal verification (by tests, analyses, inspections, demonstrations, and/or similarity) of design requirements including margin, product robustness, and workmanship. Although space flight units have varying missions and requirements, the general qualification elements consist of a common set of activities which typically include the following:

- Functional and performance verification to confirm margin over the required environments and lifetime
- Circuit analyses to confirm worst case performance, parts de-rating, failure propagation containment, mitigation of single point failures, and acceptable susceptibility to single event effects
- Life testing of components susceptible to wear-out, drift, or fatigue type failure mode, or a performance degradation, due to mechanical movement, thermal and/or pressure cycling, and/or electro-chemical degradation, such as batteries
- Environmental modeling and analysis to verify design margin relative to loads, random vibration, acoustics, shock, thermal, vacuum, electro-magnetics, surface/bulk charging, corona, contamination, micrometeoroid, and orbital debris
- Environmental testing to verify design margin and workmanship (and validate modeling) relative to loads, random vibration, acoustics, shock, thermal cycling, thermal vacuum, electro-magnetic compatibility and interference, grounding and bonding
- Inspection and test verification of critical dimensions, processes, and testing
- Verification of functionality and configuration of any firmware, embedded software, and/or application flight software

The flight unit qualification process is implemented by the product team, typically in an Integrated Product Team (IPT) environment. Oversight is provided by an independent **Qualification Review Board** or equivalent Independent Review Authority (hereafter referred to as the "**QRB**") comprised of qualification process experts and supporting subject matter experts (SMEs). This board is implemented for all new, modified, and heritage products. The "independent" aspects of the QRB are defined in Section 3.3.4, under Roles and Responsibilities.

The basic Qualification Process and Independent Review Model is shown in Figure 3-1. The qualification life cycle begins during the proposal phase when the initial qualification approach to the architecture at hand is defined. The process continues through the design and development phase where detailed qualification plans are prepared and executed, and ends at the Pre-Ship Readiness Review (or equivalent), when qualification data are verified to ensure compliance with requirements.

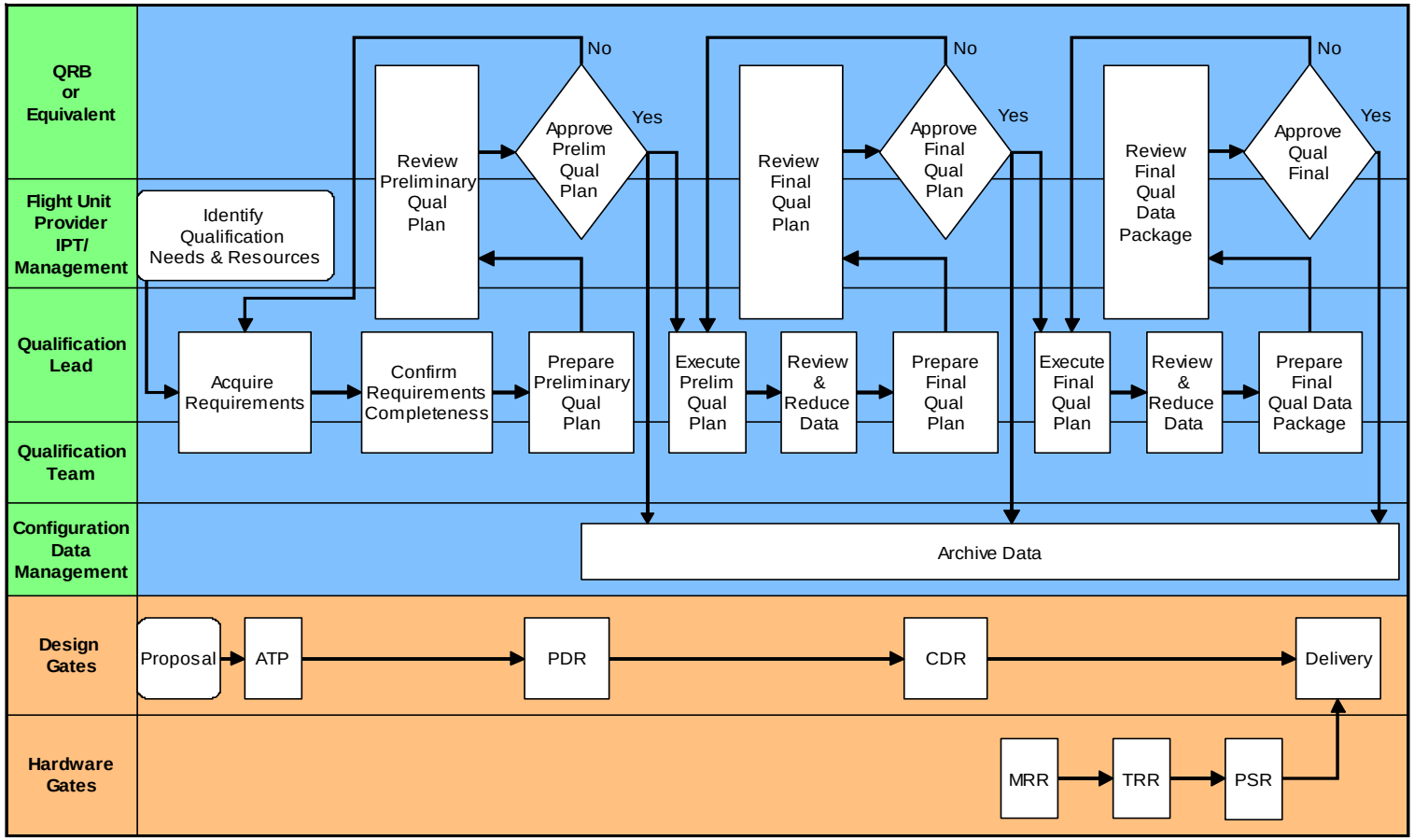


Figure 3-1. Qualification process and independent review model.

The overall qualification process and associated independent reviews consist of two basic focus areas - **planning and execution** - which are reviewed at specific gates along a typical program development cycle by the QRB.

A **Qualification Plan** is produced by the flight unit provider and approved by the QRB prior to beginning any qualification or verification activity. Qualification Plans are intended to be reviewed in a preliminary and final fashion at gates coincident with program PDR (Preliminary Design Review) and CDR (Critical Design Review) respectively. If desired, the two reviews can be integrated into a single review prior to the CDR.

A **Qualification Data Package** (QDP), sometimes referred to as Qualification Description Document or QDD, is produced by the flight unit provider. The QDP is approved by the QRB after the test plans have been executed, any anomalous results have been adjudicated, all requirement compliance evidence have been provided, and all associated liens have been cleared at a gate roughly corresponding to program Manufacturing Readiness Review (MRR) or the start of flight production. This activity continues up through contractual flight unit delivery.

3.2 Qualification Process

Although specific details of the flight unit qualification process may differ between organizations, it is important to maintain the following key qualification principles throughout the flight unit development:

- Develop appropriate flight unit qualification requirements and plans, in conjunction with approval by all stakeholders, including internal/external customers and QRB or equivalent
- Ensure that Qualification by Similarity of a flight unit satisfies the same rigorous qualification process as a new flight unit, including demonstrating by objective evidence that any differences between the similar and qualified units do not invalidate the unit's prior qualification. All stakeholders, including internal/external customers and independent QRB or equivalent, should review and approve the qualification approach
- Maintain agreement between internal/external customers and QRB relative to the qualification requirements and plan, with all changes and deviations documented and approved and configuration control of document revisions maintained
- Ensure that all parts, materials, and manufacturing/assembly processes are fully qualified, and reviewed/approved by internal/external customers (e.g., PMPCB) and/or PMP QRB or equivalent, prior to fabricating the flight hardware. Deviations between the qualification unit PMP and the flight unit PMP should be identified in the Flight Unit Qualification Plan
- Ensure proper execution of the qualification plan and compliance of qualification requirements, with appropriate review and approval of a QDP by internal/external customers and QRB or equivalent

Figure 3-1 provides an overview of the top level process for space flight unit qualification. For new, modified, and heritage units, qualification requirements should be defined and implementation and verification plans developed to ensure that the unit is appropriately qualified to meet flight system specific requirements and internal/external customer standards. In general, the process starts during the proposal phase, when the program qualification strategy and preliminary qualification requirements are defined, based on the flight system requirements that are flowed down from the internal/external customers. After ATP (Authority to Proceed), the flight unit provider prepares the program-level qualification requirements for approval by the customers and the QRB, based on the finalized Statement of Work and Technical Specifications. In cases where the contractual test

requirements documents permit tailoring, the prime contractor will appropriately tailor the requirements, with concurrence of the internal/external customer. A justifiable and sound rationale for tailoring must be provided, typically based upon any one or more of the following criteria:

- Specific type of space program (e.g., DOD-HDBK-343 Spacecraft Class definitions, A, B, C, or D[1])
- Maturity level of the hardware
- Anomaly/failure history for unit/product for similar subsystem/vehicle application and environment
- Specific type of product/unit
- Mission requirements (e.g., lifetime, radiation, thermal, and mechanical stress environments, etc.)
- Sufficient historical data on similar units/products to support proposed "best value" test requirements

The planning phase of the process is critical to successful flight unit development and operation. Many implementation and operational problems and failures can be traced to escapes in this phase of qualification. Therefore, the preliminary qualification plan should be submitted for review and approval by the customers and QRB prior to the flight unit PDR. This plan should include detailed definition of the analysis, inspection, and test planning, along with applicable supporting documentation. If facilities must be developed to support qualification testing, that effort must be identified during the proposal phase and refined after ATP.

Between the PDR and the CDR, the majority of the flight unit requirements that will be "qualified by analysis" at the unit level should be completed and verified. For requirements that will be "qualified by inspection" or "qualified by test" the flight unit provider should define all inspection and test requirements and clearly show the correlation to the contractual requirement source (e.g., applicable requirements sources such as MIL-STD-1540 [2]). Prior to the start of any qualification verification activities, any changes to qualification requirements and/or updates to the qualification plan should be made available to the customer and QRB for final approval. If an update to the plan is rejected, the flight unit provider will rework the plan and return it for approval. Once the updated plan is accepted the qualification team will proceed with executing the agreed-upon plan.

Following CDR, the flight unit provider should prepare and conduct a qualification/flight unit MRR where the detailed manufacturing and assembly procedures and inspection plans are reviewed and approved. After successful completion of assembly and inspection of the qualification/flight unit, the flight unit provider should prepare and conduct Test Readiness Reviews (TRRs) where the detailed Test Plans and Test Procedures are reviewed and approved by all stakeholders. Prior to the TRR, any proposed changes to the qualification plan need to be brought to the QRB for review and approval. After approval of the TRR by appropriate SMEs, the flight unit provider is responsible for executing the qualification tests, reviewing/analyzing all test data to verify compliance with test requirements, documenting test results, adjudicating any anomalous results, and clearing all associated liens. Any anomalies that may have occurred during the qualification test effort should be documented with root cause and resolution. This includes rationale for continued testing and/or corrective action based on root-cause assessments. Post-test inspection results should be documented with discrepancies identified.

After completion of all analyses, examinations, and test activities, the flight unit provider should review the qualification results to confirm that success criteria have been satisfied and any discrepancies have been identified. In addition, recommendations for additional corrective action,

testing and/or evaluation should be stated. The flight unit provider is then responsible for preparing the QDP, which represents the final data (including analyses and examinations data) from the qualification effort. The QDP is used to verify that the flight unit meets all the requirements.

Prior to the pre-ship review (PSR), a QRB meeting should be held where the flight unit provider presents the product QDP including requirement compliance verification documentation for review and approval by the customers and QRB. If the full complement of test data is not available for review and approval at the QRB meeting, then the final test data should be reviewed and approved at the PSR.

At the pre-ship review, the QRB should state whether the unit is deemed fully qualified or conditionally qualified, with liens for qualification activities that have not yet been completed. These liens may be for outstanding analyses, inspections, environmental tests, life tests, demonstrations, or perhaps open discrepancies reports, FRBs, UVF, NSMARS, NSPARS, waivers, etc. The conditional qualification is used to prevent flight units from being exposed to the next higher level assembly integrated test environments when they have not yet been verified on the qualification, protoqualification, or protoflight units. Conditional qualification liens should be tracked by the QRB. These liens are the responsibility of the flight unit provider responsible engineer to close.

After all liens have been closed and final approval of the QDP has been obtained from the QRB, the unit should be deemed qualified. The approved and archived documentation constitutes the unit's certification record. A qualification certification may also be generated to document the successful completion of the delivery review.

3.3 Roles and Responsibilities

3.3.1 External and Internal Customers

The external customer defines the qualification requirements and approves the qualification approach, including approval of tailoring of the requirements as appropriate. The external customer has the responsibility for final approval/acceptance of the delivered flight hardware. The internal customer, or internal company institutional standards, establishes the qualification process and approves any deviations from the process. In particular, the internal customer and/or company institutional standards should define the requirements and process for establishing an Independent QRB or equivalent Independent Review Board.

Participants from the external customer who may be involved in defining the qualification requirements and reviewing/approving the qualification approach include:

- Mission Assurance Manager
- Contract Technical Manager or Chief Engineer
- SMEs from Federally Funded Research and Development Centers (FFRDCs)
- SMEs from SETAs (System Engineering and Technical Analysis) representing the customer
- Program Execution Advisors

3.3.2 Prime Contractor

The prime contractor has ultimate responsibility for ensuring that the flight unit qualification complies with the external customer requirements and providing proof (necessary and sufficient evidence) that the flight unit meets or exceeds all requirements. The Prime Contractor assigns a

Program Manager/IPT with responsibility and accountability for program execution. The Program Team has the responsibility to comply with both external customer requirements and the internal "customer" requirements (e.g., internal company institutional standards). In cases where the contractual test requirements documents permit tailoring, the prime contractor is responsible for ensuring that the qualification requirements are appropriately tailored, with concurrence of the external customer, based on the specific type of space program (e.g., DOD-HDBK-343 Spacecraft Class definitions, A, B, C, or D [1]), the specific type of product/unit, and associated mission requirements (e.g., lifetime, radiation, thermal, and mechanical stress environments, etc.). For subcontracted units, the prime contractor has the responsibility to appropriately flow down the requirements for performing the qualification process to the subcontractor through the subcontract requirements documents (Statement of Work, Technical Specifications, and Subcontract Deliverable Requirements) and for ensuring that the flight units developed (designed, developed, fabricated, qualified, tested, and delivered) by subcontractors/suppliers and their lower tier suppliers, have been appropriately qualified prior to delivery. The prime contractor has the responsibility for reviewing and approving the subcontractor's qualification plan prior to qualification testing and the QDP prior to unit delivery. In order to effectively perform these functions, the prime contractor should establish an Independent QRB, or equivalent function.

The Qualification Process at the Prime Contractor may include the following participants:

- Space Segment Systems Engineering Manager
- Technical Lead/Chief Engineer
- Space Segment Quality Assurance Lead
- Systems Engineering Integration and Test Reliability Engineering Lead
- Vehicle Program Director
- Product Responsible Engineers
- Engineering discipline Subject Matter Experts
- Mission Assurance Manager
- Internal/External Customer and/or customer technical representatives

3.3.3 Flight Unit Provider

The flight unit provider can either be an "in-house" team (e.g., part of the prime contractor's program IPT) or a subcontractor/supplier that is responsible for the design, development, fabrication, qualification, and acceptance testing of the Flight Unit. The flight unit provider is responsible for developing the Qualification Plan, ensuring that the Qualification Plan is approved by an Independent QRB and the prime contractor QRB prior to start of qualification testing, executing the analysis, examination, and test activities per the approved plan, documenting all results, verifying that the qualification results meet the success criteria, preparing and presenting the QDP for approval to an Independent QRB, and certifying that the hardware will meet its defined mission and contractual requirements. The flight unit provider will typically assign a qualification lead (e.g., responsible engineer), who has overall responsibility for performing the flight unit qualification effort. In order to ensure that these functions are performed appropriately, the flight unit provider will often establish an internal Independent QRB or equivalent function. The prime contractor should either participate as a stakeholder in the Flight Unit Provider's QRB or should perform a separate review and approval of the Flight Unit Provider's Qualification Plan and QDP at the prime contractor's QRB.

