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Dynamic Environments Tailoring and Updates to TR-RS-2014-00016/SMC-S-016 (2014), Test Requirements for Launch, Upper-Stage and Space Vehicles

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Arash Mehrparvar
Environments, Test and Assessment Department
Vehicle Systems Division

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

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14. ABSTRACT

This document addresses vibration, shock, and acoustic environments. Tailoring and updates were motivated by lessons learned on launch and space programs, and by the increase in scope and applicability necessary in longstanding baseline requirements with the realization of reusable systems and evolving vehicle and mission architectures. It is intended that this document expands the applicability of dynamic environments requirements to a broader range of industry systems and practice.

The content in this document was drawn largely from LE-T-013 (2019), entitled Dynamic Environments Tailoring and Guidance to SMC-S-016 for Expendable and Reusable Launch Vehicles. Material drawn from this was reviewed for further content updates and to ensure applicability to space vehicles with additions or modifications made where necessary.

The updates that were proposed are presented as a tailoring document comprising the limited updates to the baselined requirements, rather than as an update to the core document.

15. SUBJECT TERMS

Test; space vehicle; launch vehicle; upper-stage; standard; tailoring; vibration; shock; acoustics

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Foreword

This document is a tailoring of The Aerospace Corporation report number TR-RS-2014-00016, entitled *Test Requirements for Launch, Upper-Stage and Space Vehicles*, which focuses on design verification and workmanship screening of flight hardware to help ensure a high level of confidence in achieving successful space missions. TR-RS-2014-00016 was also issued as USAF Space and Missile Systems Center (SMC) standard number SMC-S-016 (2014).

These documents, together, are intended for use in acquisition and study contracts. The standard tailored by this document (hereafter referred to as the "tailored standard") is intended to be used as a compliance document.

All content in this document addresses vibration, shock, and acoustic environments. Tailoring and updates were motivated by lessons learned on launch and space programs, and by the increase in scope and applicability necessary in longstanding baseline requirements with the realization of reusable systems and evolving vehicle and mission architectures. It is intended that this document expands the applicability of dynamic environments requirements to a broader range of industry systems and practice.

The content in this document was drawn largely from SMC Launch Enterprise (LE) tailoring (T) document LE-T-013 (2019), entitled *Dynamic Environments Tailoring and Guidance to SMC-S-016 for Expendable and Reusable Launch Vehicles*, originally written for the SMC Phase 2 Launch Service Procurement and authored by Arash Mehrparvar, Shawn H. Lin, and Thomas R. Cole of the Aerospace Corporation. Material drawn from this was reviewed for further content updates and to ensure applicability to space vehicles with additions or modifications made where necessary.

Format of this tailoring document

The outline and organization in this tailoring document are consistent with TR-RS-2014-00016/SMC-S-016 (2014). To avoid ambiguity, the formatting, section titles, section numbering, including any inconsistencies, has been preserved as originally published.

Tailoring Definition

Tailoring is a process by which individual requirements from specifications, standards, or related documents are evaluated and applied to a specific program by deletion, modification, or addition of requirements. Tailoring of requirements must be undertaken with consultation and approval of the procuring authority and their subject matter experts to align the standard with the acquisition authority's requirements and the mission needs. The diversity of missions, buses, payloads, environments, and unique approaches of contractors makes tailoring of standard requirements mandatory.

The tailored TR-RS-2014-00016/SMC-S-016 (2014) establishes a baseline for requirements, which in turn may be tailored or revised with rationale for specific project needs upon approval by the procuring authority.

Summary of tailoring

The following table summarizes the changes imposed by this document on TR-RS-2014-00016/SMC-S-016 (2014).

Section	Title	Change Summary
	Foreword	Added background for this tailoring.
1.5	Test Categories	Added Flightproof
3.12	~~Effective Duration for Acoustics and Random Vibration~~ Fatigue Equivalent Duration (FED) for Dynamic Environments	Nomenclature and definition updated. Expanded discussion to clarify applicability to various dynamic events.
3.26-3.29	3.26 Maximum Predicted Environment (MPE) for Acoustics 3.27 Maximum Predicted Environment (MPE) for Random Vibration 3.28 Maximum Predicted Environment (MPE) for Shock 3.29 Maximum Predicted Environment (MPE) for Sinusoidal Vibration	Deleted, superseded by addition in 3.66.
3.51	Statistical Estimates of Vibration, Shock, and Acoustic Environments	Deleted, superseded by updates made to Appendix B.1.1.
3.65	(Add) Environmental Design Margin	Addition to definitions to describe basis for margins imposed on design verification tests.
3.66	(Add) Maximum Predicted Environment (MPE) for Acoustics, Shock, and Vibration	Consolidated into one updated definition of MPE. Expansion of scope to consider potential uncertainties in analytical methods. Discussion of environment origins and processing relocated to Appendix B.
4.2.3	Protoqualification Tests	Updated content and added Flightproof testing discussion as a subsection (4.2.3.1)
4.2.4	Acceptance Tests	Updated content
4.3.2.2	Qualification Test Levels and Durations	Added content on updated basis for dynamic environments qualification margin (99/90 basis deleted, hardware and test uncertainty reinstated).
4.3.3.2	Protoqualification and Flightproof Test Levels and Durations	Updated content and added Flightproof testing discussion
4.3.4.2	Acceptance Test Levels and Durations	Updated requirements, added brief discussion for dynamic environments.
4.7	Test Input Tolerances	Added requirements for dynamic environments test tolerances for cases using minimum qualification margin.
4.11	Dynamic Environments Testing of Units at Higher Level of Assembly	Added discussion and requirements on testing of launch vehicle propulsion at higher levels of assembly and acknowledged consideration of similar practice for non-prop and space vehicle units.

5.2	Flightproof Strategy	Deleted due to its inclusion in 4.2.3. Not considered an “alternative strategy” for single vehicle procurements.
6.1	General Requirements	Updated to remove vague requirement and for more clarity on reference to 4.11.
6.3.4.3	Test Level and Exposure (6.3.4 Unit Shock Test)	Added Flightproof
6.3.4.4	Supplementary Requirements (6.3.4 Unit Shock Test)	Added criteria to disposition unit shock acceptance test
6.3.5.2	Test Description (6.3.5 Unit Vibration Test)	Updated for clarity on reference to 4.11 and non-applicability of fixture consistency to those cases. Consolidation of requirements.
6.3.5.3	Test Levels and Duration (6.3.5 Unit Vibration Test)	Updated and clarified discussion, added Flightproof
6.3.5.3.1	Minimum Unit Test Level for Random Vibration	Added subsection on minimum workmanship spec
6.3.5.8	Options for Vibration Testing	Deleted with child subsections. Discussion is redundant to or superseded by content throughout SMC-S-016 (2014) and this document.
6.3.6.1	Purpose (6.3.6 Unit Acoustic Test)	Updated to not over-enforce minimum acoustic spec
6.3.6.2	Test Description (6.3.6 Unit Acoustic Test)	Acknowledgement of Direct Field Acoustic Testing
6.3.6.3	Test Levels and Duration (6.3.6 Unit Acoustic Test)	Updated for brevity and consistency (much of the text was redundant)
6.3.6.3.1	Minimum Test Level for Acoustics	Added subsection on minimum acoustic spec and clarified intent.
6.3.6.5	Options for Acoustic Testing	Deleted with child subsections. Discussion is redundant to or superseded by content throughout SMC-S-016 (2014) and this document.
8.3.4.3	Test Activations (8.3.4 Vehicle Shock Test)	Added Flightproof
8.3.5.2	Test Description (8.3.5 Vehicle Acoustic Test)	Updated to acknowledge Direct Field Acoustic Test practice
8.3.5.3	Test Level and Duration (8.3.5 Vehicle Acoustic Test)	Updated for brevity and consistency (much of the text was redundant)
8.3.5.5.1	Flightproof Acoustic Test	Deleted, superseded by addition to section 4.2.3
8.3.5.5.4	Option to Perform Acoustic Test After Thermal Vacuum	Deleted protoqualification/flightproof “not available” statement at end
8.3.6.3	Test Levels and Duration (8.3.6 Vehicle Vibration Test)	Updated for brevity and consistency, and for intended application to hardware adjacent to space vehicle interface.

8.3.6.3.1	Minimum Test Level for Random Vibration of Vehicle Hardware	Added subsection on minimum vehicle random vibration spec and updated/clarified intent.
8.3.6.5	Options for Vehicle Random Vibration Testing	Clarified consistency in practice with acoustic test items in 8.3.5.5.
8.3.6.5.1	Flightproof Random Vibration Test	Deleted, superseded by addition to section 4.2.3
B.1	Test Considerations for Acoustic, Shock, and Vibration Environments	Updated introductory wording for consistency with updates in this section.
B.1.1	~~Statistical Basis for Test Level~~ Statistical Basis for Maximum Predicted Environment	Title updated. Replaced content with discussion specific to MPE, as updated philosophy assigns all necessary capture of uncertainty in flight environment in the MPE. The 99/90 basis for qualification margin has been deleted and updated to the consideration of hardware and test capability. These aspects constitute the fundamental origins of margin in design verification.
B.1.2	~~Acceleration of Acceptance Life for Acoustic and Random Vibration Tests~~ Calculation of Acoustic and Random Vibration Qualification and Protoqualification Test Durations	Updates improve clarity in baseline duration calculations and intended tailorability.
B.1.2.1	Qualification Duration for Reusable Hardware	Added subsection to provide requirements and discussion for reusable hardware.
B.1.3	~~Margin and Retest Implications of Acoustic and Random Vibration Qualification and Protoqualification Tests~~ Minimum Duration for Acoustic and Shaker Table Random Vibration Testing	Original deleted (redundant to updates in B.1.2) and replaced. Dedicated subsection to more clearly address minimum lab test duration requirement and necessary tailoring considerations.
B.1.4	~~Two-Phase Qualification and Protoqualification Test for Vibration and Acoustics~~ Two-Phase and Band-Split Approaches	Expansion of method, added requirements and discussion of band-splitting practice.
B.1.5	Damage-Based Analysis of Flight Vibroacoustic Data	Deleted, content superseded by updated discussion in section B.1.8.
B.1.7	(Add) Shock Qualification for Reusable Hardware	Requirements and considerations added to expand scope to reusable hardware
B.1.8	(Add) Analysis of Dynamic Environments Data for Design Specifications, and subsections	Discussion on physical origins, required signal analysis, and establishment of frequency ranges for test specification relocated from MPE definition for expanded applicability and smoother requirement flow. Expanded awareness of more recently incorporated methods, and disposition of exceedances to specs.