The Qualification Process at flight unit provider may include the following participants:

- Qualification Board Chairperson (if applicable)
- System Engineering Manager
- Mission Assurance Manager
- Verification Lead
- Reliability Lead
- Subject Matter Experts
- Responsible Engineer
- Procurement or contracting representatives (if unit is subcontracted)
- Customer

3.3.4 Qualification Review Board

To ensure that a robust qualification is performed, it is strongly recommended that an Independent QRB or equivalent be formed to provide oversight of the flight qualification process. The QRB achieves this oversight by reviewing and approving the Qualification Plan, reviewing and approving the QDP, and validating that necessary and sufficient evidence is provided to certify that the flight unit meets the specified mission requirements. This team is comprised of qualification experts, product-specific technical SMEs, and engineering discipline SMEs.

For subcontracted hardware, the QRB, or equivalent function, may exist at the subcontractor organization as well as at the prime contractor. In those situations, the subcontractor QRB (or equivalent function) performs the initial review/approval of the Qualification Plan and initial review/approval of the QDP and then presents the supporting artifacts to the prime contractor QRB (or equivalent) for final review and approval. Some organizations do not separate the roles and responsibilities of the Independent QRB from those performed by an Independent "Standing Review Board." Others have a "sell-off board" that engages only at the end of the flight qualification process. For the purpose of this document, an Independent QRB or equivalent should satisfy the following criteria:

- Board has a reporting path that is "independent" of the program infrastructure, which enables the board to identify areas of concern/risks to high level program and functional management internal to the company. In particular, the Board shall be independent of the producing organization
- Board is comprised of qualification experts, product-specific SMEs, and engineering discipline SMEs with the technical expertise, accountability and authority to approve or disapprove qualification plans and qualification data packages
- Board has responsibility to review and approve the key products (Qualification Plans and the QDP) prepared and presented by the flight unit provider. Formal reviews of these documents should be aligned with the program/product CDR and program/product PSR (Project Status Review)

3.3.4.1 Qualification Board and Verification Support Membership

The Qualification Board is typically composed of the following cross-disciplines to ensure adequate qualification assessments and reviews are made:

- Qualification Board Chairperson
- System Engineering Manager
- Mission Assurance Manager
- Verification Lead
- Reliability Lead
- Subject Matter Experts

Verification of product designs is performed by the owners of the product specification and the requirements. The Verification Team consists of Responsible Engineers (REs), typically including the following cross-disciplines:

- Mechanical
- Electrical
- Structural
- Dynamics
- Thermal
- Parts, Materials and Processes
- Survivability
- Performance

Other product experts and stakeholders may be invited to participate as required.

The specific responsibilities of the QRB are as follows:

- Review the Product Qualification/Requirement Verification plans to ensure the adequacy of qualification approaches and verification methods
- Ensure plans are compliant with subsystem/product specifications, Customer Test Requirements Documents (TRD), Environmental Specification, and Internal Command Media
- Ensure that contractual flow-down environmental test requirements are appropriately tailored for the type of program/product
- Assess hardware pedigree usage plans to assure that the hardware and design represents the design which will fly
- Perform a rigorously review of an “analysis of the differences” for Qualification by Design Similarity approaches
- Provide senior guidance and direction when requirements conflict, when they are inadequate, or when lack of requirements exist

- Identify/implement Lessons Learned from previous Product Qualification Program on similar products
- Review Product Team's final QDP and supporting artifacts to ensure that the package provides adequate validation that the flight unit was appropriately qualified per the previously approved requirements
- Ensure that all changes from the original, approved qualification plan (hardware design, requirements, verification approach, other) have not compromised the validity of the qualification program

3.3.5 SME Roles

Technical SMEs assist in the flight qualification process. In general, Technical SMEs can be divided into two categories: (1) Product-Specific Technical SMEs and (2) Engineering Discipline SMEs. The Product-specific SMEs typically have a broad technical knowledge of the specific product and can provide lessons learned from previous product qualification efforts and/or in-flight performance. The Engineering Discipline SMEs typically have an in-depth technical knowledge of critical engineering disciplines, such as EMI/EMC, radiation, etc.

3.4 Qualification Strategies

Various qualification strategies are available to the flight unit provider [1-4] and can be utilized to balance the often competing needs to meet contractual requirements, reduce risk, and operate within challenging budget and schedule constraints. Experience has shown that qualification risk often manifests itself very late in the development cycle where impacts are felt well beyond the unit in question. Careful consideration should be given to weighing the benefits, risks, and impacts from a more holistic perspective prior to settling on a given qualification strategy. Such considerations include trading the cost of a rigorous qualification against unplanned activities required to prosecute late developing qualification failures, associated schedule impacts to Integration & Test activities, and possible reach-across or reach-back investigations.

Selecting the appropriate qualification strategy is typically a trade between affordability and risk with the former usually being the most apparent input to the trade space. The challenge then becomes one of carefully assessing the real risk involved in selecting strategies that do not completely reduce qualification risk. Figure 3-3 provides a graphical depiction of the most commonly employed qualification strategies and their respective benefit/risk profiles. While the benefits and risks listed are by no means comprehensive, they have proven to be key drivers in the ultimate success or failure of any given qualification effort.

Table 3-1 provides additional information of the more common qualification strategies in order to aid the qualification practitioner in making a more informed decision when considering and comparing the available options. In addition to benefits and risks, Table 3-1 also includes strategy, verification hardware and test requirements descriptions, and applicability or typical usage guidelines.

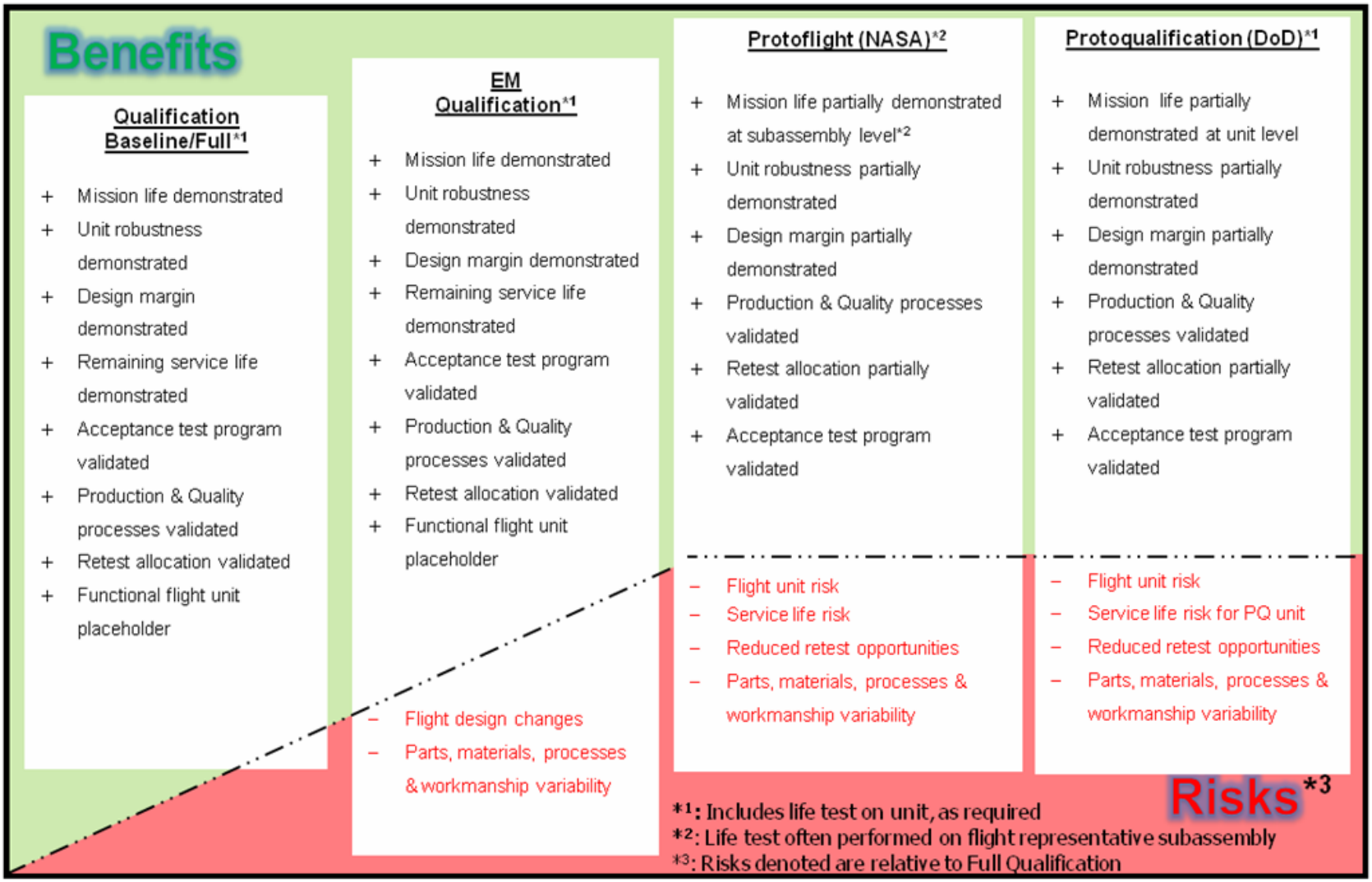


Figure 3-2. Flight unit qualification strategy overview.

Table 3-1. Qualification Strategy Comparisons*

Strategy	Description	Design Verification Hardware	Design Test Verification Requirements	Applicability	Benefits	Risks
Qualification (Baseline/Full) [1-3]	Design hardware to all qualification requirements Test a dedicated hardware unit to all qualification requirements to verify the design requirements and screen for workmanship defects Acceptance tests the follow-on flight hardware to screen for workmanship defects	A dedicated test article, identical to flight article The test article is not planned for flight usage	The qualification test article of a given design will be exposed to all applicable environmental qualification tests (e.g. Table 6.3-1 of [2])	New unit designs Heritage unit design in a new application Modified unit design in a new application Units subject to wear-out, drift, fatigue-type failure mode, EOL performance degradation, and/or mission critical assemblies Class A Program	Mission life demonstrated Unit robustness demonstrated Design margin demonstrated Remaining service life demonstrated Acceptance test program validated Production and quality processes validated Retest allocation validated Functional flight unit placeholder	Minimal Risk

Strategy	Description	Design Verification Hardware	Design Test Verification Requirements	Applicability	Benefits	Risks
EM Qualification	Same as Qualification Baseline except that testing is performed on an EM instead of a unit that is identical to the flight article	A dedicated EM with high design fidelity to the flight units Produced in the same flight production environment The EM is not planned for flight usage	Same as Qualification Baseline	Where cost/ schedule constraints prohibit using dedicated test article that is identical to flight article	Mission life demonstrated Unit robustness demonstrated Design margin demonstrated Remaining service life demonstrated Acceptance test program validated Production and quality processes validated Retest allocation validated Functional flight unit placeholder	Risk is higher than baseline/full qualification program Flight design changes not qualified Parts, materials, process, and workmanship variability

Strategy	Description	Design Verification Hardware	Design Test Verification Requirements	Applicability	Benefits	Risks
Protoflight [4]	Design hardware to all qualification requirements Test the PF hardware to all PF requirements to verify the design and screen for workmanship defects Implement auxiliary life test mitigation strategy to demonstrate lifetime requirements Protoflight test the follow-on flight hardware to screen for workmanship defects	First and follow-on flight units	The PF unit of a given design will be exposed to all applicable environmental PF tests (e.g., Table 2.2-2 of [4]) Protoflight test levels and durations are the same as those for qualification except that for dynamics tests, acceptance durations are specified Life test mitigation addressed during design and dedicated life test on a dedicated unit or on a critical unit assembly	Designs with extremely limited production and a single mission application (e.g., science instrument) Designs where Prototype Qualification is not required [4] Design where demonstration of a specific mission lifetime is not required and test unit will be used for flight Designs with extremely limited production, where there is significant design heritage and known design margins, and test unit will be used for flight Class A & B programs (NASA)	Mission life may be partially demonstrated at subassembly level with additional life testing of representative subassemblies Unit robustness partially demonstrated Design margin partially demonstrated Acceptance test program validated Production and quality processes validated Retest allocation partially demonstrated (using design capabilities and analysis results)	Medium Risk Mission life not demonstrated on units without life testing No formal demonstration of remaining service life for flight Presumes a higher risk by testing actual flight article to demonstrate margins, unless mitigated by other testing and analyses Presents reduced retest opportunities in the event of hardware failure, and the potential for the discovery of design defects Parts, materials, process, and workmanship variability

Strategy	Description	Design Verification Hardware	Design Test Verification Requirements	Applicability	Benefits	Risks
Protoqualification [2, 3]	Design hardware to all qualification requirements Test the first flight hardware to all PQ requirements to verify the design and screen for workmanship defects Acceptance test the follow-on flight hardware to screen for workmanship defects	First flight unit	The first flight unit of a given design will be exposed to all applicable environmental PQ tests (e.g. Table 6.3-1 of [2]) Protoqualification testing applies reduced amplitude and duration margins to flight hardware	Designs with limited production, where there is significant design heritage and known design margins, and test unit will be used for flight Class A and B Program (DoD)	Mission life partially demonstrated at unit level by test duration/cycle requirements for PQ unit and/or by life test unit Service life demonstrated for acceptance units up to PQ levels and durations Unit robustness partially demonstrated Design margin partially demonstrated Acceptance test program validated Production and quality processes validated Retest allocation validated for acceptance units (up to PQ levels) and partially demonstrated for PQ unit (using design capabilities and analysis results)	Medium Risk Mission life only partially demonstrated for PQ unit through life tests on representative units No formal demonstration of remaining service life for the PQ unit for flight Presumes a higher risk by testing actual flight article to demonstrate margins, unless mitigated by other testing and analyses Presents reduced retest opportunities in the event of hardware failure, and the potential for the discovery of design defects Parts, materials, process, and workmanship variability

*Other less common strategies include Prototype Qualification [4] and Flightproof [2, 3]

3.4.1 Benefits and Risks Description

The following is a brief description of benefits and risks which are paraphrased in both Table 3-1 and Figure 3-2 and ascribed to the appropriate qualification strategies:

3.4.1.1 Benefits

Mission life demonstrated – sufficient empirical testing has been accomplished to demonstrate the actual service life of the unit for the duration of the mission, typically through some form of accelerated environmental test program; known and unknown issues are quantified and any pertinent resolutions dispositioned for incorporation into flight designs or processes

Unit robustness demonstrated – sufficient qualification testing has been accomplished to verify that the unit can withstand the rigors of exposure to parameters that exceed worst case manufacturing, test, and service conditions; unit is capable of handling reasonable variations in parts, materials, processes, and production workmanship

Design margin demonstrated – testing to qualification levels and duration/cycles in order to verify worst case analytical predictions and margins

Remaining service life demonstrated – testing to qualification levels in order to establish a "known good" unit life capacity; critical in determining an empirical basis for the Cumulative Damage Index (CDI) and subsequent retest allocation for a given unit

Acceptance test program validated – screening methods, test sequences, procedures, equipment, and processes are ready for flight unit production

Retest allocation validated – related to remaining service life; the amount of retest capacity available to units which undergo acceptance testing

Production and Quality processes validated – production methods, facilities, processes, and equipment are ready for flight unit production; quality systems including inspection, anomaly resolution, configuration management, and related documentation procedures are operating as intended

Functional flight unit placeholder – qualification, EM, or development unit capable of being inserted as a functional placeholder for test bed, subsystem, or systems level activities in the event of contingency needs

3.4.1.2 Risks

Parts, materials, processes and workmanship variability – off-nominal risk associated with lot-to-lot variability in materials, piece parts, production processes, and workmanship

Flight design change risk – design changes made after the qualification baseline has been established and which have not undergone explicit qualification testing in the intended application

Design margin risk – testing to less than qualification levels and/or durations reduces demonstrated design margins and can seriously inhibit root cause investigations should a unit failure occur

Service life risk – testing to less than qualification levels and/or durations reduces the "known good" useful life capacity of a unit and can severely limit the number of retest exposures without an

exhaustive CDI analysis being completed; conversely, testing flight units to more than acceptance levels and/or durations can erode remaining useful life

Flight hardware risk – testing flight hardware to protoflight or protoqualification levels/durations adds risk to flight hardware by reducing remaining service life; employing certain design verification tests such as shock, radiation, or certain EMI/EMC tests on flight units vs. dedicated qualification articles can put the hardware at risk for test execution failures, unintended damage, and/or the introduction of undetected latent failure mechanisms

3.4.2 Life Testing Relationship to Qualification Strategies

Life testing is an intrinsic part of any given qualification strategy and is often called for explicitly in cases where the unit is deemed to be a critical item that may have a wear-out, drift, performance degradation, or fatigue type failure mode [1-4]. Such items typically include mechanisms, batteries, solar arrays, and pressure vessels. There are however, many other items that fall under the broad umbrella of fatigue type or degradation failure modes including virtually all microelectronics, electronics, optical assemblies, and many structural items. It is critical that any qualification strategy contain a life risk assessment for all components, materials, processes, packaging technology, and sub-assemblies that will make up the unit design. This is especially true for designs that will utilize new or unproven technologies, existing technologies used in new applications, or new production processes.