B.2	~~Response Limiting Criteria for Units Weighing More than 50 lb (23 kg)~~ Force and Response Limiting	Complete revision with discussion/requirements that acknowledge hardware and physics of excitation to guide practice. Remove subsections (B.2.1 and B.2.2) as they are redundant to minimum workmanship updates and updated force limiting content.
B.2.1	Broadband Reduction	Deleted. Content effectively moved to 6.3.5.3.1 of this document.
B.2.2	Narrowband Notching	Deleted. Content superseded by revision to B.2.
B.4	References	Incorporated additional references cited

Contents

Figures

1. Scope

1.5 Test Categories

ADD THE FOLLOWING between **Protoqualification Tests** and **Acceptance Tests**. Otherwise use SMC-S-016 (2014) verbatim.

Flightproof Tests. Tests conducted on single vehicle procurements to demonstrate satisfaction of design requirements and screen quality of workmanship. Flightproof testing is performed using the same amplitude margin as protoqualification and with duration reduced to that of acceptance since no subsequent builds are presumed. The flightproof strategy does not validate an acceptance test program in the event of any follow-on builds. The flightproof test program is supplemented with analyses as well as development and other tests to demonstrate margin and life for flight of the test hardware. Flightproof as described in this standard applies to vibration, shock, and acoustic testing.

2. Reference Documents

Use SMC-S-016 (2014) verbatim.

3. Definitions

3.12 Effective Duration for Acoustics and Random Vibration

REPLACE WITH

3.12 Fatigue Equivalent Duration (FED) for Dynamic Environments

FED is the duration required at a specified acoustic or vibration level that induces the same cumulative fatigue damage as that of a reference acoustic or vibration environment. In the context of a test specification, FED is the time required for a stationary dynamic exposure to induce the same fatigue damage as another, potentially nonstationary, event.

To establish basic requirements for test or analysis in the absence of measured data, the FED for liftoff and ascent acoustics and resultant random vibration is defined to be 15 sec, applied to a maximum predicted environment. Initial estimates of FED for reentry and descent aero/vibroacoustics should compare the respective flight profile to that of ascent to estimate a preliminary duration if no data are available.

For components or vehicle zones in which structural vibration is self-induced (liquid engines, solid motors, auxiliary pumps, etc.) and in the absence of measured data, the FED is defined to be the duration corresponding to a specific operating condition (burn duration at high throttle, for instance.)

FED can be calculated explicitly when measured data are available. This will determine the duration required for an environmental specification level to induce the same fatigue damage as the targeted event. For discussion of methods to calculate FED, see section B.1.8.5 of this document.

3.26 Maximum Predicted Environment (MPE) for Acoustics

DELETE

Note: MPE definitions have been merged, see section 3.66 of this document.

3.27 Maximum Predicted Environment (MPE) for Random Vibration

DELETE

Note: MPE definitions have been merged, see section 3.66 of this document.

3.28 Maximum Predicted Environment (MPE) for Shock

DELETE

Note: MPE definitions have been merged, see section 3.66 of this document.

3.29 Maximum Predicted Environment (MPE) for Sinusoidal Vibration

DELETE

Note: MPE definitions have been merged, see section 3.66 of this document.

3.51 Statistical Estimates of Vibration, Acoustic, and Shock Environments

DELETE

ADD THE FOLLOWING DEFINITIONS

3.65 Environmental Design Margin

Environmental design margin is an increase in environment level and/or duration above a maximum prediction imposed for the design and qualification of hardware. Environmental design margin is intended to cover the following:

- Variability in strength and fatigue life capability between qualification and flight hardware resulting from variations in material properties, manufacture and assembly processes, and rate of degradation during usage

- Allowable test level tolerances, to prevent as-tested acceptance levels exceeding as-tested qualification levels

Risk of an operational failure for flight hardware is reduced by accounting for a level of variability in its structural and performance capability, as affected by peak and cyclic loading throughout exposure to dynamic environments. Variability in application of the input load in test is also accounted for, per the consideration of test tolerances.

3.66 Maximum Predicted Environment (MPE) for Acoustics, Shock, and Vibration

MPE is a level that is not expected to be exceeded in service given an accepted amount of analytical or statistical confidence and risk posture. The intent of this level is to capture uncertainties involved in the derivation of an environment limit. The MPE for dynamic environments is defined as no lower than the P95/C50 statistical limit (or its equivalent) derived from processed data for the environment of interest and subject to the assumptions and practices discussed in section B.1.1 of this document. Standard practice and discussion on data processing techniques for random vibration, acoustic, sine vibration, and shock data for derivation of MPE specifications are given in section B.1.8 of this document.

Derivation of a service environment limit may incorporate uncertainties beyond those inherent in measured data, thereby raising the level above the minimum statistical limit specified. Relevant sources of additional uncertainty in the generation of an MPE may include the following:

- Spatial variability for a zonal environment definition
- Modeling fidelity of structures and forcing functions in analytical approaches
- Extrapolation of data from prior, similar, or subscale systems to the current one

Reference B1 provides discussion on the accounting of these additional uncertainties if deemed necessary. Data from subsequent service exposures are compared to their respective MPE to validate design and analysis criteria, or to recalculate the MPE as needed.

4. General Requirements

4.2 Testing Philosophy

4.2.3 Protoqualification Tests

REVISE AS FOLLOWS

The protoqualification strategy applies when a first-build article will be tested to demonstrate design margin and then put into service. The intent of protoqualification is to:

- Test to an amplitude higher than acceptance level but lower than the basic qualification level to simultaneously demonstrate a level of design margin in addition to workmanship screening
- Test at a reduced duration or reduced cycles relative to basic qualification to provide limited coverage for acceptance testing of future builds and reduce risk of an operational failure to the first build

For the first build, the protoqualification strategy is conducted at elevated technical risk. This is because a reference point for hardware fatigue or wear-out capability is not established through test as is done in qualification; there is no test demonstration of life remaining for flight or any additional environmental testing following a potential rework. Consequently, any required rework/retest and the potential for late discovery of design defects resulting from protoqualification testing can also pose increased risk. The protoqualification strategy also results in reduced retest capability for subsequent hardware builds that are acceptance tested (see section B.1.2 of this document). These risks shall be mitigated by analysis and/or prior testing of development hardware to establish design capability above protoqualification test amplitude and duration.

ADD THE FOLLOWING (NEW SECTION)

4.2.3.1 Flightproof Tests

For first-build articles that are non-recurring (mission unique or “one-off” designs), a flightproof strategy for dynamic environments (vibration, shock, acoustics) testing is recommended. A flightproof test is performed in the same manner as protoqualification and carries the same amplitude margin on test level but is conducted at a test duration further reduced to acceptance duration. This serves a similar purpose as protoqualification testing, but with additional reduction in risk for the flight article. The limited duration of the flightproof test precludes validation of a subsequent acceptance test program and, as a result, flightproof testing is recommended for single vehicle procurements.

4.2.4 Acceptance Tests

REVISE AS FOLLOWS

Acceptance testing shall be conducted on each deliverable item to demonstrate acceptable quality of workmanship and performance to specifications. The intent of an acceptance program is to minimize the escape of latent defects into subsequent testing at higher levels of assembly or into service, and to demonstrate that performance requirements are met for each deliverable flight item. This is accomplished by means of controls and inspections implemented throughout the manufacture and assembly process, functional testing, and the environmental tests discussed in this standard.

Acceptance testing shall be conducted prior to the first service use and after hardware rework. If the equipment is to be used by more than one program or in different vehicle locations, the acceptance test conditions shall envelop the worst-case environments. Acceptance testing as discussed in this section does not apply to hardware acquired through lot acceptance testing. See section 4.11 of this document for alternative approaches to dynamic environments exposure for acceptance testing of certain hardware types.

4.3 Testing Approach

4.3.2 Qualification

4.3.2.2 Qualification Test Levels and Durations

ADD THE FOLLOWING. Otherwise use SMC-S-016 (2014) verbatim.

Qualification testing demonstrates environmental design margin (section 3.65 of this document) over potential peak stress and fatigue failure modes resulting from the planned service environment, including acceptance testing. Qualification amplitude margin provides coverage against peak loading, while qualification amplitude and duration margin provide coverage against fatigue. Duration is discussed further in section B.1.2 of this document.

Basic qualification amplitude margin shall be 6 dB over the envelope of the MPE and acceptance test level. Any reduction in qualification amplitude margin shall maintain a minimum of 3 dB over the envelope of the MPE and acceptance test level and shall be evaluated and approved on an individual basis. Considerations for reducing qualification margin may include:

- Situations in which hardware is to be qualification tested at the unit level, but not acceptance tested at the unit level.