Once a life risk assessment has been made, some form of life test program is often indicated in order to further mitigate unit life risk. Such programs can range in scope from key components or sub-assemblies up through a dedicated life test unit depending on which aspects of the design require additional life test data. Architecting a life test typically includes the following elements:

- One or more flight-like development units, prototypes, subscale units, sub-assemblies, or critical components are selected based upon the life risk features being prosecuted
- Test conditions are designed to simulate service conditions including environments and operating modes [2]
- Test limits and durations are designed to simulate the maximum operating time and maximum number of operational cycles predicted during service life including all manufacturing and ground test exposures
- Functional testing is conducted before, during, and after service life testing in a manner sufficient to establish trends
- Accelerated life testing is often conducted to a 1X or 2X mission profile in order to generate the required data in a timely manner; adherence to generally accepted analytical practices for fatigue accumulation are required in order to avoid over-test conditions
- Life testing may be allowed to proceed to failure to better understand fatigue and failure mechanisms
- Disassembly and inspection of the life test unit after completion of the life testing to better understand fatigue and failure mechanisms

3.4.3 Qualification Strategy Recommendation

It is strongly recommended that a minimal risk qualification strategy, including life testing, be considered for any Class A and B missions, regardless of build quantities, as the downstream impacts of a qualification failure often far outweigh the cost of a rigorous unit level qualification. Class C and D missions may select a higher risk qualification strategy, based on acceptable mission risks, as approved by the QRB and the customer.

3.5 Qualification by Similarity

The use of identical or similar flight units on multiple different programs is of interest to both industry and the customer community since it offers the opportunity for reduced cost, schedule, and technical risk. If previously qualified hardware can be used in new applications, not only are the design, tooling, and qualification costs eliminated and the production costs reduced, but the continuing flight usage increases confidence in the unit's reliability. In practice, however, obsolescence of parts and/or unique requirements of the different programs may result in minor changes to the previously qualified unit design, manufacturing, and/or testing. If those changes are within reasonable bounds, as defined herein, then it may be possible to qualify the modified unit based on its similarity to the previously qualified unit by following the process described in this section.

3.5.1 Qualification by Similarity Process

Qualification by similarity (QBS) of a candidate flight unit is a rigorous qualification process similar to that of a new flight unit as described in Section 3.2. Figure 3-3 shows a general QBS process flow diagram. QBS involves two units: a candidate unit (Unit A) seeking flight unit qualification and a previously qualified unit (Unit B). The candidate unit is generally derived from the previously qualified unit with minor modifications or is subject to minor differences in requirements. The intent of QBS is to qualify Unit A by using the QDP of Unit B (e.g., analyses, test data, etc.) to satisfy the verification requirements based on similarity. Qualification by similarity requires two evaluations: (1) review of the QDP and flight usage record of Unit B, and (2) verification of the similarity between Unit A and Unit B in terms of performance/functional requirements, environments, design (including parts, materials, and processes), manufacturing and testing.

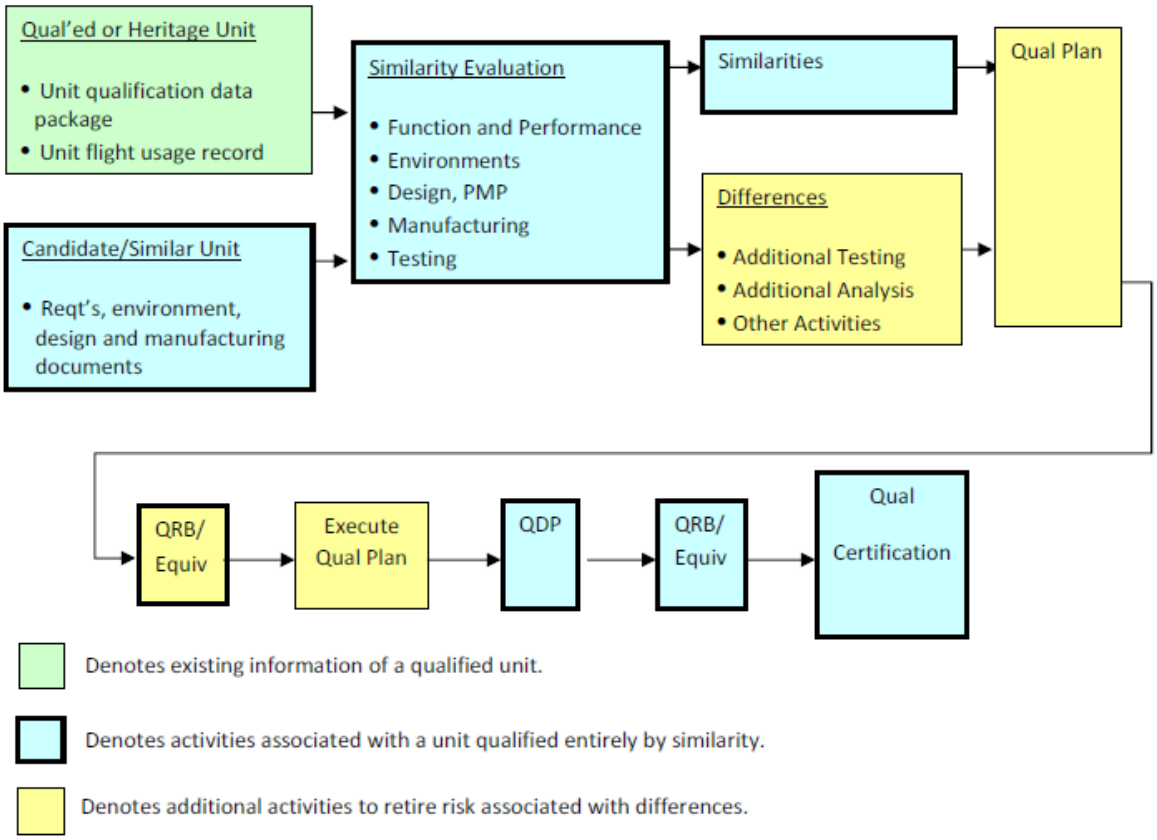


Figure 3-3. Qualification by similarity process flow diagram.

The QDP of the previously qualified unit serves as objective evidence for the basis of QBS. The previously qualified unit can be from a different program, different customer, or the same customer/program. For heritage hardware, the QDP and flight usage history should be used to determine the Heritage Hardware Readiness Level (HRL) per the criteria defined in Heritage Hardware Reuse [12]. Even though a unit may have flight heritage and a favorable HRL, the unit should still be qualified for its intended use by following the QBS process described herein. The effort required to establish the HRL becomes a part of the formal qualification process.

In order to be used as part of the QBS process, the previously qualified unit must meet the following criteria:

- Unit B is a test-qualified unit (i.e., Unit B was not qualified by similarity).
- Unit B was a representative flight article or a heritage (flown) unit.
- Unit B should have successfully passed a post-environmental functional test series, without the need for performance-associated waivers, indicating that the unit survived the qualification stresses.
- Supporting documentation for Unit B is available and includes specifications, drawings, qualification test procedures, descriptions of test configurations, records of modifications during tests, qualification and acceptance test reports, problem failure, and deviation reports with closure history, test waivers, and flight history summaries.

The major activity in QBS is performing the "similarity" evaluation between the candidate unit and previously qualified unit. Similarities and differences are evaluated in five categories: performance requirements, environments, design, manufacturing, and testing. A set of criteria for similarity evaluation is provided below. A checklist for QBS is provided in Section 4.6, Table 4-9.

- **Function and performance.** Units A and B should perform similar functions, with B having equivalent or greater operating life and performance requirements, with variations only in terms of performance such as accuracy, sensitivity, formatting, and input-output characteristics.
- **Environments.** The environments (e.g., shock, vibration or acoustic, acceleration, thermal, EMC/EMI, radiation, etc.), both amplitude and duration, encountered by Unit B during its qualification or flight history have been equal to or more severe than the qualification environments intended for Unit A.
- **Design and PMP.** The design requirements of Unit A should be enveloped by those of Unit B. Unit A should be a minor variation of Unit B.

  Dissimilarities of interface, safety, reliability, maintainability, weight, mechanical configuration, thermal effects, dynamic response, and structural, mechanical, and electrical configurations require that Unit A characteristics be enveloped by the characteristics of Unit B.

  Minor design changes involving substitution of piece parts and materials with equivalent reliability items from the program approved parts and materials list can generally be tolerated. Design dissimilarities resulting from addition or subtraction of piece parts and particularly moving parts, ceramic or glass parts, crystals, magnetic devices, and power conversion or distribution equipment usually compromise qualification based on similarity.
- **Manufacturing.** Units A and B were produced by the same manufacturer using same materials, parts and packaging techniques, and identical tools, manufacturing processes, quality control procedures, and in the same facility. A change in workmanship may invalidate previous hardware qualification.
- **Test.** The test requirements of Unit A should be enveloped by those of Unit B. The test sequence and test configuration of Unit B should be consistent with the intended use of Unit A. Any modifications during testing to enable a successful completion of the test program should be reviewed.

Because of the complexity of QBS, the criteria stated above may not fully cover all flight units, all missions, all qualification strategies, and all combinations of similarities and dissimilarities. Therefore, it is important that the similarity evaluation be performed by SMEs using the latest versions of specifications, drawings, analysis reports, test reports, failure reports, discrepancy reports, etc., of the two units as objective evidence. The assessment of the SMEs should be reviewed and approved by the QRB, with the results of the review documented in a QBS certificate, or equivalent, and included in the verification package. If the candidate unit is entirely qualified by similarity, the unit can be treated as qualified and need only to be subjected to acceptance level test requirements with the approval of the QRB. In practice, it is not common for a unit to be entirely qualified by similarity. Often, minor design changes are necessary due to material and parts substitution as a result of obsolescence, new facilities, minor differences between performance requirements and/or minor differences in environmental conditions, etc. The degree of similarity or differences between the two units should be evaluated by a team of SMEs, including product and PMP specialists, as well as engineering discipline experts (e.g., thermal, structures, electrical, etc.). As part of the assessment, the SMEs should provide recommendations of additional activities (e.g., testing, analysis, etc.) to mitigate risk associated with differences between the units. The delineation between the type/extent

of differences that result in the need for additional qualification activities versus those that do not, as well as the extent of the risk reduction activities required, is subject to the judgment and experience of the SMEs. Therefore, the technical rationale for the SME QBS assessment should be clearly documented and presented to the QRB for review and approval.

For situations where additional qualification activities are recommended, a qualification plan should be prepared and presented to the QRB for review and approval, as shown in Figure 3-3. In some cases, additional analysis or re-evaluation of existing analysis can be performed to show compliance, (e.g., evaluating margins of safety of the qualified unit with respect to increase in launch loads). In other cases, unique M&P requirements may require a lower-level confirmatory test, (e.g., coupon-level tests of a composite material). On the other hand, a delta qualification test program may be required to provide test verification of the identified differences, (e.g., a change in manufacturing process, facility, supplier, etc.). In this case, a test plan should be developed to verify the identified differences. The delta qualification test requirements can be addressed by performing additional testing on the original qualification article (e.g., perform additional pressure and/or thermal cycle tests to verify new mission life requirements) or by performing protoqualification or protoflight tests on the candidate flight unit. The effects of performing limited qualification testing on either the qualification unit or the candidate unit must be understood and addressed in the test plan. Sufficient perceptive/functional and environmental testing should be performed to ensure that the differences have been adequately verified and that no new problems have been introduced. This may entail a set of accompanying tests for perceptiveness of potential failure modes, followed by unit functionality checks, (e.g., a protoqualification shock test followed by an acceptance level random vibration test to precipitate potential failures). In any event, a qualification plan of the candidate unit should be prepared and submitted to the QRB for approval, in a manner similar to a new unit (Section 3.1). Discussions at the QRB should focus on achieving a balance between threshold of differences, perceived and tolerated risk, and extent of additional activities. The active participation of SMEs, REs and qualification experts in the QRB provide the check and balance necessary for a robust QBS.

Upon completion of additional activities, if any, a QDP (see Table 4-7) of the candidate flight unit should be prepared. The package should consist of objective evidence of the qualification and usage evaluation of the previously qualified unit, documentation of the similarity evaluation performed by the appropriate SMEs, technical rationale and/or additional analysis demonstrating that the differences between the two units (including design, parts, materials, and processes) do not invalidate the previous unit's qualification, and results from the delta qualification analysis and/or tests, including demonstrating compliance to the VCRM. The package should be presented to the QRB for review, approval, and certification. The package should then be archived.

3.6 Retest

3.6.1 Introduction

In the context of flight unit qualification, *Retest* is the repeat of previously conducted tests (functional, performance, and/or environmental) due to a redesign, a change in a manufacturing process, a test discrepancy, an increase in flight environments, or rework/refurbishment of items previously tested [2, 4]. Minor changes in design, manufacturing processes, flight environments, or rework can sometimes have a significant effect on the reliability of flight hardware. Retesting of a unit is very often performed due to:

- Requalification/Re-protoqualification after *Redesign*
- Requalification/Re-protoqualification after a *Change in Manufacturing Process*
- Retest after *Test Discrepancy*

- Retest after *Change in Flight Environments*
- Reacceptance after *Rework/Refurbishment*

The results of analyses play a key role in decisions on the degree of retest. Nonetheless, regardless of the extent of the analyses, retesting is often necessary to restore complete confidence in the functional and environmental performance of flight items [2, 3, and 7]. Although maximum confidence exists in the integrity of a redesigned or repaired test article following corrective action if all previous tests are repeated, this path is not necessarily followed. If compromises are made in the degree of retest to maintain critical program constraints, the resulting risk should be assessed. The degree of retest has to be evaluated on a case-by-case basis considering the amount of redesign, the nature of the failure, the rework/refurbishment required, the opportunity for unknown collateral damage from the repair, and whether any previous tests could possibly have induced the failure or were invalidated by the corrective action. Therefore, the decision becomes a judgment on the amount of acceptable risk to both acquisition and mission success.

3.6.2 Definitions

Major Redesign and Requirement Changes. Corrective redesign and requirement changes for a component are defined as *"major"* if the test article, after the changes, violates one or more of the commonly used ground rules for qualification by similarity (see [3 and12], and Section 3.5).

Significant Rework. The corrective rework of a unit is defined as *"significant"* if the rework has caused a loss in confidence that tests prior to the rework are still valid.

Minor Redesign or Rework. A *"minor"* redesign or rework is one that does not fit the definitions for major redesign or significant rework. A minor redesign may involve no parts replacement such as tuning a system by adjustable devices. A minor rework may involve replacement of an easily unplugged or detachable part. A minor rework may have relatively small effect on the validity of previous tests.

3.6.3 General Guidance for Retest

The primary purpose of this discussion is to provide guidance for the degree of a retest on a unit should the need arise. The retest may be triggered by a redesign necessity, a change in a manufacturing process, a test anomaly, an increase in flight environments, or rework/refurbishment of items previously tested.

3.6.3.1 Retest Triggered by a *Redesign* Necessity

- The **degree of requalification** should be evaluated for each case considering the *nature of the redesign, criticality of the hardware, degree of redundancy, and cost of requalification.*
  - A key consideration is whether the design change can, in any way, affect the confidence gained from qualification of the originally designed item.
  - The decision to re-qualify, or on the degree of requalification, is a judgment on the tradeoffs between cost and the amount of acceptable risk.
- Any design change, modification, or configuration change occurring after completion of unit testing, in general, invalidates the test and analysis program, and depending upon the nature of the change, will be the cause for re-testing and updating of the analyses.

- Any design change or modification occurring after flight unit qualification testing requires an assessment to determine if reiteration of qualification testing and analysis is required.

3.6.3.2 Retest Triggered by a *Change in a Manufacturing Process*

- The **degree of process** change that can be made without requiring requalification must be evaluated for each case considering the *nature of the change, criticality of the hardware, degree of design redundancy, and cost of requalification*.
  - Minor changes in the process of a simple manufacturing step would generally not necessitate requalification.
  - Relocation of a manufacturing facility, even with no overt change in manufacturing processes, would require requalification.

3.6.3.3 Retest Triggered by a *Test Discrepancy or Anomaly*

- Failures of spacecraft hardware resulting from unit environmental testing, in general, invalidate the test program for that unit. Re-testing to prescribed environments is essential after the cause of the failure is corrected.
- The necessity for re-testing spacecraft hardware as a result of test equipment malfunction or failure should be determined by the project in consultation with the QRB or equivalent.

3.6.3.4 Retest Triggered by an *Increase in Flight Environments*

- If the predicted environments have increased to the point that qualification margins have been reduced to less than half the original qualification margins, then requalification should be performed.
  - This requalification, or delta qualification, may only involve the specific environments that have been revised. For example, if vibration predictions were to increase by 6 dB for units only a requalification or delta-qualification of the affected units to higher vibration levels may be necessary.

3.6.3.5 Retest Triggered by *Rework/Refurbishment*

- Rework as a corrective action frequently occurs during acceptance testing. The rework may be a repair which does not change the design. The major item of concern is the adequacy of the manufacturing and repair processes to perform the rework.
- The risk of the rework action may be divided into two categories:
  - The risk of degrading the unit by the repair operation
  - The risk of replacing a part with one that has not been screened by the previous component tests
- If hardware requires *considerable disassembly* to obtain access to perform the repair and subsequent reassembly, the majority of previous tests are probably invalidated, even if the actual repairs are relatively simple.

- The *number of disconnects* to remove a failed part or failed hardware, the *nature of the disconnects*, and the *complexity of performing the repair* are important in evaluating the risk of degrading the hardware.
  - If a part or unit can be simply unplugged, the risk of invalidating a previous test would appear less, since a functional test after the repair is completed could verify the adequacy of the repair, and possible damage to surrounding hardware is low.
  - A repair requiring soldering or welding involves the risk of damage to surrounding hardware which could invalidate previous tests.
- If a repair can be *inspected locally* in the same manner as it was inspected during original manufacture, considerable confidence in its adequacy can be obtained. In general, it is noted that *a repair which does not allow the same degree of in-process inspection* as was done during original manufacture has invalidated previous tests.
- If *a repair* is performed *under different conditions*, using considerably *different tooling and techniques* than were used during original manufacture; it has invalidated the previous tests.
- If *a part is replaced*, it is necessary to know its *previous test experience*. If the replaced part has not been screened to the *same degree or in a more severe environment* than it experienced *during unit tests*, the unit tests conducted prior to the failure have been invalidated.

3.6.4 General

The *accumulated test time on test articles* must be considered when dynamic retests are planned, so that their *fatigue life* is not expended. Similar fatigue considerations are subject to different conditions and exist for thermal cycling, life cycle testing, and burn-in tests.

Figure 3-4 is a simplified logic flow diagram that can be used for evaluating the level of retest required based on the cause of the retest, the type of corrective action, and whether the change is classified as major or minor. Specific decision point values stated in the logic flow should be in agreement with established requirements and with customer approval.

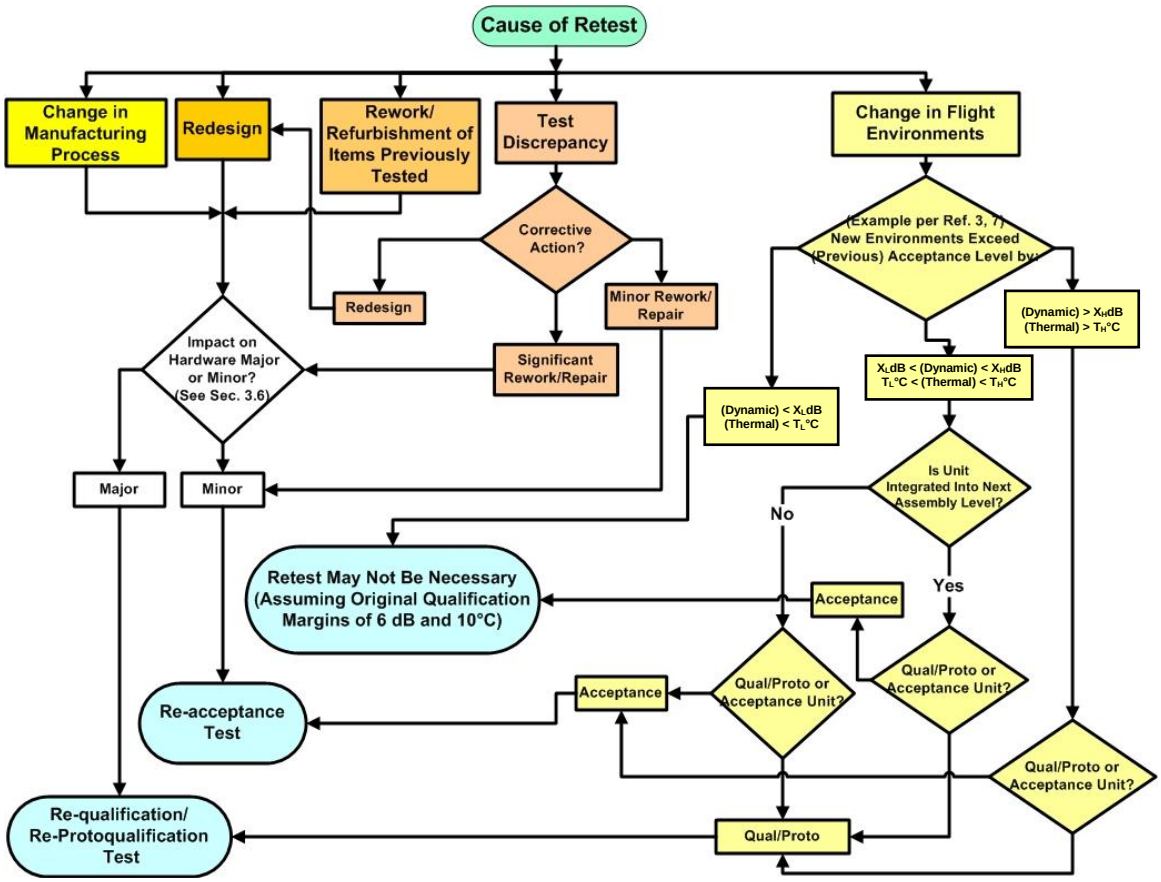


Figure 3-4. Retest logic flow diagram.

3.7 Best Practices for Flight Unit Qualification Success

Although flight programs can vary in organization, it is important to maintain some key qualification principles throughout the flight unit development process in order to ensure hardware reliability and robustness. The following best practices and themes have been found to greatly enhance the successful execution of qualification processes:

3.7.1 Qualification Review Board (or equivalent Independent Review Board): Functions and Timeline

1. An independent QRB, or equivalent comprised of appropriate SMEs, including qualification experts, product-specific technical experts, and engineering discipline experts, should be established by the prime contractor and, as applicable, by the flight unit provider.
2. The program-specific qualification requirements should be reviewed and approved by an Independent QRB (or equivalent) and internal/external customers.
3. The Qualification Plan should be reviewed and approved by an independent QRB or equivalent prior to implementing qualification activities; best practice is to perform a review/approval of the qualification requirements and preliminary qualification plan prior to PDR and review/approval of final qualification plan and specific testing requirements prior to CDR. Requirement compliance verification methods and levels should be thoroughly reviewed and approved prior to implementing the Qualification Program.
4. The QRB should conduct formal reviews that are aligned with, but separate from, the standard product development milestones such as PDR/CDR, MRR, and TRR. This will

ensure sufficient emphasis on the qualification planning and implementation as well as ensure that the appropriate SMEs are in attendance.

5. The QRB should have a reporting path that is independent of program reporting structure which enables the board to identify areas of concern/risks to high level program and functional management internal to the company. In particular, the Board shall be independent of the producing organization.
6. For situations where the independent QRB and internal program team are unable to reach agreement, the issue should be elevated to a higher level internal company risk board for adjudication.
7. The QRB should verify that agreement between all the stakeholders (customer, prime contractor, and flight unit provider) has been maintained, with all changes and deviations documented and approved by stakeholders.
8. The QRB should issue action items as necessary to ensure that concerns regarding qualification plans and/or resultant qualification data evidence are properly closed. These actions should be managed in a real time action item database. Their status and metrics are regularly briefed to program management to ensure that program resources are focused in qualifying units for flight per schedule commitments.

3.7.2 Qualification Process: Qualification Plan, Qualification Data Package, Qualification Description Document, and Qualification Certificate Content

1. The flight unit provider should ensure that the Qualification Plan and QDP include all elements of the qualification effort including analysis, evaluation, inspection, similarity, and test. In particular, the qualification process should include all elements of the hardware qualification effort including design analysis (electrical stress analysis, WCA, Transient analysis, BOL/EOL analysis), reliability, product-specific performance analysis, MMA, lifetime, PMP, SW, environmental testing, etc.
2. For all flight units (products), the program should stratify each flight unit (product) design as new, modified heritage, or full heritage, with a corresponding baseline qualification approach of full qualification, protoflight qualification, protoqualification, qualification by design similarity or some combination thereof as necessary to meet qualification process verification requirements and mitigate program risks. New products should be qualified on a full qualification unit. Modified heritage units may be qualified on full qualification models or tested as protoflight or protoqualification units as approved by QRB or equivalent. Modified heritage and full heritage qualification strategies are established based upon detailed Heritage Reuse assessments [12].
3. The flight unit provider should develop an appropriate flight unit qualification strategy, requirements, and implementation plan early during the program life-cycle (e.g., preferably during the proposal activity with refinement during the preliminary design phase), with appropriate review and approval by all stakeholders, including internal/external customers and independent review boards.
4. During the requirements definition and qualification planning phase, the flight unit provider should prepare a comprehensive listing of all flight unit qualification activities/products, define the appropriate SMEs to produce/review the products, and specify the timeline (relative to program milestones) that the activities/products should be performed. If activities/products are deleted, the technical justification and risk assessment associated with eliminating any of these activities, products, or assessments should be documented. Appendix C provides a representative example of the type of listing that should be prepared.

5. The flight unit provider should ensure that the primary customer Contractual Requirement Document (e.g., MIL-STD-1540) is appropriately tailored based on the type of program and the specific products, including ensuring that technical rationale for the tailoring of the requirements is defined with a technical Risk Assessment performed for variation from best practices. Tailored test requirements should be reviewed and approved by the QRB or equivalent and internal/external customers.
6. The qualification plan should address embedded software and firmware in addition to the hardware. The electronic flight unit qualification should verify the performance of the integrated HW, embedded software and firmware. Embedded SW is generally verified and validated by the microcircuit (e.g., ASIC, etc.) manufacturer. Non-up-loadable firmware is generally verified and validated by the electronic unit responsible engineering team prior to integration into the flight unit and prior to unit test. Up-loadable firmware may be a surrogate for unit qualification test with appropriate regression test when the final up-loadable firmware is available. The program software development plan should provide any special emphasis or constraints.
7. When practical, complete or partial approval of the QDP should occur at a separate QRB meeting prior to the PSR (e.g., incremental or "rolling" sell-off), which will enable a more focused activity at the PSR.
8. Following review and approval of the QDP and closure of all action items, the flight unit provider certifies that the flight unit is qualified for flight per a set of certificates, including Qualification by Test (QBT) certificates and Qualification by Design/Manufacturing Similarity (QBS) certificates, and/or a combination of QBS and QBT certificates. The certificates should be prepared by the flight unit provider and approved by the QRB Chair and Missions Assurance Manager.

3.7.3 Qualification Hardware Pedigree

1. Qualification is performed on hardware with the appropriate pedigree (EM/EQM (Engineering Model/Engineering Qualification Model) fidelity, Development/Qualification Units fidelity, etc.). The full qualification unit should be completely representative of the flight units and is usually the first production unit representative of all flight units. In some cases the IPT responsible engineer and supplier may choose an EQM with minor differences from the flight unit design. In other cases the IPT, responsible engineer, and supplier may present a case for EM usage or development model (DVM) usage for qualification. In all cases where the qualification unit is not identical to the flight unit, all differences are disclosed and dispositioned with justification evidence/analysis presented to QRB for approval.
2. The flight unit baseline qualification test approach should follow a TLYF approach [7, 14], where practical and/or beneficial in terms of driving representative failure modes. The flight units (products) are tested in their mission configuration and mission environments to the extent that is practicable and within cost and schedule constraints. All TLYF deviations are disclosed and dispositioned, with justification presented to QRB for approval.
3. Qualification by Design/Manufacturing Similarity is rigorously reviewed for any differences. It is the responsibility of the flight unit provider to provide an analysis to demonstrate that the differences between the similar and tested units (including design, parts, materials, and processes; manufacturers/suppliers on heritage hardware assemblies and/or subassemblies) do not invalidate the unit's prior qualification and that program risks have been addressed.
4. Heritage Hardware Reuse should follow the HRL rating. This reuse assessment defines program level reuse risk or HRL ratings for heritage item qualification. Lower reuse HRL

ratings indicate that the heritage product does not envelope current program application, environments and use, such that a full re-qualification is needed. Higher reuse HRL ratings indicate that the heritage product is a better match for current program application, environments and use, such that delta qualification may or may not be necessary.

3.7.4 Subcontractor/Lower Tier Supplier (LTS) Hardware Qualification

1. The prime contractor and flight unit provider should ensure that requirements for flight unit qualification are appropriately flowed down to subcontractors and lower tier suppliers, including requirements for developing/providing a Qualification Plan, executing the qualification activities per the qualification plan, and documenting the qualification data, analysis, and results in a QDP for review and approval by an independent QRB and internal/external customers.
2. For subcontracted hardware, the prime contractor should define the specific technical content required in the Qualification Plan and QDP in a Data Item Description (DID) that is flowed down to the supplier as part of the subcontractor Statement of Work (SOW) or equivalent contractual document.
3. The internal customer's QRB has review and approval authority over any and all supplier sub-QRB decisions.

4. Qualification Process Checklists

The checklist tools contained herein are intended to aid the qualification team in architecting comprehensive qualification plans and data packages. These checklists are intended to guide both the qualification team and review authorities in assessing the quality of the plans and data products. Lastly, special treatment checklists have been provided in the event that QBS and/or retest scenarios are needed for a given development.

Table 4-1 provides a mapping to detailed planning, execution, and assessment checklist tools used in the preparation of qualification materials.

Table 4-1. Qualification Process to Checklist Tool Mapping

Category	Checklist Tool	Document Mapping
Planning	Qualification Plan Verification Methodology	Table 4-2, Qualification Plan Checklist Table 4-5, Qualification Verification Methodology Checklist
Execution	Test	Table 4-6, Test Planning and Execution Checklist
Data Review and Assessment	Qualification Data Package	Table 4-7, Qualification Data Package Checklist Table 4-8, Qualification Data Package Assessment Checklist
Special Treatments	Qualification by Similarity Retest	Table 4-9, Qualification by Similarity Checklist Table 4-10, Retest Checklist

4.1 Qualification Plan

This section provides guidelines and criteria for the planning prior to the execution of qualification testing.