- Hardware complexity characterized by variability in its structural and performance capability and means of production, and by predictability of failure modes.

All uncertainties pertaining to the service environment input level are to be covered in the MPE. Section 4.7 of this document discusses test tolerances for cases where qualification margin is reduced.

4.3.3 Protoqualification

4.3.3.2 Protoqualification and Flightproof Test Levels and Durations

ADD THE FOLLOWING. Otherwise use SMC-S-016 (2014) verbatim.

Basic protoqualification and flightproof amplitude margin shall be 3 dB over the envelope of the MPE and acceptance test level. It should be noted that regarding the intent of environmental design margin, the need to cover variability in the structural and performance capability of the design could be considered null for the prototype build with respect to peak loading. This is because the prototype hardware has demonstrated its ability to withstand peak loads above the max predicted prior to flight.

Protoqualification and Flightproof test durations shall be two minutes and one minute respectively for acoustic testing or per axis for random vibration, subject to the discussion in section B.1.2 of this document.

4.3.4 Acceptance

4.3.4.2 Acceptance Test Levels and Durations

ADD THE FOLLOWING. Otherwise use SMC-S-016 (2014) verbatim.

Acceptance test amplitude at the unit level shall be the envelope of the MPE and the minimum workmanship spectrum, subject to the conditions discussed in section 6.3.5.3.1 of this document. Acceptance test duration shall be one minute for acoustic testing, or one minute per axis for random vibration, subject to the discussion in section B.1.3 of this document. The basic duration requirement of one minute is a historically reliable duration to effectively screen for workmanship defects and allow time for functional monitoring of hardware during test exposure. Exceptions to these amplitude and duration requirements may also be appropriate for some hardware types at the system level.

4.7 Test Input Tolerances

ADD THE FOLLOWING. Otherwise use SMC-S-016 (2014) verbatim.

For cases where the minimum qualification margin of 3 dB is to be implemented for random vibration, test tolerances for qualification and acceptance spectra shall be no wider than ± 1.5 dB, or it must be shown that as-run qualification test levels maintain positive margin to as-run acceptance test levels and MPE.

For cases where the minimum qualification margin of 3 dB is to be implemented for acoustic or shock, test tolerances for qualification and acceptance spectra shall be halved, or it must be shown that as-run qualification test levels maintain positive margin to as-run acceptance test levels and MPE.

ADD THE FOLLOWING (NEW SECTION)

4.11 Dynamic Environments Testing of Units at Higher Level of Assembly

Dynamic environments testing of certain non-avionics units, such as propulsion units on a motor, engine, or vehicle stage, may be incorporated in system-level engine, stage, or vehicle test firings as a substitution for unit level acceptance and/or qualification testing if it can be established that the environments and duration meet the intent of the individual test criteria, and/or if such units are not amenable to testing individually. For acceptance testing, intent refers to the ability to minimize the escape of latent defects in hardware workmanship into subsequent service. For qualification, intent refers to the ability to demonstrate environmental design margin. It is recognized that system-level testing may provide more realistic and simultaneous environments (vibration, shock, acoustic, thermal, pressure, fluid flow phenomena) and boundary conditions for certain units.

The acceptability of system-level testing as a substitute for unit level testing shall be evaluated on an individual basis. The following criteria should be considered in the assessment:

- Similarity in dynamic environments (spectral content and overall level) imposed during subsystem or vehicle level test and those expected for flight
- Component redundancy and criticality to system operation
- Potential workmanship and design sensitivities and failure modes of component
- Functional checks and/or inspections conducted to ensure the component is operating nominally before, during, and after environmental exposure
- For on-engine qualification, consideration that while margin to fatigue and/or wear out may be demonstrated, explicit amplitude margin typically cannot. Therefore, supplemental analysis and/or unit-level testing is required to reduce risk.

If unit-level random vibration testing is planned for a given unit as part of its acceptance test flow, a corresponding unit-level random vibration qualification test shall be conducted to account for that provision and all other events comprising its service life.

A similar approach could be considered for launch or space vehicle units integrated onto other subsystem- or vehicle-level tests, e.g. a solenoid valve or pressure vessel on a payload fairing acoustic qualification test. However, it is acknowledged that unit design and workmanship screening, and efficiency in any necessary rework are most effective when performed at the unit level. This is especially true for units integrated onto a space vehicle, for which the decrease in test perceptivity and potential break in vehicle assembly configuration needed in the event of a unit malfunction during a system level test may pose excessive program risk. For all proposed cases of unit level testing at a higher level of assembly, the potential for a unit rework scenario to impact program cost and schedule should be considered.

5. Alternative Strategies

5.2 Flightproof Strategy

DELETE

Note: This discussion has been placed under sections 4.2.3.1 and 4.3.3.2 of this document.

6. Unit test Requirements

6.1 General Requirements

REVISE AS FOLLOWS

Unit tests are accomplished entirely at the unit level. However, in certain circumstances where one or more units are needed to complete a function, unit test requirements may be satisfied at the next level of assembly. Tests of units such as interconnect tubing, radio-frequency circuits, and wiring harnesses are examples where at least some of the tests may be accomplished at higher levels of assembly. See section 4.11 of this document for testing of non-avionics units at higher levels of assembly. If moving mechanical assemblies or other units have static or dynamic fluid interfaces or are pressurized during operation, those conditions should be replicated during unit testing.

6.3 Test Program for Units

6.3.4 Unit Shock Test

6.3.4.3 Test Level and Exposure

ADD THE FOLLOWING identified in *italic font*. Otherwise use SMC-S-016 (2014) verbatim.

Qualification: MPE + 6 dB applied 3 times

Protoqualification: MPE + 3 dB applied 2 times

Flightproof: MPE + 3 dB for one application

Acceptance: MPE for one application

6.3.4.4 Supplementary Requirements

ADD THE FOLLOWING. Otherwise use SMC-S-016 (2014) verbatim.

In cases where units such as moving mechanical assemblies generate a self-induced shock environment during function or actuation, and that shock constitutes the unit's worst-case shock environment, shock qualification testing may be considered covered through life testing. Comparison of the measured self-induced shock against either data or predictions of all externally induced shock for the unit shall be used as rationale for this substitution. The number of actuations performed in life test shall be greater than the number of exposures otherwise require for unit shock qualification (see sections 6.3.4.3 and B.1.7 in this document for expendable and reusable hardware, respectively). Any force or energy margin implemented in life test should be used to gauge the resultant amplitude margin for shock in such cases. If multiple units undergo life testing, that may serve as a basis to partially address the coverage of build-to-build variability intended by qualification amplitude margin.

In general, shock acceptance testing of units is not recommended. Shock acceptance testing may be omitted with no engineering evaluation required, with the following exceptions:

- Sensitivities uncovered in qualification or protoqualification testing that may imply a workmanship sensitivity not otherwise uncovered by vibration testing

- A shock MPE specification with modal velocity of at least 100 in/s in certain frequency bands, notably those beyond the typical 2000 Hz limit of random vibration test capability, and/or where unit resonant frequencies may exist

Either of these criteria warrant an engineering evaluation for shock acceptance test, and typically bear more consideration for avionics units. Evaluation should consider other screens being conducted as part of acceptance, unit criticality to mission, redundancies, shock test repeatability, and additional development test and analysis to determine shock transmission into subcomponents of concern.

6.3.5 Unit Vibration Test

6.3.5.2 Test Description

REVISE AS FOLLOWS

For random vibration testing, the unit shall be mounted to a test fixture through the normal mounting points of the unit. For any unit, the same test setup and fixture shall be used in the qualification, protoqualification, and acceptance vibration tests, unless it can be shown that the fixture and control strategy used on subsequent acceptance tests provides similar input spectra (minus amplitude margin) to flight units. Fixture and fixture consistency requirements do not apply to cases in which the test provisions described in section 4.11 of this document are followed, since testing of a unit at a higher level of assembly involves flight-like mounting and not a test fixture.

Attached wiring harnesses and hydraulic and pneumatic lines, instrumentation, and other connected items shall be connected using flight-like connectors and be equivalent to, or simulate the flight configuration to, the first attachment point. The intent of these requirements is to simulate the external interconnecting mass, damping, and stiffness effects on the unit's dynamic response, unless shown to be insignificant. This also serves as a test of the connection hardware and test configuration itself. Note that qualification or protoqualification must cover the acceptance test setup on subsequent units, in addition to the flight interface conditions described here. Such a configuration shall also be required when units that employ shock or vibration isolators are tested on their isolators.

The suitability of the fixture and test control shall have been established, per the requirements in section 6.3.5.6 of SMC-S-016 (2014), prior to qualification testing. The unit shall be tested in each of three orthogonal axes.

If it is desired to simultaneously test multiple units on a fixture, input consistent with the test specification shall be demonstrated for all units. This may require monitoring or control at the respective input locations for each unit during test. If qualification testing of a single unit intends to provide coverage against an acceptance test strategy involving multiple units under test simultaneously, dynamic mass simulators may be used alongside the qualification unit with their inputs controlled or monitored to demonstrate a consistent test setup.

If a unit is to be flown on isolators, acceptance testing must often be run in a hard-mounted configuration in order to achieve minimum workmanship input levels to the unit. For these cases, qualification vibration testing shall require the following two configurations, with test duration split accordingly for each:

- Unit hard-mounted to qualify for acceptance testing provisions
- Unit mounted on isolators to qualify for the flight environment

The unit shall be mounted on isolators of the same manufacturer as those used in service. Units mounted on isolators shall be controlled at the locations where the isolators are attached to the fixture. Hard-mounted units shall be controlled at the unit mounting attachment or attachments as appropriate.

6.3.5.3 Test Levels and Duration

REVISE AS FOLLOWS

The basic test levels and durations required for units, assuming an FED of 15 seconds, are as follows:

Qualification: 6 dB above acceptance for 3 min/axis (see B.1.2 in this document)

Protoqualification: 3 dB above acceptance for 2 min/axis (see B.1.2 in this document)

Flightproof: 3 dB above acceptance for 1 min/axis (see B.1.2 in this document)

Acceptance: Envelope of MPE and minimum level shown in Figure 6.3.5-1, subject to the discussion in section 6.3.5.3.1 of this document, for 1 min/axis

This standard defines these test conditions to constitute the basic dynamic environments test requirements. These amplitudes and durations are consistent with exposure to the liftoff and ascent vibration environment for a single flight. The qualification test demonstrates that adequate fatigue life remains for flight units after up to eight minutes of acceptance testing for each axis. The protoqualification test demonstrates that adequate life remains for subsequent flight units after one minute of acceptance-level testing for each axis. However, the protoqualification test does not demonstrate adequate life left for flight of the protoqualification unit itself. The acceptance test demonstrates quality of workmanship and performance to specifications. For single procurements, flightproof testing blends elements of design verification (for amplitude exposure only) with demonstration of workmanship. For flightproof tests of units, the minimum workmanship specification given in section 6.3.5.3.1 of this document should be incorporated, but amplitude margin should only be added to the MPE.

See section B.1.2 in this document for consideration of the following conditions:

- FED not equal to the assumption of 15 seconds due to consideration of environments separate from liftoff and ascent acoustics, or more generally from an FED that is calculated
- Hardware designed for reusability (multiple flights)
- Desired coverage for a number of acceptance tests different than those stated in this section

Low-level testing shall be performed in each axis before and after the specified vibration tests to detect any structural changes, unless this test can be justified as unnecessary in the detection of design or workmanship defects.

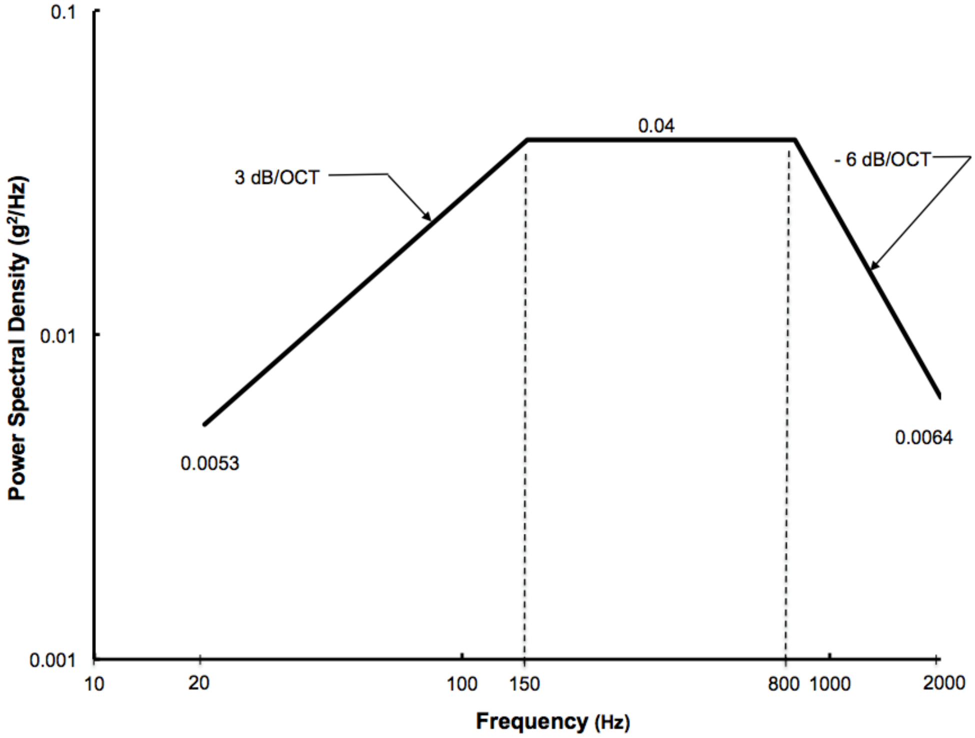
ADD THE FOLLOWING (NEW SECTION)

6.3.5.3.1 Minimum Unit Test Level for Random Vibration

The minimum workmanship random vibration spectrum is shown in Figure 6.3.5-1. This level was derived from heritage practice as well as testing conducted by various agencies to determine an effective minimum environmental stress screen level for avionics unit hardware. The intent of this level is to identify latent defects in hardware containing electronics when acceptance random vibration is conducted on a shaker table. For a given unit, the minimum workmanship random vibration specification shall be applied. This spectrum may be modified or omitted based on technical considerations and evaluation on an individual basis. Examples of considerations that may justify modification or omission of the minimum workmanship spectrum are:

- A unit (such as sensitive instruments, optics, etc. that are part of a mission payload) is deemed “fragile” via development test and/or analysis such that the application of the minimum workmanship spectrum would jeopardize its intended design capability
- A unit does not contain electronics and/or is not considered workmanship-sensitive to vibration exposure
- Testing of a unit at a higher level of assembly has been deemed acceptable practice, as described in section 4.11 of this document
- An alternate minimum workmanship vibration specification that is perceptive to workmanship defect(s) has been created for a unit

Note that omission of the particular minimum workmanship specification in Figure 6.3.5-1 does not eliminate a need for acceptance vibration testing.



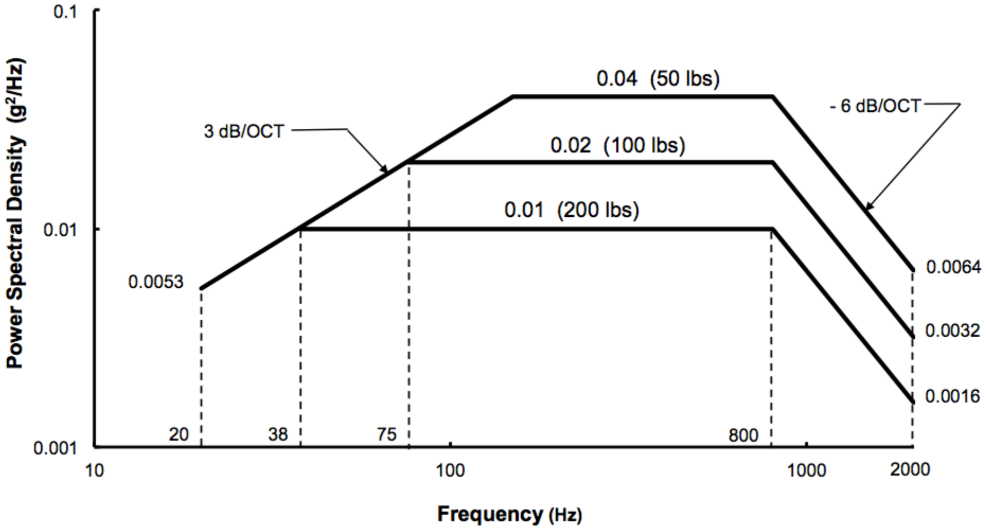
Spectrum Values	
Frequency (Hz)	**Minimum PSD (g^2/Hz)**
20	0.0053
20 to 150	+3 dB per octave slope
150 to 800	0.04
800 to 2000	-6 dB per octave slope
2000	0.0064
The overall acceleration level is 6.9 grms.	

Figure 6.3.5-1. Minimum random vibration spectrum, unit acceptance test.

For units exceeding 50 lb, this minimum workmanship specification may be reduced by using the following relation:

$$\text{Reduced spectrum level } (g^2/\text{Hz}) = 0.04\left(\frac{50}{W}\right)$$

where W is the unit weight in pounds. The reduction cannot be more than 6 dB. Figure 6.3.5-2 shows the minimum spectra for units weighing 50, 100, and 200 lb, respectively. For each of these weights, the spectral plateau was extended into the low-frequency regime without reducing the spectrum roll-off level to assure adequate excitation of lower frequency modes that could be characteristic of the relatively higher unit weight.



Weight (lb)	Overall Acceleration (Grms)
50	6.9
100	4.9
200	3.5

Figure 6.3.5-2. Minimum workmanship random vibration spectrum with unit weight compensation.

6.3.5.8 Options for Vibration Testing

DELETE

6.3.5.8.1 Two-Phase Testing

DELETE

6.3.5.8.2 Alternate Vibration Test for Qualification and Protoqualification

DELETE

6.3.6 Unit Acoustic Test

6.3.6.1 Purpose

REVISE AS FOLLOWS

The acoustic qualification and protoqualification tests demonstrate the ability of a unit to endure a limited duration of acceptance testing and meet requirements during and after exposure to a margin over the acceptance test level. The acceptance test level is an envelope of the MPE and the minimum acoustic spectrum shown in section 6.3.6.3.1 of this document, subject to the discussion presented there. Acoustic testing is required for a unit having large surfaces, causing its vibration response to be due predominantly to direct acoustic excitation. For such units, the vibration test is discretionary except as noted in section 6.3.5.1 of SMC-S-016 (2014).

6.3.6.2 Test Description

ADD THE FOLLOWING. Otherwise use SMC-S-016 (2014) verbatim.

Direct field acoustic testing may be used as an alternative to a reverberant chamber acoustic test.