Table 4-2. Qualification Plan Checklist

Instructions for use: Check off all relevant data items and include a brief clarification comment and/or rationale for why the item has been excluded or is not required. Place a link to any supporting evidence or attach as appropriate.

Data Item	Yes	No	N/A
Product Familiarization Pictorials and History			
• Product Assembly	☐	☐	☐
• Product location on Payload or Spacecraft	☐	☐	☐
• Product Functional Block Diagram	☐	☐	☐
• Product major interfaces	☐	☐	☐
• Part numbers for HW to be used for Qualification testing (pedigree)	☐	☐	☐
• Previous Qualification failures on similar units	☐	☐	☐
Comments/Rationale:			
Evidence:			
Product Specifications Highlights			
• Requirement flow down path to the current product Specifications, TRD, Test Plans and related documents	☐	☐	☐
• Known/expected requirement changes in progress, impacts, ECDs	☐	☐	☐
• Interface Control Document (ICD)	☐	☐	☐
Comments/Rationale:			
Evidence:			
Applicable Unit Verification Compliance Requirements Matrix (VCRM) Sections			
• Qualification by Inspection Summary	☐	☐	☐
• Qualification by Demonstration Summary	☐	☐	☐
• Qualification by Similarity Summary	☐	☐	☐
• Qualification by Analysis Summary	☐	☐	☐

Data Item	Yes	No	N/A
• Qualification by Test Summary	☐	☐	☐
• Qualification Method differences between Qualification Plan and Product Specification (if any), and provide rationale	☐	☐	☐
Comments/Rationale:			
Evidence:			
Environmental Specification (EV) Requirements Summary			
• Graphical qualification test flow and sequence	☐	☐	☐
• Individual environment summaries (e.g., temperature cycling/thermal vacuum, shock, sine vibration, random vibration, acoustic, EMI/EMC/ESD, Flash X-Ray, life test, etc.).	☐	☐	☐
• Critical testing details including spectrums, cycles, extremes, durations, powered or unpowered during test, etc.	☐	☐	☐
• Test Like You Fly exceptions	☐	☐	☐
• Other unit specific EV caveats that require explanation (e.g., rationale for excluding a test, modifying profiles, etc.)	☐	☐	☐
Comments/Rationale:			
Evidence:			
Qualification Unit Fidelity and Configuration vs. Flight Design			
• Form/Fit/Function	☐	☐	☐
• Primary/Redundant	☐	☐	☐
• Piece parts/screening levels	☐	☐	☐
• Materials & Processes	☐	☐	☐
• Technology insertion qualification status	☐	☐	☐
Comments/Rationale:			
Evidence:			
Qualification Unit Production and Test Fidelity vs. Flight			
• Production processes utilized	☐	☐	☐
• Test procedures utilized	☐	☐	☐

Data Item	Yes	No	N/A
• Quality assurance procedures utilized • Different production facilities utilized **Comments/Rationale:** **Evidence:**	☐ ☐	☐ ☐	☐ ☐
Test Equipment Summary and Status **Comments/Rationale:** **Evidence:**	☐	☐	☐
Test Plans and Test Procedures Showing Document Number/Revision and Release Status **Comments/Rationale:** **Evidence:**	☐	☐	☐

4.2 Qualification Verification Methodology

Verification can be accomplished using one or more of the following methods: test, analysis, inspection, demonstration, and similarity.

- **Test.** Verification by test is the operation of flight or ground equipment with the necessary test-support equipment and test environment to verify compliance.
- **Demonstration.** Verification by demonstration is the operation of flight or ground equipment or teams to evaluate functional performance and/or interfaces to other equipment or teams. The primary distinction between demonstration and test is that demonstrations provide qualitative results (e.g., pass/fail), whereas tests provide quantitative results.
- **Analysis.** Verification by analysis is a process used in lieu of (or in addition to) testing to verify compliance with requirements. The selected techniques may include statistics and qualitative analysis, computer and hardware simulations, and computer modeling. Verification by analysis only should be used strictly when all of the following conditions apply:
  - Rigorous and accurate analysis is possible
  - Testing is not feasible or cost-effective
  - Verification by inspection is not adequate
- **Inspection.** Verification by inspection is the physical evaluation of equipment and/or documentation to verify design features. Inspection is used to verify construction features, workmanship, and physical dimensions, and condition (such as cleanliness, surface finish, and locking hardware).
- **Similarity.** Verification by similarity is the process of qualifying a unit by showing that a similar unit has been designed, manufactured, and tested to the same or greater environments and performance requirements. Similarity requirements are described in detail in Section 3.5.

A requirements verification compliance matrix is a convenient tool for tracking implementation and verification of flight unit qualification requirements. Table 4-3 is a sample format for a Verification Compliance Requirements Index (VCRI) that should be "cut and paste" from the Unit Technical Specification and used to index the specific verification method for each technical requirement in the Specification. Table 4-4 is a sample format for a Verification Compliance Requirements Matrix or Verification Cross-Reference Matrix (VCRM) that should be used to document the specific verification compliance for each technical requirement in the Specification corresponding to each line item in the VCRI.

Table 4-3. Verification Compliance Requirements Index (VCRI) Template

Requirement Source	Requirement Title	Not Applicable	Inspection	Analysis	Demonstration	Similarity	Test	Qualification	Protoflight or PQ	Acceptance	Success Criteria
		Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
Enter the [document #, section #]											

Table 4-4. Verification Cross Reference Matrix (VCRM) Template

Section # Requirement	Requirement Title	Pass/Fail	Link

A representative example of a filled out VCRI and VCRM is included in Appendix D.

The test requirements for the flight unit are typically specified in a Test Requirements Document (TRD) and/or a military and/or industry standard, such as MIL-STD-1540. Product-specific demonstration and inspection requirements are typically specified in the Unit Specification. Table 4-5 provides guidance on the minimum set of analysis requirements that should be included in the VCRI for all products, as well as examples of demonstration and inspection methods for specific products. The list of analyses is representative of those typically performed on a space program. In some cases, these analyses are combined or redundant with other analyses.

Table 4-5. Qualification Verification Methodology Checklist

Instructions for use: Check off all relevant data items and include a brief clarification comment and/or rationale for why the item has been excluded or is not required. Provide links to evidence as applicable. It is recognized that there may be redundancy between data items depending upon how contractors perform analyses.

Data Item	Yes	No	N/A
Structural/Dynamic Analysis Determines the margins of safety (MS) for the physical structure of the hardware given the dynamic environments to which it will be subjected. **Comments/Rationale:**	☐	☐	☐

Data Item	Yes	No	N/A
Evidence:			
Thermal Analysis Determines thermal design margins from devices up through the Unit interface against qualification environments. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Failure Modes and Effects Criticality Analysis (FMECA) Examines potential failure modes within the unit which would constitute either single point or propagating failures within the system. If either are found the design will almost always need to be modified. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Thermal Stress Determines device junction temperatures, and compares them to the thermal derating limits. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Electrical Stress Determines voltages, currents, and powers for each device, and compare the results to the device ratings. **Comments/Rationale:** **Evidence:**	☐	☐	☐

Data Item	Yes	No	N/A
Reliability Calculates the unit reliability based on the FIT rates of the entire collection of parts within a unit at a stipulated operating temperature. FIT rates are failures per billion hours based on military handbook or other reference sources. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Thermomechanical Stress Calculates the changes in material dimensions, tolerances, and properties associated with combined mechanical and thermal environments with an emphasis on mechanisms and moving assemblies. These studies also include thermal distortion analyses. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Wear Out, Durability Determines the expected operational life limits of the unit based upon expected usage and environments. Analyses take into account reliability, fatigue, cyclic loading, and environmental stresses on the unit. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Worst Case Circuit Analysis (WCCA) Examines the unit performance under the worst case conditions of temperature, radiation exposure, and component aging. As it becomes necessary to substitute alternate parts, this analysis should be checked to be sure any new factors are properly considered. **Comments/Rationale:** **Evidence:**	☐	☐	☐

Data Item	Yes	No	N/A
Transient Analysis Analyzes circuit under transient conditions such as start-up, shut-down, and intermediary conditions. It is important to ensure that the device operating limits are not exceeded during transient conditions. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Radiation or Total Dose Determines the margin or factor between the expected total radiation dose the unit will experience on orbit and the radiation the device can withstand and still meet its specified parameters. The result is a listing of the active devices and their radiation design margins. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Single Event Effects (SEE) Assesses several types of single event effects, including Single Event Transients (SETs), Single Event Upsets (SEUs), Single Events Gate Ruptures (SEGRs) and others. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Electrostatic Discharge (ESD) Determines by analysis and/or test the unit's ability to withstand electrostatic discharges applied externally to the unit. The analysis determines whether the electron flux can cause a charge accumulation on any ungrounded circuit elements, metals, or dielectric, which could cause a discharge and result in circuit performance upsets or permanent damage. Analysis should also include consideration for Internal Electrostatic Discharge (IESD). **Comments/Rationale:** **Evidence:**	☐	☐	☐

Data Item	Yes	No	N/A
Electromagnetic Interface/Electro Magnetic Compatibility (EMI/EMC) Determines the unit susceptibility to external electromagnetic fields (radiated susceptibility), to conducted noise (conducted susceptibility), and the unit's radiated and conducted emissions. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Contamination Examines the out-gassing of materials, particularly soft materials like epoxies and coatings, to ensure that they won't contaminate hardware around them. Optical sensors and solar panels are particularly sensitive. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Micrometeoroids Determines the unit susceptibility to damage from micrometeoroids strikes. Analysis is most often performed at the system level. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Product Functional Performance Determines the functional performance to requirements of the product. **Comments/Rationale:** **Evidence:**	☐	☐	☐

Data Item	Yes	No	N/A
Product-Specific Analysis Analyzes performance to requirements for specific types of products. For example, “slosh analysis” for a propellant tank. **Comments/Rationale:** **Evidence:**	☐	☐	☐
Product-Specific Demonstration Demonstrates requirements for specific types of products such as deployables. **Comments/Rationale:**	☐	☐	☐
Evidence:			
Product-Unique Inspection Inspects features of a design to confirm an attribute of the product such as color. **Comments/Rationale:** **Evidence:**	☐	☐	☐

4.3 Qualification Test Planning & Execution

The following checklist provides guidance for qualification test preparation and the generation of relevant test procedures in accordance with the Qualification Plan. It may be applied toward the creation of a comprehensive test procedure template to ensure critical information is recorded and readily accessible following test operations in support of test data reporting and analysis.

As part of test planning and execution, Ground Support Equipment (GSE) and test facilities must be identified and their usage secured. Certification of equipment and facilities must also be coordinated and accomplished prior to test execution.

Table 4-6. Test Planning and Execution Checklist

Instructions for use: Check off all relevant data items and include a brief clarification comment/rationale why the item has been excluded or is not required. Place a link to any supporting evidence or attach as appropriate.

Data Item	Yes	No	N/A
Test Identification			
• Test name, description, and purpose	☐	☐	☐
• Identification of the unit under test by name, part number, and serial number	☐	☐	☐
• Record of date and time of the test	☐	☐	☐
• Record of the name of the test conductor	☐	☐	☐
Comments/Rationale:			
Evidence:			
Ground Support Equipment (GSE)			
• Identification of all GSE by part or property number and recorded calibration certification date	☐	☐	☐
• Verification that GSE has been certified for use for testing (Certification is required to ensure protection of the flight unit under test from GSE failures. To be complete, certification should include a first-circuit interface review and an Interface Failure Mode and Effects Analysis (IFMEA), also with the review of GSE)	☐	☐	☐
• Verification that GSE safe-to-mate procedure has been successfully completed prior to test initiation	☐	☐	☐
Comments/Rationale:			
Evidence:			

Data Item	Yes	No	N/A
Test Configuration			
• Identification of the test configuration illustrating or describing the interconnection between all custom and general purpose test equipment and the unit under test	☐	☐	☐
• Identification of any relevant software installed in unit under test, including version number	☐	☐	☐
• Identification of any relevant firmware embedded in the unit under test, including version number	☐	☐	☐
Comments/Rationale:			
Evidence:			
Test Execution and Data Capture			
• Identification of initial test conditions (e.g., loads, speeds, environments, etc.) and test profile indicating levels and durations	☐	☐	☐
• Identification of power-up and power-down procedures	☐	☐	☐
• Identification of all key parameters to be monitored during the test, with provision for manually recorded data on data record sheets or electronic recording	☐	☐	☐
• Identification of unique test data log file names or file-naming conventions for automated and semi-automated tests for cases in which data is stored electronically	☐	☐	☐
• Identification of test-abort conditions (e.g., exceeding monitored parameter thresholds, test-induced over-stress, etc.)	☐	☐	☐
• Limited life item record logs (e.g., EEPROM write cycles performed, etc.)	☐	☐	☐
• Connector mate and de-mate count record logs	☐	☐	☐
Comments/Rationale:			
Evidence:			

Data Item	Yes	No	N/A
Test Procedures • Verify that test procedures have been written for each test to be conducted as identified in the VCRM • Verify that test procedure approvals include responsible engineers and the performance assurance engineer • Identify procedures for red-lining or modifying as-run test procedures (e.g., guidance on altering test parameters; identify required approvals) **Comments/Rationale:** **Evidence:**	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐
Test Facilities • Verify that test facilities have been identified and are approved for qualification testing and that the test facility schedule is realistic of anticipated activities. **Comments/Rationale:** **Evidence:**	☐	☐	☐

4.4 Qualification Data Package Checklist

This checklist provides guidance in establishing key elements that should be included in a typical flight unit qualification data package.

Table 4-7. Qualification Data Package (QDP) Checklist

Instructions for use:

1. Check off all relevant data items
2. Include a brief clarification comment and/or rationale for why the item has been excluded or is not required
3. Place a link to any supporting evidence or attach as appropriate

Data Item	Yes	No	N/A
Scope **Comments/Rationale:** **Evidence:**	☐	☐	☐
Qualification Plan(s) **Comments/Rationale:** **Evidence:**	☐	☐	☐
Hardware Identification			
• Unit Name	☐	☐	☐
• Top Assembly Number	☐	☐	☐
• Serial Number	☐	☐	☐
• Any Relevant Designations	☐	☐	☐
Comments/Rationale: **Evidence:**			

Data Item	Yes	No	N/A
Verification Strategy			
• Engineering Analyses	☐	☐	☐
• Testing	☐	☐	☐
• Inspection	☐	☐	☐
• Demonstration	☐	☐	☐
• Qualification by Similarity	☐	☐	☐
• Delta Qualification	☐	☐	☐
Comments/Rationale:			
Evidence:			
General Requirements			
• Approved Verification Compliance Requirements Matrix (VCRM)	☐	☐	☐
• Testing Requirements	☐	☐	☐
• Overall Testing Sequence	☐	☐	☐
• Summary of Test Levels, Durations, Number of Activations, Number of Cycles, Tolerances	☐	☐	☐
Comments/Rationale:			
Evidence:			
Summary of Key Verification Results			
• Engineering Analyses Results	☐	☐	☐
• Test Matrix Results	☐	☐	☐
• Inspection Outcome	☐	☐	☐
• Demonstration Outcome	☐	☐	☐
• Qualification by Similarity Assessment Summary	☐	☐	☐
• Delta Qualification Results	☐	☐	☐
Comments/Rationale:			
Evidence:			

Data Item	Yes	No	N/A
End Item Data Package (EIDP) & Reference Documents			
• Indentured Drawing List (IDL)	☐	☐	☐
• Top Assembly Drawing	☐	☐	☐
• ICD Compliance Matrix	☐	☐	☐
• Verification Plans	☐	☐	☐
• Environmental Specifications	☐	☐	☐
• Equipment Specifications	☐	☐	☐
• Test Matrix	☐	☐	☐
• Test Plans	☐	☐	☐
• Test Equipment List	☐	☐	☐
• Approved TRR Checklists	☐	☐	☐
• Test Procedures as Executed and Change Summary	☐	☐	☐
• Test Reports	☐	☐	☐
• Test Data Files	☐	☐	☐
• FRB Minutes/Actions and Open/Closed status	☐	☐	☐
• Final Analyses Reports Documenting All Compliance by Analysis Items	☐	☐	☐
• Retest Reports	☐	☐	☐
• Final Examination Reports Documenting All Compliance by Demonstration/Inspection Items	☐	☐	☐
• As-Built versus As-Tested versus As-Designed Records	☐	☐	☐
• Product Certifications	☐	☐	☐
• Non-Conformance Documentation Along With Open/Closed status	☐	☐	☐
• Limited Life Item Log	☐	☐	☐
• Total Unit Operation Time	☐	☐	☐
• Connector Mate/Demate Log	☐	☐	☐
Comments/Rationale:			
Evidence:			

4.5 Qualification Data Review & Analysis

This checklist provides additional assessment questions to be used during the QDP review.