6.3.6.3 Test Levels and Duration

REVISE AS FOLLOWS

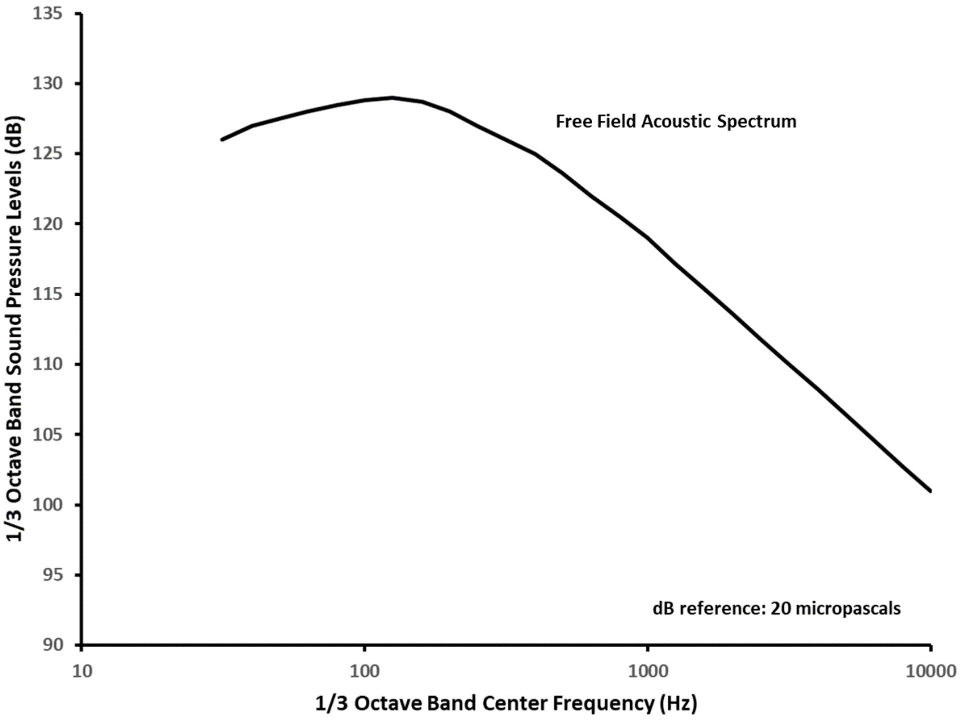
Requirements and discussion are the same as for unit vibration in section 6.3.5.3 of this document with the following exceptions:

- Acoustic test amplitude and duration is applied one time, not per axis
- Discussion on minimum acoustic test level is contained in this section

ADD THE FOLLOWING

6.3.6.3.1 Minimum Test Level for Acoustics

The minimum acoustic spectrum is shown in Figure 6.3.6-1. This level was derived from measured flight data on several medium and heavy launch vehicles. This spectrum is not considered a standard environmental stress screen level in the same manner as minimum workmanship random vibration, because vibroacoustic response can vary significantly between different structures and acoustic forcing function types. Rather, the intent of this level is to serve as a benchmark for design and/or test level early in a program when the launch vehicle is undefined. When a specific acoustic MPE is established for the program, this minimum level may be omitted.



Spectrum Values			
1/3 Octave Band Center Frequency (Hz)	Minimum Sound Pressure Levels (dB)	1/3 Octave Band Center Frequency (Hz)	Minimum Sound Pressure Levels (dB)
31.5	126	630	122
40	127	800	120.5
50	127.5	1000	119
63	128	1250	117.2
80	128.5	1600	115.3
100	128.8	2000	113.6
125	129	2500	111.8
160	128.7	3150	110
200	128	4000	108.2
250	127	5000	106.4
315	126	6300	104.6
400	125	8000	102.7
500	123.6	10000	101
Overall Sound Pressure Level (OASPL) = 139 dB			

Figure 6.3.6-1. Minimum acoustic spectrum, unit and vehicle.

6.3.6.5 Options for Acoustic Testing

DELETE

6.3.6.5.1 Two-Phase Testing

DELETE

6.3.6.5.2 Alternate Acoustic Test for Qualification and Protoqualification

DELETE

7. Subsystem Test Requirements

Use SMC-S-016 (2014) verbatim.

8. Vehicle Test Requirements

8.3 Test Program for Flight Vehicles

8.3.4 Vehicle Shock Test

8.3.4.3 Test Activations

ADD THE FOLLOWING identified in *italic font*. Otherwise use SMC-S-016 (2014) verbatim.

Qualification:	All explosive-ordnance devices and other potentially significant shock-producing devices or events, including those from sources not installed on the vehicle under test, shall be activated at least one time, or simulated, as appropriate. The significant shock events shall be activated two additional times to provide for variability in the vehicle test and to provide data for prediction of maximum and extreme expected shock environments for units. Activation of both primary and redundant devices shall be carried out in the same sequence as they are intended to operate in service.
Protoqualification:	Same as qualification except only one additional activation of significant shock producing events is required.
Flightproof:	One activation of significant shock-producing events is required.
Acceptance:	One activation of significant shock-producing events is required.

8.3.5 Vehicle Acoustic Test

8.3.5.1 Test Description

ADD THE FOLLOWING. Otherwise use SMC-S-016 (2014) verbatim.

Direct field acoustic testing may be used as an alternative to a reverberant chamber acoustic test.

8.3.5.2 Test Level and Duration

REVISE AS FOLLOWS

Requirements and discussion are the same as for unit vibration in section 6.3.5.3 of this document with the following exceptions:

- Acoustic test amplitude and duration is applied one time, not per axis
- Discussion on minimum acoustic test level is contained in section 6.3.6.3.1 of this document

8.3.5.5 Options for Acoustic Testing

8.3.5.5.1 Flightproof Acoustic Test

DELETE

8.3.5.5.4 Option to Perform Acoustic Test After Thermal Vacuum

DELETE THE FOLLOWING identified in ~~strikethrough font~~ and replace with the text below it. Otherwise use SMC-S-016 (2014) verbatim.

~~A major purpose of the protoqualification, or flightproof, testing is design verification requiring maximum test effectiveness. As a result, the modified sequence approach is not available for protoqualification and flightproof vehicle testing.~~

Maximum test effectiveness is achieved when thermal vacuum occurs as the final environmental test in the test sequence. For qualification, protoqualification, or flightproof test articles, for which design verification is a primary goal, it is recommended that the standard sequence be maintained.

8.3.6 Vehicle Vibration Test

8.3.6.3 Test Levels and Duration

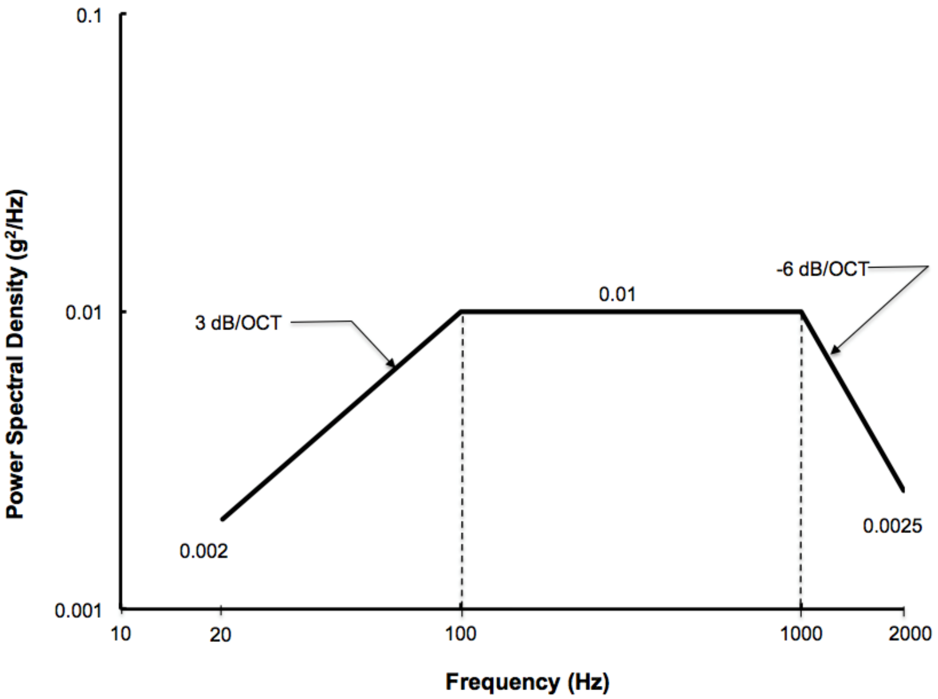
REVISE AS FOLLOWS

Discussion and requirements are the same as for unit vibration in section 6.3.5.3 of this document, noting that the discussion of vibration test here pertains to space vehicle units mounted adjacent to the space vehicle interface plane. Base shake testing at the vehicle level is not recommended. Vehicles classified as small satellites, CubeSats, or similar should be vibration tested in accordance with unit requirements presented in the preceding sections of this document and section 6 in SMC-S-016 (2014).

ADD THE FOLLOWING

8.3.6.3.1 Minimum Test Level for Random Vibration of Vehicle Hardware

The minimum random vibration spectrum for acceptance testing of vehicle hardware as described in this section is given in Figure 8.3.6-1. This level was derived from flight data measured at or near the space vehicle interface on several medium and heavy launch vehicles. The application of this minimum spectrum is intended for space vehicle units adjacent to the space vehicle interface for which an MPE has not yet been established. If an MPE does exist for the specific unit(s), it shall supersede this minimum level. Note that the minimum workmanship random vibration spectrum given in section 6.3.5.3.1 of this document also applies to units, subject to the discussion there.



Spectrum Values	
Frequency (Hz)	**Minimum PSD (g^2/Hz)**
20	0.002
20 to 100	+3 dB per octave slope
100 to 1000	0.01
1000 to 2000	-6 dB per octave slope
2000	0.0025
The overall acceleration level is 3.8 grms.	

Figure 8.3.6-1. Minimum random vibration spectrum for space vehicle unit hardware adjacent to the space vehicle interface.

8.3.6.5 Option for Vehicle Random Vibration Testing

ADD THE FOLLOWING

Discussion and requirements are the same as for acoustics in section 8.3.5.5 of this document.

8.3.6.5.1 Flightproof Random Vibration Test

DELETE

9. Prelaunch Validation and Operational Tests

Use SMC-S-016 (2014) verbatim.

Appendix A. Thermal Test Considerations

Use SMC-S-016 (2014) verbatim.

Appendix B. Dynamic Test Considerations

B.1 Test Considerations for Acoustic, Vibration, and Shock Environments

REVISE AS FOLLOWS

The following subsections describe considerations for the statistical analysis approach used in this document to derive MPEs, as well as the considerations and basis of calculations used to generate qualification and protoqualification test durations for dynamic environments.

B.1.1 Statistical Basis for Test Level

REVISE AS FOLLOWS

B.1.1 Statistical Basis for Maximum Predicted Environment

The discussion in this section is intended for application to samples of dynamic environments data measured at a consistent location and their variability between occurrences, or “flight-to-flight”. If it is desired to account for other uncertainties (such as those from analytical models or spatial variability) in a similar manner, see Reference B1 for guidance on generating bounding statistical levels for multiple sources of uncertainty.

Spectral data for dynamic environments is assumed to be log-normally distributed. That is, the normal distribution applies to the logarithms of the spectral values at a particular frequency. It follows that the estimated mean spectrum is the antilog of the average of the logarithmic values of available spectra. The standard deviation of spectra from the mean is denoted by σ and is assumed to equal 3 dB. The assumption of log-normal distribution with 3 dB standard deviation is based on measured vibration, shock, and acoustic data for ballistic missiles and medium and heavy launch vehicles (References B2 and B3). When a sufficient sample size exists for a dataset, it is recommended that its statistics be analyzed to determine an estimate of variability and evaluate the log-normal assumption. Analysis following the criteria used by Womack in Reference B5 suggests a low sample limit of at least three for a P95/C50 statistical limit. Note that this limit increases with the P/C limit.

The MPE in this standard is defined to be at least the P95/C50 or equivalent level applied to processed data, as presented in section 3.66 of this document. The P95/C50 level is a 95th percentile upper bound estimated with 50% confidence. This means that 50% of the time, the technique used generates a level that bounds the 95th percentile of the underlying distribution of data. In cases where the data sample size is low (less than three for P95/C50), it is recommended that the statistical limit level be calculated with

$$L_{P/C} = \sigma\left(z_p + \frac{z_c}{\sqrt{N}}\right)\ dB \qquad \text{(B1)}$$

in which $L_{P/C}$ is the level at probability P estimated with confidence C, σ is the standard deviation, N is the number of samples, and z_p and z_c are read from a table of the standardized normal density function (Reference B6, amongst many others). This equation was presented by Owen (Reference B9) for the case where the true standard deviation is assumed known and the mean is estimated from the samples available. For the low-sample $L_{95/50}$ limit estimate, σ is assumed to be 3 dB. Since $z_{0.95} = 1.645$ and $z_{0.50} = 0$, this puts the limit at approximately 5 dB above the mean environment.

If no data are available, a P95/C50 equivalent MPE is defined as 5 dB added to an estimate of the mean environment. If one sample is available it is assumed to be the mean environment, to which 5 dB is added for a P95/C50 equivalent MPE. For a sample size of $N \geq 3$, it is recommended that normal tolerance limits be considered to determine a P95/C50 level for which the standard deviation at each frequency is calculated directly from the available spectra. References B1 and B5 provide direction for this procedure.

Equation B1 and the normal tolerance limit method referenced in this section are not limited to only the P95/C50 calculation and may be used for any P/C statistical limit. While it is preferable that data measured from a specific dynamic event be used to generate the MPE for that event, data from other events may be used if the dynamics are deemed sufficiently similar – e.g. engine or booster static fire data may be applicable to the generation of a flight MPE for certain vehicle zones.

B.1.2 Acceleration of Acceptance Life for Acoustic and Random Vibration Tests

REVISE AS FOLLOWS

B.1.2 Calculation of Acoustic and Random Vibration Qualification and Protoqualification Test Durations

Qualification duration requirements are developed assuming hardware is susceptible to a life limiting fatigue failure mode. The associated failure is assumed to be modeled by mid- to high-cycle fatigue characteristics presented in material S-N curves. It is further assumed that Miner's Rule for fatigue accumulation applies, and that induced stress is proportional to a cyclic exposure amplitude (typically taken as acceleration or pressure). Miner's Rule (Reference B4) states that the summation of the product of the number of cycles and their stress amplitude raised to an exponent "b" is proportional to the fraction of life exhausted. Therefore, since qualification or protoqualification tests are performed at a higher amplitude than acceptance (or MPE), durations computed on this basis are "accelerated" to account for the increase in amplitude. The expression relating the qualification duration required given its amplitude margin to an established specification level is,

$$T_Q = L_{TF}\left[T_{FED}\left(\frac{1}{10^{Mb/20}}\right)\right] \qquad \text{(B2)}$$

in which variables are defined as:

T_Q	Qualification duration
L_{TF}	Fatigue life test factor
T_{FED}	Duration greater than or equal to the FED of the specification level
M	Margin in dB between levels (qualification and MPE for instance), assumed uniform through frequency
b	Fatigue exponent, taken as the absolute value of the inverse slope of a log-log S-N curve
$10^{Mb/20}$	Time acceleration factor

Standard practice sets $L_{TF} = 4$. The factor of four on design fatigue life demonstration has been a historically successful factor to cover variability in fatigue-induced design failure modes for hardware under test. The fatigue exponent is typically assumed to be $b = 4$; Reference B4 recommends this for solder as a conservative value when accelerating test duration. If another value can be justified for a driving fatigue failure mode in a component, that value may be used instead.

Generally, a qualification test covers the duration of exposure in flight and several acceptance test exposures. Since MIL-STD-1540C, the qualification test duration of 3 minutes has been interpreted as the sum of two durations: the first part being that necessary to qualify for flight, and the remainder serving as a demonstration of the total allowable fatigue life expended during acceptance testing of a flight unit. In this historical context, the calculation of qualification test duration in line with the basic amplitude and fatigue margin is given as,

$$T_Q = L_{TF}\left[T_{MPE} + T_A\left(\frac{1}{10^{Mb}/_{20}}\right)\right] \tag{B3.1}$$

In which T_{MPE} is the assumed FED (previously referred to as effective duration) for MPE, and T_A is the total duration corresponding to the allotted number of unit-level acceptance tests on subsequent flight hardware builds. This form does not accelerate the FED of the flight event as a conservative measure and was intended for use with the assumption of a 15 sec FED corresponding to liftoff and ascent dynamic environments. Noting the basic qualification amplitude margin of 6 dB and allowing for eight acceptance tests of 60 sec duration each yields the qualification duration as,

$$180\ sec \approx 4\left[15\ sec + \frac{(8*60\ sec)}{10^{(6*4)/20}}\right]$$

Following the same assumptions, the approach for Protoqualification has been formulated by,

$$120\ sec \approx 4\left[15\ sec + \frac{(1*60\ sec)}{10^{(3*4)/20}}\right]$$

In which the test time of 120 sec at an amplitude margin of 3 dB provides coverage for one acceptance test prior to flight for subsequent builds, in addition to the unaccelerated FED of 15 sec for flight.

Acceleration of the flight environment duration is more in line with the fundamental relationship presented in Equation B2 and is given as,

$$T_Q = L_{TF}\left[T_{MPE}\left(\frac{1}{10^{Mb}/_{20}}\right) + T_A\left(\frac{1}{10^{Mb}/_{20}}\right)\right] \tag{B3.2}$$

If several service environments are to be accounted for (MPEs for different flight and ground test events), they must be included with their respective FEDs in the above equation.

Equation B3.2 is typically recommended for hardware exposed to flight environments with longer durations, such as those on or near engines. More generally however, it may be used to guide tailoring of the qualification test duration to that deemed appropriate for specific hardware and the associated program given the amount of qualification amplitude margin, planned acceptance test strategy, and number of allocated acceptance tests. It may also be used to help mitigate risk for retest where duration demonstration for subsequent builds is more limited, notably for programs leveraging a protoqualification approach. A required constraint on test duration is the minimum of 60 sec but is subject to the discussion in section B.1.3 of this document.

ADD THE FOLLOWING

B.1.2.1 Qualification Duration for Reusable Hardware

For calculation of qualification durations intended to cover multiple missions, it is reasonable to assume that not all service environment exposures may occur at their MPEs as is done when designing for a single use. The likelihood of this assumption increases with the number of planned service exposures. For cases in which a unit is to be used for multiple missions, the following approach may be used to define an extended qualification test duration:

- Determine the single-use (one mission) qualification duration $\mathrm{T_{Q1f}}$ for a given event using Equation B2,

$$T_{Q1f} = L_{TF}\left[T_{MPE}\left(\frac{1}{10^{Mb/20}}\right)\right]$$

If a more conservative approach is desired, the unaccelerated accounting of T_{MPE} may be used, as in Equation B3.1, to calculate T_{Q1f}.