Table 4-8. Qualification Data Package (QDP) Assessment Checklist

Instructions for use:
Answer “yes” or “no” to the assessment items and provide a risk assessment and rationale. Place a link to any supporting evidence or attach as appropriate.

Data Item	Yes	No	N/A
Was the flight unit qualification article that has been analyzed and tested identical to the flight configuration? **Comments/Rationale/Risk Assessment:** **Evidence:**	☐	☐	☐
Were all the design analyses completed and all required unit design changes resulting from the analyses incorporated into the unit before performing formal environmental and functional testing? **Comments/Rationale/Risk Assessment:** **Evidence:**	☐	☐	☐
Were all the waivers and engineering change requests approved and the required changes incorporated before formal environmental and functional testing performed? **Comments/Rationale/Risk Assessment:** **Evidence:**	☐	☐	☐
Did the required ground support equipment (including test and handling fixtures and test software) function within requirements during the flight unit qualification program? **Comments/Rationale/Risk Assessment:** **Evidence:**	☐	☐	☐

Data Item	Yes	No	N/A
Were any anomaly reports generated during the flight unit qualification program? • Anomaly disposition satisfactory? • Were there any retests performed? **Comments/Rationale/Risk Assessment:** **Evidence:**	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐
Did the test article successfully pass all pre- and post-environmental functional tests? **Comments/Rationale/Risk Assessment:** **Evidence:**	☐	☐	☐
Were all the tests required for the flight unit qualification successfully performed on this test article? **Comments/Rationale/Risk Assessment:** **Evidence:**	☐	☐	☐

4.6 Qualification by Similarity

Prior to using this checklist, the user should read Section 3.5 herein in order to understand usage constraints.

Table 4-9. Qualification by Similarity Assessment (QBS) Checklist

Instructions for use:

Answer “yes” or “no” to each of the assessment items along with associated risk assessment and rationale.

Provide links to evidence to support the risk assessment.

For the purpose of answering the questions, the following definitions apply:

Unit A = a candidate unit to be considered for QBS to Unit B
Unit B = a unit that has been qualified and/or flown in a space application

Assessment Item	Yes	No
Unit B is a test qualified unit (i.e., Unit B was not qualified by similarity). **Risk Assessment/Rationale:** **Evidence:**	☐	☐
Unit B is a representative flight article. **Risk Assessment/Rationale:** **Evidence:**	☐	☐
Unit B successfully passed a post-environmental functional test series without performance waivers. **Risk Assessment/Rationale:** **Evidence:**	☐	☐
Unit B has complete supporting documentation. **Risk Assessment/Rationale:** **Evidence:**	☐	☐

Assessment Item	Yes	No
Units A and B have similar function and the performance requirements of **Unit A** are enveloped by **Unit B**. Differences have been documented. **Risk Assessment/Rationale:** **Evidence:**	☐	☐
The environments of **Unit A** are enveloped by **Unit B**. Differences have been documented. **Risk Assessment/Rationale:** **Evidence:**	☐	☐
The design, including PMP, of **Unit A** is similar to **Unit B.** Differences have been documented. **Risk Assessment/Rationale:** **Evidence:**	☐	☐
The manufacturing, including processes, tooling, facility, etc., of **Unit A** is similar to **Unit B**. Differences have been documented. **Risk Assessment/Rationale:** **Evidence:**	☐	☐
The test requirements of **Unit A** are enveloped by **Unit B**, and the test sequence and test configuration of **Unit B** are consistent with the intended use of **Unit A**. Differences have been documented. **Risk Assessment/Rationale:** **Evidence:**	☐	☐

4.7 Retest Testing

This checklist will provide guidance in determining the degree of a retest on a flight unit should the need arise. The retest may be triggered by a redesign necessity, a change in a manufacturing process, a test anomaly, an increase in flight environments, or rework/refurbishment of items previously tested. Prior to using checklist, the user should read Section 3.6 herein in order to understand usage constraints.

Table 4-10. Retest Checklist

Instructions for use:

1. Check off all relevant data items
2. Include a brief clarification comment and/or rationale
3. Place a link to any supporting evidence or attach as appropriate

For help on answering the checklist questions, [2, 3, & 7] may be consulted.

Data Item	Yes	No	N/A
Cause of Retest			
• Redesign	☐	☐	☐
• Change in Manufacturing Process	☐	☐	☐
• Test Discrepancy	☐	☐	☐
• Increase in Flight Environments	☐	☐	☐
• Rework/Refurbishment of Items Previously Tested	☐	☐	☐
Comments/Rationale:			
Evidence:			
Requalification after Redesign			
• Is redesign major (e.g., changes in requirements/performance, architectural, technology, intended use, parts change impacting performance like relays, switches, oscillators)?	☐	☐	☐
• Is redesign minor (e.g., changes in parts and/or materials shown to be "benign")?	☐	☐	☐
Comments/Rationale:			
Evidence:			

Data Item	Yes	No	N/A
Requalification after Process Change • Is process change major (e.g., new supplier, new processes, relocation of manufacturing facility, gap in production lines, facility changes, significant loss of expertise at facility)? • Is process change minor? **Comments/Rationale:** **Evidence:**	☐ ☐	☐ ☐	☐ ☐
Retest after Test Discrepancy • Is corrective action a redesign? • Is corrective action a significant rework/repair? • Is corrective action a minor rework/repair? **Comments/Rationale:** **Evidence:**	☐ ☐ ☐	☐ ☐ ☐	☐ ☐ ☐
Retest after Increase in Flight Environments • Example, Environment exceeds Acceptance Level By: Dynamic (dB), Thermal (C) – < 3 dB or 5 C? – > 3 dB or 5 C < 6 dB or 10 C? – > 6 dB or 10 C? • Is the unit integrated into the next higher assembly level? • Is the unit Qualification/Protoqualification unit? • Is the unit Acceptance unit? **Comments/Rationale:** **Evidence:**	☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐

Data Item	Yes	No	N/A
Reacceptance after Rework/Refurbishment • Is rework/refurbishment major (e.g., considerable disassembly, large number of disconnects and reconnects, complex repair such as soldering or welding, lesser degree of access to in-process inspection than original manufacturing, repair techniques under different conditions using techniques, considerably different tooling)? • Is rework/refurbishment minor? **Comments/Rationale:** **Evidence:**	☐ ☐	☐ ☐	☐ ☐

Appendix A. Operational Definitions

The list of operational definitions in this document has been limited to the terms deemed important for understanding the Flight Unit Qualification Process. Users should refer to their enterprise and program documentation and their subject matter experts (SMEs) for interpretation and clarifications. Since some of these high-level terms have different meanings and connotations to the various organizations procuring for, or supplying, products to the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) activities, the list includes references to several definitions from different sources. Participants should acknowledge the existence of other interpretations and clarify them in their qualification documentation for their program and enterprise.

Acceptance Tests

Acceptance tests are formal vehicle, subsystem, and unit tests conducted to demonstrate that flight hardware is free of workmanship defects, meets specified performance requirements, and is acceptable for delivery [2]; see also [1, 3, and 4].

Analysis

Analysis includes the techniques of system engineering analysis, reliability engineering analyses, statistics, and qualitative analysis, computer and hardware simulations, and computer modeling. Analysis may be used when it can be determined that rigorous and accurate analysis is possible, testing is not feasible or cost-effective, similarity is not applicable, or verification by inspection is not adequate. Stress, fracture, thermal, ionizing radiation, mass properties, power, and energy requirements are examples of requirements that are particularly conducive to analysis, though these are, by no means, the only possibilities [4].

(Anomaly) Test Discrepancy

A test discrepancy is a functional or structural anomaly that occurs during testing, which may reveal itself as a deviation from specification requirements for the test item. A test discrepancy may be a momentary, unrepeatable anomaly, or it may be a permanent failure to respond in the predicted manner to a specified combination of test environment and functional test stimuli. Test discrepancies include those associated with functional performance, premature operation, failure to operate or cease operation at the prescribed time, and others that are unique to the item.

A test discrepancy may be due to a failure of the test item, or may be due to some unintended cause such as from the test setup, test instrumentation, supplied power, test procedures, or computer software used. [2]; see also [1 and 3].

(Anomaly) Test Item Failure

A failure of a test item is defined as a test discrepancy that is due to a design, workmanship, or quality deficiency in the item being tested. Any test discrepancy is considered to be a failure of the test item unless it can be determined to have been due to some unintended cause. [2]; see also [1 and 3]

Demonstration

Demonstration is a method of verification in which witnessing of an observable phenomena is used to verify compliance to a requirement. When demonstration is used as part of qualification, it must be performed by appropriately certified individual(s). This method is notably applicable to reliability and maintainability requirements (“the ‘-ilities’”: serviceability, accessibility, transportability) and human engineering. Demonstration should be performed at the highest practical assembly level. Pass/fail

criteria should be established prior to the start of testing. Example: Verification of crew hardware interfaces and accessibility for an on-orbit equipment removal and replacement would be performed by demonstration. [4]

Development Test Article

A development test article is a representative vehicle, subsystem, or unit dedicated to provide design and test information. The information may be used to check the validity of analytic techniques and assumed design parameters, to uncover unexpected response characteristics, to evaluate design changes, to determine interface compatibility, to prove qualification and acceptance test procedures and techniques, or to determine if the equipment meets its performance specifications. Development test articles include engineering test models, thermal models, and structural static and dynamic models. [2]

Electromagnetic Compatibility (EMC)

Electromagnetic compatibility is the condition that prevails when various electronic devices are performing their functions according to design in a common electromagnetic environment. [2]

Electromagnetic Interference (EMI)

Electromagnetic interference is electromagnetic energy which interrupts, obstructs, or otherwise degrades or limits the effective performance or life of electrical equipment. [2]

End Item Data Package (Unit)

The End Item Data Package (EIDP) is the document assembled by the flight unit provider at the completion of manufacture and testing that is delivered to a customer. For flight unit qualification, this package is one element of the Qualification Data Package. The EIDP includes, but is not limited to, data regarding the as-built configuration, manufacturing and quality history, test documentation, resultant test data, non-conformance reports, other data, and certifications. See Section 4.5 Table 8 Qualification Data Package Checklist (EIDP section) for additional suggested content.

Enterprise

Enterprise is a business organization. It is frequently used as an adjective to describe a corporate-wide policy, directive, process, practice, or guideline used for conducting business throughout an organization, e.g., enterprise guideline. [5]

Flight-Type Hardware

Flight-type hardware is defined to be hardware or firmware built to the flight design, or to a design considered to be sufficiently representative of the flight design for purposes of formal qualification testing. The definition would include items of hardware/firmware assigned for flight, flight spares, or protoflight use. It would also include prototypes or engineering model units (or equivalent) which are scheduled for use in formal design qualification testing. [3]

Flight Unit Qualification

Flight unit qualification is the formal verification (by tests, analyses, inspections, demonstrations, and/or similarity) of design requirements including margin, product robustness, and workmanship.

Functional Tests

Functional tests are the operation of a unit in accordance with a defined operational procedure to determine whether performance is within the specified requirements. [2]

Hardware

There are two major categories of hardware [2]:

1. **Prototype Hardware**: Hardware of a new design; it is subject to a design qualification test program; it is not intended for flight.
2. **Flight Hardware**: Hardware to be used operationally in space. It includes the following subsets:

    a. **Protoflight Hardware**: flight hardware of a new design. It is subject to a qualification test program that combines elements of prototype and flight acceptance verification, that is, the application of design qualification test levels and flight acceptance test durations

    b. **Follow-On Hardware:** flight hardware built in accordance with a design that has been qualified either as prototype, protoqualification, or as protoflight hardware; follow-on hardware is subject to a flight acceptance test program

    c. **Spare Hardware**: hardware the design of which has been proven in a design qualification test program. It is subject to a flight acceptance test program and is used to replace flight hardware that is no longer acceptable for flight

    d. **Reflight Hardware**: flight hardware that has been used operationally in space and is to be reused in the same way. The verification program to which it is subject depends on its past performance, current status, and the upcoming mission

Inspection

Inspection is the physical evaluation and/or documentation to verify the presence of a required feature or the absence of a prohibited flaw. Inspection is used to verify construction features, workmanship, dimensions, and physical conditions such as cleanliness, surface finish, and locking hardware. Inspection can also confirm that certain manufacturing inspection points (MIPs) were performed by inspection of route sheets and documentation. [4]

Life Test

Life testing may be required on selected assemblies/subsystems to identify hardware failure modes which are mission lifetime-related, and which cannot be verified by the limited duration qualification, protoflight or flight acceptance testing (e.g., thermal or vibration fatigue, bearing wear-out, etc.). Life testing is performed to determine the influence of time and environment on the assembly/subsystem design integrity including the nature and extent of flight hardware degradation. Data may also be collected to support in-flight problem diagnosis. Approved life tests shall be formally controlled and shall meet the formal requirements associated with the environmental test program. [3]

Program

A program is a group of related projects managed in a coordinated way. Programs usually include an element of ongoing work. [5]

Project

A project is a temporary endeavor undertaken to create a unique product, service, or result.[5]

Protoflight

A protoflight (PF) test is a formal environmental test performed on flight hardware which is intended to be flown and which has no qualification test article. Protoflight testing accomplishes in one test the combined purposes of design qualification and flight acceptance (workmanship).

Protoflight test levels and durations are the same as those for qualification except that for dynamics tests, acceptance durations are specified. Protoflight testing implies meeting all functional specifications and performance factors in the PF operating environments. [3]

Protoqualification Tests

Protoqualification tests are conducted to demonstrate satisfaction of design requirements using reduced amplitude and duration margins. This type of test is generally selected for designs that have limited production and supplemented with development and other tests and/or analysis to demonstrate margin. Protoqualification tests shall validate the planned acceptance program. [2]

Qualification Data Package

The Qualification Data Package (QDP) is the document package assembled by the supplier at the completion of the flight unit qualification program that is delivered and reviewed by the Qualification Review Board or equivalent and subsequently delivered to the program data archive. See Section 4.5 Table 8 Qualification Data Package Checklist for content.

Qualification Margin

An environmental qualification margin is the increase in an environmental condition, over that expected during service life, including acceptance testing, to demonstrate that adequate ruggedness exists in the design and in its implementation. A margin may include an increase in level or range, an increase in duration or cycles of exposure, as well as any other appropriate increase in severity. Environmental qualification margins are intended to demonstrate the ability to satisfy all of the following on a single qualification item:

- Be tolerant of differences in ruggedness and functionality of flight items relative to the qualification item, due to reasonable variations in parts, material properties, dimensions, processes, and manufacturing
- Be immune to excessive degradation (such as fatigue, wear, loss of material properties or functionality) after enduring a specified maximum of acceptance testing prior to operational use of a flight item
- Meet requirements under extreme conditions of flight, which when expressed statistically are the P99/90 estimates [2]

Qualification by Similarity

Qualification by similarity is the procedure of comparing an item which has not undergone qualification to another item having only minor differences in configuration and functional characteristics which has been:

- Tested and analyzed to stress levels at least as severe as those specified for the item to be qualified
- Tested and analyzed under equivalent program controls
- Manufactured by the same supplier using similar application

The item also may be identical to one previously qualified and successfully flown. [3]

Qualification Test

Qualification tests are formal tests conducted to demonstrate satisfaction of design requirements including margins and product robustness for designs than have no demonstrated history. A full qualification validates the planned acceptance program, in-process stress screens, and retest environmental stresses resulting from failure and rework. Qualification hardware that is selected for use as flight hardware shall be evaluated and refurbished as necessary to show that the integrity of the hardware is preserved and that adequate margin remains to survive the rigors of launch and provide useful life on orbit. [2]

Regression Testing

Regression testing is any type of software testing of a software program (used for design, analysis, test, or flight purposes) to confirm that the modified code corrects a previously identified software functionality problem and ensures that functionality features that were proven during previous testing remain intact and that no errors (old or new) have been introduced with the code modifications. Common methods of regression testing include rerunning previously run tests and checking whether previously fixed faults have re-emerged.