- Calculate a "reuse factor" R for the service event,

$$R = 16e^{-0.46M_0}N^{0.77} \qquad \text{(B4)}$$

Where M_0 is the margin in dB between the planned qualification test level and the mean environment for the event of interest (this differs from the margin M between test and FED levels), and N is the planned number of service uses corresponding to the event ($N > 1$). If a mean environment has not been defined, it must be inferred from the MPE.

- Calculate the qualification time required to cover any allocated number of unit level acceptance tests T_{QA}, again using Equation B2,

$$T_{QA} = L_{TF}\left[T_A\left(\frac{1}{10^{Mb/20}}\right)\right]$$

- Apply the reuse factor R to the single-use qualification time T_{Q1f} and sum with the time to cover acceptance test T_{QA} to yield the total qualification duration T_Q as,

$$T_Q = T_{Q1f}(1 + R) + T_{QA} \qquad \text{(B5)}$$

If there are multiple service events to be accounted for, they are to be included in the equation above with their respective values for T_{Q1f} and R. Equation B5 accounts for the occurrence of one service exposure at MPE level, with the other $N - 1$ exposures accounted for by R. Again, the minimum test duration of 60 sec applies to T_Q, subject to the discussion in section B.1.3 of this document.

The reuse factor calculation in Equation B4 was derived by curve fitting to the 99th percentile upper bound of Monte Carlo runs conducted on the fundamental relationship given by the time acceleration factor in Equation B2. Variation of input parameters for the runs involved the qualification test level relative to the mean environment M_0, the margin between that qualification level and the random occurrence of an exposure level, and the number of service exposures N. The following assumptions were applied:

- Fatigue exponent of $b = 4$
- Service environment is log-normally distributed with a standard deviation of 3 dB

These assumptions were kept in accordance with those presented in this standard. Note that while the assumption of 3 dB standard deviation is conservative, Equation B4 may not encompass all cases if the fatigue exponent b is set higher than 4 and the qualification margin to mean M_0 is less than 11 dB. This overall approach is intended to:

- For a given service environment, cover for one occurrence at the MPE explicitly
- Cover the other $N - 1$ exposures in a manner that is bounding while remaining aware that service exposures will vary about a mean level
- Provide flexibility for the definitions of MPE and qualification levels associated with a program
- Serve as an extension to the standard single-use definition of qualification amplitude and duration margin

Regarding the final bullet above, it must be noted that the inherent risk posture taken in one's definition of MPE and qualification margin (for both amplitude and duration) is in effect amplified with its extension to multiple service uses. The methodology presented here does not extend in use beyond the application to a dynamic environment input duration. Test and/or analytical demonstration of fatigue life capability for reusable hardware should consider other external load cases that may combine with the dynamic environments input in generating an overall stress state.

The output of this method shall be the minimum time required to qualify reusable hardware at the unit level for a given number of planned uses and qualification amplitude margin.

Different approaches to this calculation that meet the same intent may be used as a tailored approach, based on technical rationale for any changes to the assumed standard deviation or fatigue exponent values.

Regardless of the method used to calculate qualification test duration for reuse, fatigue exposure shall be calculated and tracked for reusable hardware to ensure that adequate life margin is maintained prior to each subsequent use. See section B.1.8.5 in this document for a brief discussion of fatigue tracking of dynamic environments data with references for both time and frequency domain implementation.

B.1.3 Margin and Retest Implications of Acoustic and Random Vibration Qualification and Protoqualification Tests

REPLACE WITH THE FOLLOWING

B.1.3 Minimum Duration for Acoustic and Random Vibration Testing

Minimum duration for acoustic or random vibration testing shall be 60 sec. This minimum applies to qualification, protoqualification, flightproof, and acceptance tests. Criteria for tailoring this minimum duration may include:

- Per test control spectral resolution and averaging, sufficient time exists to achieve 100 statistical degrees of freedom at the target test level

- Sufficient time exists to allow for critical resonant modes of the hardware under test to achieve steady state response

- Sufficient time exists to perform the necessary functional checks on hardware under test

- FED and subsequently test duration are calculated to be much lower than 60 sec, such that imposition of this minimum duration may be excessively conservative

- Acceptance testing of units at higher levels of assembly has been deemed appropriate, as discussed in section 4.11 of this document

B.1.4 Two-Phase Qualification and Protoqualification Test for Vibration and Acoustics

REVISE AS FOLLOWS

B.1.4 Two-Phase and Band-Split Approaches

Cases where a single test specification is separated into amplitude and fatigue coverage tests are known as "two-phase" tests. Although a given test specification is preferentially achieved with one exposure at the established amplitude, duration, and frequency range, practical limitations on test equipment may prevent the simultaneous application of all specification requirements (certain sine-on-random spectra for instance). Limitations may be exacerbated in cases of large or high-mass hardware, or high environment amplitudes.

A simple example of a two-phase approach for a qualification test is: (1) 1x life (or minimum required duration) performed at qualification level to cover amplitude, and (2) the remaining 3x lives performed at MPE level to cover fatigue. This example is only one of many ways a test specification may be satisfied in parts. Further subdivisions of the amplitude or fatigue coverage portions may be necessary in some circumstances.

For cases where a single test specification is satisfied in several parts, the following criteria shall be met:

- Verification that the totality of exposure is equivalent to the original test specification in terms of amplitude and fatigue

- All exposure counted towards demonstration of fatigue capability occurs at MPE level or higher

- All tests comprising the original test specification are conducted on the same hardware article

- Any individual test is subject to the requirement on minimum duration per section B.1.3 of this document

If a test spectrum is broken into several frequency ranges, the practice is known as "band-splitting." When implementing band-splitting, these additional criteria shall be met:

- Each band-split breakpoint of the original test spectrum is at a frequency well-separated from a critical resonant frequency of the hardware in the test configuration, with a goal of one octave away

- A maximum of four separate bands cover the original test spectrum (no more than three splits), with a goal to maintain approximately equivalent energy within each band

- Bands are overlapped at least 1/6th octave about their respective split frequencies

- Consistent margin maintained in each band

- Each band achieves original test specification amplitude and duration requirements

A limitation of band-splitting is the implicit assumption that the total response in each band is due to the excitation in that frequency band only. In general, total response is due to the excitation and coupled response across the full test spectrum. As a result, there may be coupling effects and other contributions that may not be adequately exercised by the band-split approach. This should be investigated and assessed for cases where band-splitting is employed.

As an alternative to band-splitting, consider the discussion in section B.1.8.1 of this document on modification of the specification frequency range based on hardware sensitivity and flight environment.

B.1.5 Damage-Based Analysis of Flight Vibroacoustic Data

DELETE

Note: This topic is covered via updated discussion in section B.1.8.1 of this document. References to this section in SMC-S-016 (2014) should redirect there.

ADD THE FOLLOWING TO APPENDIX B.1

B.1.7 Shock Qualification for Reusable Hardware

For a given shock environment, reusable hardware could be affected in a cumulative damage sense, in addition to the typical consideration of peak stress. This is due to its repeated nature since multiple service uses are to be accounted for.

If no amplitude-cycle relationship is established for a given shock test specification, reusable hardware shall undergo the following for qualification:

- Three applications at qualification level

- $N_f - 1$ applications at MPE level, where N_f is the number of exposures through all planned service uses

The number and amplitude of shock exposures in addition to the three at qualification level may be tailored with analysis or development test to establish a relationship between shock exposure and hardware damage accumulation. A more efficient means to test for shock reuse may be realized if a reduced number of qualification level applications (relative to $N_f - 1$ at MPE) can be justified, since only one round of equalization would be needed for test setup. As a starting point, a tailoring of Equation B3.2 or Equations B4 and B5 could be considered, with any variables describing duration replaced by number of shock exposures. For any such approach, the three required applications at qualification level may be counted towards the equivalencing strategy. If the shock MPE is above 100 in/s, the assumptions made in section B.1.2 of this document for life test factor L_{TF} and fatigue exponent b may require reevaluation.

Requirements in section 6.3.4 of SMC-S-016 (2014) and corresponding additions in this document apply. All significant shock events should be considered, and it is advisable to address separate events individually if they differ greatly in nature (source type, impulse time, waveform). Because of the potentially cumulative effect of a given shock event through multiple service uses, added importance is placed on replicating the characteristic of the service shock event to the extent possible in test.

B.1.8 Analysis of Dynamic Environments Data for Design and Test Specifications

The following details basic practice for signal processing of vibration, shock, and acoustic data to support the generation and/or validation of design specifications for test and analysis. Requirements on frequency ranges for design and test specifications are also given. Specifications should be developed in a manner that replicates the underlying service environment to the extent practical.

B.1.8.1 Random Vibration

Random vibration is borne from structural receptance to various phenomena in launch and space vehicle operations. Of note are vibroacoustic responses due to impingement of fluctuating pressures, rough combustion due to rocket engine operation, and turbulent or cavitating flow in fluid lines. It is nondeterministic in nature and is therefore analyzed in a statistical sense. Random vibration requirements presented in this document are specified in terms of auto spectral density with units of g_{rms}^2/Hz, typically abbreviated to g^2/Hz. The auto spectral density, sometimes referred to as power spectral density, can be computed via Fourier transform based methods or Damage Potential Analysis (DPA), sometimes referred to as damage-based analysis. Regarding the former, standard practice is to calculate spectral densities for a series of 1 sec tapered windows incremented by 0.5 sec following Welch's method. Spectra generated by this means should be integrated to frequency bandwidths no wider than 1/6th octave, although it is strongly recommended that a finer resolution be used if narrowband tones are detected or anticipated. The maximum value of spectral density over these windows is then taken at each frequency, resulting in a "maxi-max" spectrum.