Retest

Retest is the repeat of previously conducted tests (functional, performance, and/or environmental) due to a redesign, a change in a manufacturing process, a test discrepancy, an increase in flight environments, or rework/refurbishment of items previously tested.

Shall

Shall indicates a mandatory requirement. For example, “Designers shall implement all such mandatory requirements to ensure interoperability with other IEEE Std 1156.4 conformant products.” [5]

Should

Should indicates flexibility of choice with a strongly preferred implementation. The phrase it is recommended is used interchangeably with the word should. [5]

Temperature Cycle

A temperature cycle is the transition from some initial temperature condition to temperature stabilization at one extreme and then to temperature stabilization at the opposite extreme and returning to the initial temperature condition. [2]

Test (as it relates to qualification)

Test is the preferred method of qualification for new hardware because, when properly planned, conducted, and documented, it provides the greatest confidence in the hardware's qualification. During testing, the hardware is subjected to defined physical inputs; the output parameters are measured and recorded in test program documentation. Qualification tests typically apply physical factors in excess of expected environmental conditions (factor of safety). As a result, the hardware used in the testing may have been over-stressed. Once a hardware element has been qualified, it cannot be flown without certification, or when necessary, refurbishment and acceptance testing. [4]

Test Plan (Unit)

A test plan is a plan, which defines the methods for implementing testing of a unit. A test plan normally includes the test approach, procedure, instrumentation requirements, test levels, and data monitoring and reduction requirements. [2]

Test Procedures

Test procedures are documents prepared to define the implementation process for each unit level test required by the applicable test specifications. [2]

Unit

A unit is a functional item (hardware, and if applicable, software) that is viewed as a complete and separate entity for purposes of manufacturing, maintenance, and record keeping. Examples: hydraulic actuator, valve, battery, electrical harness, and transmitter. [2], see also [1]

Validation

Validation of design implementation results in official approval by assessing or corroborating its soundness for the intended use through testing or comparisons. Did we build the right thing? [3].

Verification

Verification provides objective evidence through test and/or analysis that specified design and workmanship requirements have been fulfilled. Did we build the thing right? [3]

Appendix B. Acronyms

The following is a list of acronyms used throughout this document and/or commonly used within the industry:

ASIC	Application-Specific Integrated Circuit
ATP	Authority to Proceed
BOL	Beginning of Life
CDI	Cumulative Damage Index
CDR	Critical Design Review
DID	Data Item Description
DoD	Department of Defense
DVM	Development Model
ECD	Expected Date of Completion
ECR	Engineering Change Request
EEE	Electronic, Electrical and Electromechanical
EEPROM	Electrically Erasable Programmable Read-Only Memory
EIDP	End Item Data Package
EM	Engineering Model
EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
EOL	End of Life
EQM	Environmental Qualification Model
	Engineering Qualification Model
ESD	Electrostatic Discharge
EV	Environmental Specification
FFRDC	Federally Funded Research and Development Center
FIT	Failure Rate (per billion hours of operation)
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FRB	Failure Review Board
FTA	Fault Tree Analysis
GIDEP	Government Industry Data Exchange Program
GSE	Ground Support Equipment
HRL	Heritage Readiness Level
HW	Hardware
I&T	Integration and Test
ICD	Interface Control Document

IDL	Indentured Drawing List
IESD	Internal Electrostatic Discharge
IFMEA	Interface Failure Mode and Effects Analysis
IPT	Integrated Product Team
LTS	Lower Tier Supplier
M&P	Manufacturing and Process
MIP	Manufacturing Inspection Points
MMA	Moving Mechanical Assemblies
MRB	Manufacturing Record Book
MRR	Manufacturing Readiness Review
MS	Margin of Safety
NASA	National Aeronautics and Space Administration
NSMARS	Non-standard Material Approval Requests
NSPARS	Non-standard Part Approval Requests
PDR	Preliminary Design Review
PF	Protoflight
PQ	Protoqualification
PMP	Parts, Materials and Processes
PMPCB	Parts, Materials and Processes Control Board
PSA	Parts Stress Analysis
PSR	Pre-Ship Review
	Project Status Review
QA	Quality Assurance
QBS	Qualification by Design/Manufacturing Similarity
QBT	Qualification by Test
QDD	Qualification Description Document
QDP	Qualification Data Package
QRB	Qualification Review Board
QUAL	Qualification
RE	Responsible Engineer
SE	Systems Engineering
SEE	Single Event Effects
SEGR	Single Events Gate Rupture
SEIT	System Engineering Integration and Test
SET	Single Event Transient

SETA	System Engineering and Technical Analysis
SEU	Single Event Upsets
SMA	Safety and Mission Assurance
SME	Subject Matter Expert
SOW	Statement of Work
SV	Space Vehicle
SW	Software
TEGA	Thermal Evolved Gas Analyzer (Mars Phoenix)
TID	Total Ionization Dose
TLYF	Test Like You Fly
TRD	Test Requirements Document
TRR	Test Readiness Review
TWTA	Traveling Wave Tube Amplifiers
USG	United States Government
UVF	Unverified Failures
VCRI	Verification Compliance Requirements Index
VCRM	Verification Compliance Requirements Matrix
	Verification Cross-Reference Matrix
WCA	Worst Case Analysis
WCCA	Worst Case Circuit Analysis

Appendix C. Sample Flight Unit Qualification Planning Checklist

Although space flight units have varying specific requirements, the general qualification requirements tend to be similar. This is because the characteristics of space flight applications are similar. For example, space flight units are typically required to be highly reliable due to the inability to repair them once on orbit and due to the importance of the missions on which they are used. In addition, space flight units are typically exposed to similar launch and on-orbit environments. As a result, flight unit qualification consists of a common set of activities, products, assessments. Flight unit qualification requirements definition and planning are critical to successful flight unit development and operation. Many implementation and operational problems and failures can be traced to escapes in this phase of qualification. "Table C-1 – Flight Unit Qualification Planning Checklist" provides a recommended set of flight unit qualification activities, products, and assessments (along with their phasing) that should be considered during requirements definition and planning. In addition, this checklist can be used to document the technical justification and risk assessment associated with eliminating any of these activities, products, or assessments.

Table C-1 Flight Unit Qualification Planning Tool

ID#	Flight Unit Qualification Activities / Products	Independent Assessment Lead *	PDR	CDR	Pre-ship Review	Technical justification if eliminating task e.g., not applicable **
1	Requirements for safety, reliability, quality, EEE parts, materials/processes, contamination control ***	Mission Assurance Lead	Final			
2	Requirements for performance, interface, life, contamination allowance, orbital debris ***	Systems Engineer or Systems Engineer	Final			
3	Requirements for loads, thermal, vacuum, dynamics, electro-magnetics, electro-statics, radiation, corona, micrometeoroid, verification approach (e.g., protoflight, qualification unit)***	Environmental Engineer	Final			
4	Information and documentation archive plan and requirements ***	Configuration Management	Final			
5	Qualification Plan and Specification (Requirements Verification Compliance Matrix) ***	Qualification Lead	Final			
6	Functional failure mode/effects criticality analysis (identified critical items, wear-out items and single point failures)	Reliability Engineer	Prelim	Final	Update	
7	Worse case analysis (end of life, radiation, etc.)	Reliability Engineer	Prelim	Final	Update	
8	Electrical parts stress analysis	Reliability Engineer	Prelim	Final	Update	
9	Critical circuit failure mode/effects criticality analysis	Reliability Engineer	Prelim	Final	Update	
10	Interface failure mode/effects criticality analysis	Reliability Engineer	Prelim	Final	Update	
11	Single Event Effects analysis	Reliability Engineer	Prelim	Final	Update	
12	Reliability prediction (if required)	Reliability Engineer	Prelim	Final	Update	
13	Mechanism fault tree analysis/life testing	Reliability Engineer	Prelim	Final	Update	

ID#	Flight Unit Qualification Activities / Products	Independent Assessment Lead *	PDR	CDR	Pre-ship Review	Technical justification if eliminating task e.g., not applicable **
14	Structural stress analysis	Structural	Prelim	Final	Update	
15	Thermal stress analysis	Thermal	Prelim	Final	Update	
16	Materials and processes lists (reviewed & approved for reliability and radiation susceptibility)	Materials & Processes	Prelim	Final		
17	Materials and processes qualification reports (as needed)	Materials & Processes	Prelim	Final		
18	EEE parts list (reviewed & approved for reliability and radiation susceptibility)	EEE Parts Reliability	Prelim	Final		
19	EEE parts qualification reports (as needed)	EEE Parts Reliability	Prelim	Final		
20	Environmental modeling and analysis completion statements (review and approved)	Environmental Engineer	Prelim	Final		
21	Thermal/vacuum modeling and analysis completion statements	Thermal	Prelim	Final		
22	Loads modeling and analysis completion statements	Structural	Prelim	Final		
23	Dynamics modeling and analysis completion statements	Dynamist	Prelim	Final		
24	Electromagnetic compatibility modeling and analysis completion statements	EMC/EMI	Prelim	Final		
25	Electrostatic charging modeling and analysis completion statements	ESD	Prelim	Final		
26	Radiation modeling and analysis completion statements (total ionizing dose, single event effects, displacement damage, other)	Radiation	Prelim	Final		
27	Micrometeoroid modeling and analysis completion statements	Natural Space	Prelim	Final		
28	Contamination modeling and analysis completion statements	Contamination Control	Prelim	Final		

ID#	Flight Unit Qualification Activities / Products	Independent Assessment Lead *	PDR	CDR	Pre-ship Review	Technical justification if eliminating task e.g., not applicable **
29	Residual Risk Assessment of ECRs not closed, past review open actions, waivers/deviations, open anomaly reports, applicable GIDEP Alerts, shortage list	Mission Assurance Lead	Ongoing	Ongoing	Final	
30	Design Review (PDR, CDR) action items been adequately addressed	Mission Assurance Lead	Prelim	Prelim	Final	
31	Drawings and specifications complete, approved, released and under change control	Configuration Management	Prelim	Final	Final	
32	Released drawings and specifications reflect all approved changes	Configuration Management	Prelim	Final	Final	
33	Required SMA tests and analyses been completed	Mission Assurance Lead		Draft	Final	
34	Instructions for safe handling, cleaning, testing, packaging, storage and shipping constraints	Safety	Draft	Prelim	Final	
35	Safety Data Package	Safety		Draft	Final	
36	Environmental test procedures (review and approved)	Environmental Engineer		Prelim	Final	
37	Thermal/vacuum test procedures (review and approved)	Thermal		Prelim	Final	
38	Proof loads test procedures (review and approved)	Structural		Prelim	Final	
39	Dynamics test procedures (review and approved)	Dynamist		Prelim	Final	
40	Electromagnetic compatibility test procedures (review and approved)	EMC/EMI		Prelim	Final	
41	Grounding and bonding test procedures (review and approved)	ESD		Prelim	Final	
42	Hardware compliant to all performance and interface requirements	Systems Engineering			Final	
43	Applicable telemetry calibration data submitted	Systems Engineering			Final	

ID#	Flight Unit Qualification Activities / Products	Independent Assessment Lead *	PDR	CDR	Pre-ship Review	Technical justification if eliminating task e.g., not applicable **
44	Required mass and center of gravity data submitted	Mechanical Engineering			Final	
45	Required SE tests and analyses completed	Systems Engineering			Final	
46	Anomaly Reporting/Corrective Action	Reliability Engineer			Final	
47	Hardware meets contamination control requirements	Contamination Control			Final	
48	Firmware associated with this delivery is an approved flight version	Software Quality Assurance			Final	
49	Test software for unit acceptance testing is an approved flight version	Software Quality Assurance			Final	
50	Inspection Reports and MRBs dispositioned and concurred	Hardware Quality Assurance			Final	
51	Certified Personnel and Facilities	Hardware Quality Assurance			Final	
52	Environmental test reports (review and approved)	Environmental Engineer			Final	
53	Thermal/vacuum test reports (review and approved)	Thermal			Final	
54	Proof loads test reports (review and approved)	Structural			Final	
55	Dynamics test procedures (review and approved)	Dynamist			Final	
56	Electromagnetic compatibility test reports (review and approved)	EMC/EMI			Final	
57	Grounding and bonding test reports (review and approved)	ESD			Final	
58	Complete as-built documentation been submitted	Configuration Management			Final	

ID#	Flight Unit Qualification Activities / Products	Independent Assessment Lead *	PDR	CDR	Pre-ship Review	Technical justification if eliminating task e.g., not applicable **
59	Complete qualification data package submitted	Configuration Management			Final	
60	Final integration and test procedure been submitted to Integration & Test (I&T)	Integration & Test			Final	

* Independent assessment lead should include other subject matter experts as needed to perform a comprehensive assessment

** Flight unit provider should document technical justification, along with risk assessment, if eliminating qualification task

*** Flight unit qualification requirements should include those flowed-down from the customer and the prime contractor's "command media", as well as those requirements derived by the flight unit provider

Appendix D. VCRI and VCRM Examples

Table D-1. VCRI Example #1 – Product Specific

Requirement Source	Requirement Title	Not Applicable	Inspection	Analyses	Demonstration	Similarity	Test	Qualification	Protoflight or Protoqual	Acceptance	Success Criteria
		Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
Requirement Paragraph (DSXXXXX-XXX-XXX)											
3.2.1.13.2	**Insulation Resistance**: The insulation resistance shall be greater than XXX megohms when measured at 21.1 ±10° C (70 ±18° F) with a potential of XXX ±XX VDC applied between the shorted coil leads and the case.						X	X			Valve Qualification testing will verify requirement
3.2.1.13.3	**Valve External Leakage:** The external leakage of the valves in the closed position when pressurized internally to XXXX kPa (XXX psig) at 21.1° C (70° F) shall not exceed 1 x 10^{-X} scc/sec He to moderate vacuum of less than or equal to XXX kPa (X^{-X} Torr). The leak detector shall have a sensitivity of better than 1 x 10^{-7} scc/sec He.						X	X			Valve Qualification testing will verify requirement

Requirement Source	Requirement Title	Not Applicable	Inspection	Analyses	Demonstration	Similarity	Test	Qualification	Protoflight or Protoqual	Acceptance	Success Criteria
		Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
Requirement Paragraph (DSXXXXX-XXX-XXX)											
3.2.1.13.4	**Internal Leakage:** The internal leakage of each LAM valve seat shall not exceed X scc/hr of GN2 at an inlet pressure of XXXX ±XX kPa (XXX ±X psia) and 21 C (70 F).						X	X			Valve Qualification testing will verify requirement
3.2.1.13.5	**Pull-In Voltage:** With valve pressurized to XXXX kPa (XXX psia) GN_2 or deionized water, slowly raise the applied voltage until the valve starts to flow. The voltage shall not exceed 21.5 VDC at a valve temperature of XXX°C (XXX°F). Record the pull-in voltage at 21.1°C (70°F) or calculate from measured pull-in current and temperature.						X	X			Valve Qualification testing will verify requirement