DPA is a time domain single-degree-of-freedom (SDOF) response-based analysis that equivalences a stationary white noise spectral density input level to the response characteristics of an SDOF oscillator at each analysis frequency. This is done in consideration of peak amplitude and fatigue, by means of signal cycle-counting for the latter. See Reference B10 for additional details. Spectral densities processed by this means should be no wider than 1/48th octave bandwidth resolution for a resonant amplification factor (Q) of 50. The spectra can be subsequently band-averaged to a maximum width of 1/6th octave, if no significant narrowband content is present and/or if equivalent sine levels are to be used to address narrowband tones that are sinusoidal.

Random vibration spectra are defined between 20-2000 Hz as baseline. This is primarily based on a combination of historical practice and typical electrodynamic shaker table capability. Ideally, the affected hardware should dictate the frequency range of the design specification level. It is therefore allowable to modify (truncate, widen, extend) this frequency range with rationale based on known hardware sensitivity or significant forcing inputs.

In the case of isolated hardware, the specification frequency range shall be modified as necessary to start below the fundamental frequency of the isolation system (response of hardware on isolators.)

B.1.8.2 Acoustic and Pressure

Notable sources of acoustics, or more generally fluctuating pressures, include turbulent mixing of rocket exhaust with ambient atmosphere and turbulent external flow during atmospheric ascent and descent, in addition to the sources mentioned prior for random vibration. Pressure (acoustic) spectra as presented in this document are generated similarly to random vibration. Auto spectral density is calculated and is then converted to a decibel (dB) scale with a reference level of 2.9e-9 psi (20 μPa) root mean square in each frequency band. The result is referred to as a sound or fluctuating pressure level, denoted SPL and FPL respectively. Analysis frequency bandwidth should be no wider than 1/3rd octave, due to the generally broadband nature of such excitations. However, data should be inspected for any narrowband tones and analysis resolution increased if necessary. If using DPA, the same implications discussed for random vibration apply regarding the necessary analysis frequency resolution.

Acoustic spectra are defined between 31.5-10,000 Hz as baseline, subject to the discussion and requirement in section B.1.8.1 of this document.

B.1.8.3 Sine Vibration

Sinusoidal vibration may be due to periodic excitations stemming from an instability (such as pogo, aeroelastic flutter, unstable combustion) or to those due to rotating machinery. Because sinusoidal data are more deterministic in nature, it follows that such signals are analyzed differently than random data, and the use of an auto spectral density specification is not as appropriate. Sine environment amplitude is in the same units as the data (typically g's acceleration for vibration) and may be determined from several methods. These range from inspection of bandpass filtered data to the calculation of an equivalent sine level from existing auto spectra using a relation between peak and root mean square sine amplitude. Regardless of the calculation method used, it is advisable to verify that a given sine specification covers both peak amplitude and fatigue damage potential in the band of interest. This can be done through SDOF response-based analysis comparing a time synthesis of the sine specification against the underlying data.

Sine specifications are typically assigned to a relatively narrow frequency band dictated by the forcing function or response driving the environment analyzed. Care should be taken to ensure that any anticipated frequency variability and shifting for the phenomenon of interest is covered by the specification.

B.1.8.4 Shock

Shock transients result from the sudden application of load and/or release of strain energy associated with deployment, separation, impact, and release events. Shock requirements as discussed in this document are generated using the Shock Response Spectrum (SRS), which is a time domain SDOF response-based analysis. At each frequency, the shock response spectrum value is the absolute maximum response induced by the transient signal exciting an SDOF system with a specified natural frequency and amplification factor, typically set to $Q = 10$. Other methods of characterizing the shock environment, in addition to the SRS, may be used to better determine underlying spectral content and frequency bands in which there is a higher potential for the shock to be damaging. Of note are the Pseudo-Velocity Shock Response Spectrum (PVSRS) and energy spectra, described in References B7 and B11 respectively. Whichever method or combination of methods is used, the duration and waveform of the input data should be replicated to the extent practical during application of the shock design specification through test and/or analysis. Frequency resolution for shock response spectra should be no wider than 1/12th octave for $Q=10$. Because shock data are typically broadband in nature, the analysis results may be subsequently averaged to a maximum width of 1/6th octave if no distinct narrowband content is observed.

Shock response spectra are specified between 100-10,000 Hz as baseline, subject to the discussion and requirement in section B.1.8.1 of this document. Use of a PVSRS, energy spectra, or a reasonably equivalent analysis method can be considered as rationale to justify a test with modified frequency range to more precisely apply shock to frequency bands with higher potential to induce shock damage.

B.1.8.5 Methods to Calculate Fatigue Equivalent Duration (FED)

FED shall be calculated for an environment when measured data are available. This may be accomplished in the time or frequency domain. See References B12, B13, and B14 for discussions on the generation of fatigue spectra through analysis of time series and/or spectral data.

B.1.8.6 Exceedances to Specifications

Any exceedances to an MPE are evaluated to ensure that established environment limits and hardware design margin are sufficiently maintained. Exceedances of 1 dB or less in singular frequency bands are typically not of consequence to hardware that has gone through a baseline qualification program. Driving physics should be investigated to determine whether the MPE carried insufficient margin relative to the assumed mean level and variance of the environment, or whether the exceedance was caused by flight conditions, hardware dynamic characteristics, or engine operation pushing beyond an intended design envelope. This will inform any necessary readjustment of MPE and subsequent implications to the state of hardware design demonstration in analysis or test. Exceedances to MPE of 3 dB or more shall require a recalculation of MPE and requalification of affected hardware for the relevant environment, unless it can be demonstrated that hardware structural and performance capability are not adversely affected.

B.2 Response Limiting Criteria for Units Weighing More Than 50 lb (23 kg)

REVISE AS FOLLOWS

B.2 Force and Response Limiting

A known limitation of shaker table vibration testing of a hardmounted unit is the inability to replicate dynamic flight boundary conditions. A shaker table will by default input the required power to match an enveloped test specification regardless of the dynamic behavior of the test article, and therefore effectively provide an infinite impedance as a base structure. This will often drive much higher forces into the test unit for a given amount of interface motion. See References B15 and B16 for examples of the observable effects to unit response. It may be desirable to address this discrepancy since it could cause unrealistic failure modes in test. To help generate an input more aligned with flight excitation physics, force or response limiting may be implemented. A justifiable basis for such limiting is necessary to avoid excessive reduction of inputs that will result in inadequate acceptance or qualification. Reference B17 is recommended for guidance and direction on force limiting practices. Some general guidelines to follow when running such tests are as follows:

- Analytical methods used to derive limits should be anchored directly or by similarity to ground test and/or flight data

- Monitoring and enforcing of response limits should be applied to a location on the test unit (or subcomponent) that is consistent with a flight or system level test measurement and/or is representative of net motion about its center of gravity

- Force and response limits are not to be set solely to meet an expected design capability, but rather are intended to provide more flight-like test inputs

The general use of force limiting, response limiting, or test input notching shall be based on technical rationale and validated using analysis anchored to an applicable case and/or data obtained from flight or test at higher levels of assembly. A consistent amount of test margin shall be maintained across all limit bands and the remainder of the test spectrum. For example, limits imposed on an acceptance test must be set to their MPEs, and limits imposed on qualification test must carry the same margin as the rest of the spectrum. Consistent limiting practice shall be enforced between qualification or protoqualification and acceptance testing for a given hardware test program.

Notching of individual input bands below any applicable minimum workmanship spectra is acceptable. However, to maintain a level of workmanship screening, overall input levels shall be maintained for units as follows:

50 lb	6.9 Grms minimum
100 lb	4.9 Grms minimum
200-400 lb	3.5 Grms minimum

Following the relation:

$$\text{Grms minimum} = 6.9\left(\frac{50}{W}\right)^{1/2} \tag{B9}$$

where W is the unit weight in lb, and the weight reduction cannot be more than 6 dB. This criteria was set in accordance with overall levels for minimum workmanship spectra presented in section 6.3.5.3.1 of this document. Any justification for omission of this criteria is subject to the discussion presented there. For vehicles and for hardware weighing more than 400 lb, discussion in sections 8.3.6.3 and 8.3.6.3.1 of this document applies.

B.2.1 Broadband Reduction

DELETE

Note: This content has been moved to section 6.3.5.3.1 of this document.

B.2.2 Narrowband Notching

DELETE

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REVISE AS FOLLOWS:

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Approved Electronically by:

Thomas R. Cole, DIRECTOR - DEPARTMENT STRUCTURAL MECHANICS SUBDIV VEHICLE SYSTEMS DIVISION ENGINEERING & TECHNOLOGY GROUP	Alvar M. Kabe, PRINCIPAL DIRECTOR VEHICLE SYSTEMS DIVISION ENGINEERING & TECHNOLOGY GROUP

Cognizant Program Manager Approval:

John S. Fujita, PRINCIPAL DIRECTOR
SPACE SYSTEMS ARCHITECT DIVISION
SPACE SYSTEMS GROUP

Aerospace Corporate Officer Approval:

Malina M. Hills, SENIOR VP SPACE SYSTEMS GROUP
OFFICE OF EVP

Content Concurrence Provided Electronically by:

Arash Mehrparvar, MANAGER - ENGINEERING
ENVIRONMENTS TEST & ASSESSMENT DEPT
STRUCTURAL MECHANICS SUBDIV
ENGINEERING & TECHNOLOGY GROUP

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Technical Peer Review Performed by:

Brian E. Shaw, SENIOR PROJECT LEADER
SPACE PORTFOLIO ARCHITECTURES
SPACE SYSTEMS ARCHITECT DIVISION
SPACE SYSTEMS GROUP

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