Requirement Source	Requirement Title	Not Applicable	Inspection	Analysis	Demonstration	Similarity	Test	Qualification	Protoflight or Protoqual	Acceptance	Success Criteria
		Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
Requirement Paragraph (DSXXXXXX-XXX-XXX)											
3.1.2.2	**Flushing Solvents**: The LAM must be capable of being flushed with solvents for flow testing, propellant flushing, and calibration. The solvents are isopropyl alcohol per TT-X-XXX or distilled water, per ASTM X XXXX-XX Type I, for the fuel system and distilled water for the oxidizer					X		X			Qualified by similarity to QRXXXXX-XXX-XXX
3.2.2.3.2	**Thruster Burst Pressure:** The thruster chamber shall be able to withstand the burst pressure consisting of the maximum chamber pressure multiplied by a factor of safety of X, while taking into account the change in material properties at the maximum chamber temperature from test data. The maximum chamber pressure shall include the allowable roughness per section 3.2.1.10.			X				X			MAXXXXX-XXX-XXX revision will verify requirement
3.2.2.4	**Propellant Filtration**: The thruster valves may include propellant filters. Propellants shall be supplied to the inlet of the propellant valves after having been filtered to the cleanliness levels in Table XIV of DSXXXXX-XXX-XXX Rev B.		X						X		Proto-flight Qualification testing will verify requirement
3.2.2.5	**Alignment**: The alignment of the nozzle centerline shall be perpendicular to the mounting flange within XXXX inches.			X							Verified by proto-qualification test plan

Table D-2. VCRM Example #1 – Product Specific

Section # Requirement	Requirement Title	Pass/Fail	Link
3.2.2.3.2	Thruster Burst Pressure	Pass	QRXXXXX-XXX-XXX, Page 156, Sec 5.9 Burst Test (valve) QDP points to MAXXXXX-XXX-XXX revision for verification of chamber pressure 2009–X–XXXX
3.2.2.5	Alignment	Pass	EIDP for P/N XXXXXXX-XXX, SN XXX Page 161, Item 10

3.2.1.13.2	Insulation Resistance	Greater than XXX megohms at 21.1 $\pm$10°C (70 $\pm$18°F) with a potential of XXX $\pm$XX Vdc	All > XXk Mohms	Pass	End Item Data Package for P/N XXXXXXX-XXX, SN XXX Pages 68-69 Table 1 Para 23.0 Insulation Resistance EIDP for P/N XXXXXXX-XXX, SN XXX Pages 175 Table 1 Para 3.2.3 Insulation Resistance (ox valve rework data) Demonstrated during the 2009 Qualification, Qualification Test Report 2009-X-XXXX

3.2.1.13.3	External Leakage	< 10^{-X} scc/sec of GHe	Ox 1E-X Fuel 1E-X 1.0 x 10^{-x} sccs after X.X minutes at XXX psig	Pass	End Item Data Package for P/N XXXXXXX-XXX, SN XXX Pages 176-180 Table 1 Para 5.4 External Leakage (tested at XXX psig, OK per TTVVXX-XX-XXX, Company X also tests at XXX psig (passed) but does not put into EIDP) Demonstrated during the 2009 Qualification, Qualification Test Report 2009-R-XXXX
3.2.1.13.4	Internal Leakage	< X scc/hr of GN2	Valve Level: Ox 0.0 Fuel 0.0 Assembly Level: Ox 0.0 Fuel 0.0 Valve Level: Ox 0.0	Pass	End Item Data Package for P/N XXXXXXX-XXX, SN XXX Pages 128-180 Table 1 Para 6.4 Internal Leakage End Item Data Package for P/N XXXXXXX-XXX, SN XXX Page 117 Table 7 Para 7.0 Internal Leakage note ox was 1.75 pass after vibe pg 68 Demonstrated during the 2009 Qualification, Qualification Test Report 2009-X-XXXX
3.2.1.13.5	Pull-In Voltage	< XX Vdc at XXX°C (XXX°F).	Ox B/W XX R/G XX Fuel B/W XX R/G XX Ox B/W: XX R/G: XX	Pass	EIDP for P/N XXXXXXX-XXX, SN XXX Page 129 Table 1 Para 7.8 Correct Opening Pull-In Voltage to XXX F EIDP for P/N XXXXXXX-XXX, SN XXX Page 181 Table 1 Para 7.7 Correct Opening Pull-In Voltage to XXX F Demonstrated during the 2009 Qualification, Qualification Test Report 2009-X-XXXX

3.1.2.1	Pressurant and Propellants	Pass	End Item Data Package for P/N XXXXXXX-XXX, SN XXX Page 3, Certificate of Conformance End Item Data Package for P/N XXXXXXX-XXX, SN XXX Pages 78-79, Propellant Analytical Results form
3.1.2.2	Flushing Solvents	Pass	End Item Data Package for P/N XXXXXXX-XXX, SN XXX Page 3, Certificate of Conformance

Table D-3. VCRI Example #2 – Generic Product

	VCRI Sample: Populated with representative flight unit qualification requirements and verification methods.	Not Applicable	Inspection	Analysis	Demonstration	Similarity	Test	Qualification	Protoflight or Protoqual	Acceptance	Success Criteria
Source	Requirement Title	Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
	Systems Safety Requirements										
	Units shall be designed, fabricated, tested and utilized to be able to tolerate a minimum number of credible failures and/or operator errors dependent on the level of hazard (catastrophic or critical hazards).			A			T				
	Unit providers shall ensure safety of their personnel and hardware during development through the use of safety hazard analyses and surveys for facilities, operations and transportation.		I	A							
	Reliability Assurance Requirements										
	Design shall be controlled by applying sufficient design margins, and safety factors, selection of appropriate materials and parts.			A							
	Systems shall be designed to meet the failure tolerance and redundancy requirements.			A							
	Hardware shall be designed to meet performance requirements for life of ground storage/operation and operation in a space environment.			A			T				
	Electronic assemblies shall have a adequate operation prior to delivery for Integration and Test.				D						
	Circuit designs shall assure that electronic parts have sufficient operating margins to operate within specification under (worst case) operating conditions and performance requirements.			A							
	Circuit designs shall assure that applied stress on each EEE piece part does not exceed the derating requirements.			A							
	Circuit designs shall operate within specification after exposure to the mission Total Ionizing Dose (TID) environment, including the Radiation Design Factor.			A							
	Circuit designs shall operate with specification when exposed to the mission Single Event Effect (SEE) environment.			A							
	Failures in support equipment shall not damage flight hardware.			A							
	Design shall be verified by performing design analyses, on flight hardware, including:										
	a. fault tree analysis (FTA) of mechanical and electromechanical assemblies			A							

	VCRI Sample: Populated with representative flight unit qualification requirements and verification methods.	Not Applicable	Inspection	Analysis	Demonstration	Similarity	Test	Qualification	Protoflight or Protoqual	Acceptance	Success Criteria
Source	Requirement Title	Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
	b. worst-case analysis (WCA)			A							
	c. functional and interface failure mode effects and criticality analyses (FMECA)			A							
	d. ground support equipment interface failure mode effects analyses (FMEA)			A							
	e. parts stress analysis (PSA)			A							
	f. thermal stress analysis to support the PSA and system thermal modeling			A							
	g. structural stress analysis to demonstrate mechanical integrity of the packaging design			A							
	Critical mechanisms that function in a cyclic manner shall demonstrate a minimum life capability, operate within specified performance at the end of the life test, as well as be disassembled and inspected for unacceptable wear or debris generation.		I		D						
	Environmental Assurance Requirements										
	Environmental verification program shall include modeling and tests for random vibration.			A			T				
	Environmental verification program shall include modeling and tests for acoustic vibration.			A			T				
	Environmental verification program shall include modeling and tests for pyro-shock.			A			T				
	Environmental verification program shall include modeling and tests for thermal vacuum operation and survival.			A			T				
	Environmental verification program shall include modeling and tests for EMC/EMI operation and survival.			A			T				
	Environmental verification program shall include analyses for launch pressure profile and radiation, and (when appropriate) meteoroids.			A			T				
	EEE Parts, Materials and Processes Requirements										
	EEE Parts requirements shall meet or exceed project requirements for performance, mission life, environments, quality, reliability and radiation as demonstrated through test and/or analysis.			A							
	Microcircuits and semiconductors shall be evaluated for radiation Total Ionizing Dose (TID), Displacement Damage (DD) and Single Event Effect (SEE) sensitivity, relative to the project radiation requirements and the applicable class requirements.			A							

	VCRI Sample: Populated with representative flight unit qualification requirements and verification methods.	Not Applicable	Inspection	Analysis	Demonstration	Similarity	Test	Qualification	Protoflight or Protoqual	Acceptance	Success Criteria
Source	Requirement Title	Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
	Unit providers shall establish and maintain parts pedigree by procuring and handling parts to the detailed requirements and processes.		I								
	Unit providers shall perform failure analyses on all parts that fail during a life test, or subsequent to first application of power after part installation, to the point that lot dependency of the failure mode can be determined.			A							
	Unit providers shall address GIDEP Alerts through review, action closure, notification, and issuance of new NASA Advisories and GIDEP Alerts as needed.			A							
	Handling of parts shall be controlled by the appropriate standard for Electrostatic Discharge (ESD) Control.		I								
	Unit providers shall select, apply, and use materials and processes that meet mission requirements as specified in the appropriate standard.			A							
	Unit providers shall use approved processes for developing, evaluating, and qualifying materials and processes, as well as for accepting and using nonstandard materials.			A	T						
	Contamination Control Requirements										
	Unit providers shall conduct an evaluation of the proposed system to identify components that have a potential for degradation due to particulate and molecular contamination.			A							
	Contamination sensitive components shall be accommodated and safe-guarded consistent with the sensitivity to, and the potential degradation from, particulate and molecular contamination.		I								
	Anomaly Reporting Requirements										
	Unit providers shall implement a closed-loop formal reporting process for anomaly reporting and corrective action, which consist of detailed description of problem, verification analysis, corrective action and risk rating.		I	A	T						
	Anomaly reports are closed only after review and approval by the affected areas.		I	A	T						
	Quality Assurance Requirements										
	Suppliers shall implement hardware quality assurance processes and procedures that meet requirements derived from an accepted Quality Management System (i.e. ISO9001:2000, AS9100, AS9120, AS9003 or ISO 17025).		I								

	VCRI Sample: Populated with representative flight unit qualification requirements and verification methods.	Not Applicable	Inspection	Analysis	Demonstration	Similarity	Test	Qualification	Protoflight or Protoqual	Acceptance	Success Criteria
Source	Requirement Title	Verification Method						Category			
		NA	I	A	D	S	T	Q	P	A	
	Hardware shall be designed, fabricated and inspected to the appropriate standards for all suppliers.		I	A							
	Unit provider QA personnel shall perform receiving and shipping inspections on critical hardware whenever the hardware enters or leaves any facility.		I								
	Final inspection of flight hardware shall be performed to formally released documents.		I								
	Unit providers shall define mandatory inspections for critical hardware (e.g., in-process and final).		I								
	Personnel involved in handling or testing of hardware shall be certified to standards approved by the responsible QA organization.		I								
	Unit providers shall maintain records of the unit configuration during assembly, test and operations to know the "as-tested" and "as-operated" configurations.		I								
	Designs shall provide accessibility for: a) assembly/disassembly, handling, and transportation, b) testing and troubleshooting, including alignments, and calibrations, and c) maintenance and servicing in the planned ground operations flow including integration operations.		I								
	Configuration Management and Review Requirements										
	Unit providers shall plan and implement a configuration management process that ensures rigorous control of project configuration items and their characteristics important for mission success, project documents, requirements, design, testbeds, and other information.		I								
	Unit providers shall perform formal and informal design and test peer reviews and independent assessments throughout development and operations.		I								
	Unit providers shall support the risk management process and provide independent risk assessments.			A							

Appendix E. Examples of Qualification Escapes

Four examples of qualification escapes are described, the first two from military space programs [10] and the last two from NASA missions [13]. The examples include a description of the problem and how the qualification process was inadequate or not followed. They conclude with lessons learned.

Example 1: Non-Flight-Like Qualification

Numerous failures have occurred due to deficiencies in substitution materials that were thought to be similar of those originally specified, but were not. One example involved a rocket nozzle that failed during test firing because a replacement insulator delaminated. A supplier problem prompted the contractor to select a replacement resin for the nozzle skirt. This new material met the applicable specification, had been used on other programs, and had passed an array of tests in the laboratory. However, test results of the new material were statistically different from the original material, and test conditions were not sufficiently flight-like (properties were measured at room temperature, whereas the flight temperature approached 1600°C, and a thermal expansions test was performed at too low a heating rate). In a test firing, the new material outgassed and delaminated during firing. The flame burned through the new resin. The problem escaped qualification because slow heating rates used in testing provided time for the gas to escape. Faster heating rates would have revealed the material issue. At the time, two rockets having nozzles made from the new material were already being prepared for launch. Potential losses were narrowly averted.

Lessons learned included:

1. Qualification by similarity needs to be rigorously reviewed
2. Qualification of replacement materials needs to be tested under realistic flight conditions and not just to specification limits

Example 2: Incomplete and Inadequate Qualification

A laser pump consisted of several diodes mounted on heatsinks, soldered together into stacks. Apparently, material incompatibilities occurred in which the indium solder contaminated the gold bondwires, forming an insulating layer of intermetallics. After only a month in flight, the corroded bondwires suffered from thermo-mechanical fatigue and cracked. In retrospect, the vendor's internal processes and controls were up to space application standards. The new design was more vulnerable because current density in the contaminated bondwired increased significantly, intensifying thermal loads in the wires. During qualification, the bondwires broke several times. The vendor replaced the defective components and asserted that the failures would not recur. An analysis to determine root cause was not performed.

Lessons learned included:

1. New technologies require rigorous qualification, analysis of design changes, and a thorough understanding of failure modes
2. Vendor manufacturing processes need to be audited
3. Materials and processes for new applications need to be reviewed
4. Material incompatibilities need to be prevented
5. Qualification anomalies need to be worked to root cause

Example 3: Inadequate Qualification of Critical Inherited Designs for New Operational Uses

During design and manufacturing program phases, cost/benefit trade studies resulted in decisions not to perform developmental testing or to show whether or not there would be a problem powering the Traveling Wave Tube Amplifiers (TWTAs) during unit level pyrotechnic shock testing. A subsequent decision was made not to power the TWTAs during qualification pyrotechnic shock testing. The flight team was provided with a constraint not to operate during certain events. As a result, the TWTAs beam and cathode heaters were not powered, thus disabling downlink telemetry during a critical mission event, propulsion tank pressurization. After the event no telemetry from the spacecraft was received and the mission was lost. Such telemetry would have provided crucial spacecraft health and safety data for this event and for other spacecraft missions with similar systems or activities.

Lessons learned included:

1. Programs must consider the cost/risk of not qualifying critical inherited designs for new operational uses
2. Designs should ensure obtaining telemetry during high risk mission events

Example 4: Mars Lander Spacecraft Science Instrument Door Opening Anomaly

A spacecraft that landed in the polar region of Mars featured a robotic arm designed to deliver soil or ice samples to cells in the Thermal Evolved Gas Analyzer (TEGA) instrument. TEGA consisted of eight cells each with a pair of spring-loaded protective doors released by a pin puller device. Initial commands to open the doors resulted in the doors opening only partially. A failure investigation attributed the probable cause of the anomaly to a mechanical interference between the doors and bracket stiffeners that had raised profiles. The root cause was attributed to a breakdown in the design, verification, and validation processes. Testing of the cover release and door opening on an EQM revealed this failure mode, and the instrument contractor modified the design to avoid the interference. A set of change drawings was provided to the subcontractor for modifying the flight unit, but the necessary modification was not annotated or dimensioned for change, and the subcontractor drawings only incorporated changes that had dimensions or annotations called out. A test-like-you-fly (TLYF) exception excluded a full, post-assembly testing of the flight doors in a flight assembly, so the design flaw was not revealed on the flight unit.

Lessons learned included:

1. Subcontracts should specify documentation of all anomalies, especially those involving design changes
2. Drawings should be reviewed to ensure that redline changes have been included in final revisions
3. When EMs are used to validate flight hardware designs, additional customer oversight should be provided to maintain proper configuration control and review of reports
4. EQMs must be identical to the flight unit
5. EQM and flight unit TLYF should be followed

Additional note: Fortunately, soil samples could successfully be delivered to the TEGA cells through partially opened doors.