JSC 65829
Rev B

Loads and Structural Dynamics Requirements for Spaceflight Hardware

Loads and Structural Dynamics Branch,
Structural Engineering Division,
Engineering Directorate

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National Aeronautics and
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Lyndon B. Johnson Space Center
Houston, Texas

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REVISION HISTORY AND CHANGE LOG

Revision	CHANGE NO.	DESCRIPTION	DATE	PAGES AFFECTED
--	--	RFI Release 1 (Initial version of document to support RFI release of Commercial Crew Transportation Request for Information)	04/28/2010	All
Baseline	1	Baseline release of document to support January 2011 RFI. Changes include: - Modification of front matter, including Purpose and Roles and Responsibilities sections - Identification of three additional reference documents - Addition of separate definition of and requirements for sine vibration maximum predicted environment - Addition of requirement for crash safety load factors for winged or lifting-body vehicles - Significant reduction in the number and specificity of requirements via deletion, consolidation, and relocation of detail to the Guidelines in Appendix B. Remaining set of requirements were completely renumbered - General correction of typographical and/or grammatical errors - Deletion of contents of Appendix C, since adherence to SSP-50808 was added as a program requirement	01/17/2011	All
Rev A	2	- Add note for alternative MPE for sine vibe testing and associated rationale for sine vibe testing. - Change author	06/11/2014	12
Rev B	3	- Modification of front matter - Major rework of the requirement set to align with JSC 65829 tailorings for the Gateway, Human Landing System, EVA and Human Surface Mobility, and Commercial Low Earth Orbit Destinations Programs - Added material in Appendix B to address mission phases not applicable to the Commercial Crew Program, for which the document was originally developed - Added Appendices with guidelines for Loads Control Plan content and requirement traceability matrices to JSC 65829 Rev A and NASA-STD-5002A	03/20/2024	All

Note: Dates reflect latest signature date of Revision.

FOREWORD

This document represents the collaborative effort of numerous individuals across many NASA centers. In particular, the experience and expertise of the teams that developed NASA-STD-5002 Revision A and the requirements and criteria documents for the Space Shuttle, International Space Station, Constellation, Commercial Crew, Gateway, Human Landing System, and Extravehicular Activity and Human Surface Mobility Programs was relied on very heavily. Most, if not all, of the technical content in the current document was either adapted from or directly incorporated from those documents. The significant efforts expended in developing the Constellation Program Loads Control Plan, CxP-70137, were instrumental to the creation of this document.

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APPENDICES

1.0 INTRODUCTION

The NASA Exploration Systems Development Mission Directorate requires Crewed Space Systems (CSS) to meet the intent of a set of Engineering Technical Authority (TA) documents called out in HEOMD-003, *Crewed Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions*. For the Loads and Dynamics technical discipline, the document invoked by the HEOMD-003 is JSC 65829, *Loads and Structural Dynamics Requirements for Spaceflight Hardware*. JSC 65829 was originally developed for the NASA Commercial Crew Program as an implementation of NASA STD-5002, *Load Analyses of Spacecraft and Payloads*, for that Program.

Since that time, tailored alternatives to JSC 65829 have been produced for the Gateway, Human Landing System, and Extravehicular Activity and Human Surface Mobility Programs. Experience with those Programs has shown that the reduced set of less-prescriptive requirements in those tailored documents offers an advantage over the set of requirements in JSC 65829 Rev A and is a better fit for the paradigm of NASA procurement of commercially-developed systems for crewed spaceflight. Revision B of JSC 65829 has been constructed to align with those tailored documents.

The reduction in the number and specificity of requirements is balanced by a new requirement for hardware developers to create and provide a Loads Control Plan which describes how the approaches used to generate design-to loads and dynamic environments and substantiate dynamic model validity satisfy the requirements herein. The Plan will establish an agreement between the hardware developer and the TA for the loads and dynamics discipline and offer an opportunity for reengagement if the Plan changes during development.

1.1 PURPOSE

The purpose of this document is to establish requirements relating to the loads and structural dynamics technical discipline for NASA and commercial spaceflight launch vehicle, spacecraft, in-space transportation and habitats, and lunar and planetary surface hardware to be used for crewed spaceflight missions. Requirements are defined for the development of structural design loads and recommendations regarding methodologies and practices for the conduct of load analyses are provided. As such, this document represents a tailoring of NASA STD-5002, Rev A. Requirements are also defined for structural mathematical model development and verification to ensure sufficient accuracy of predicted responses. Finally, requirements for model/data delivery and exchange are specified to facilitate interactions between Commercial Partner hardware developers and the NASA Technical Authority providing insight/oversight and serving in an Independent Verification and Validation role.

In addition to the analysis-related requirements described above, a set of requirements are established concerning coupling phenomena or other interaction between structural dynamics and aerodynamic environments or control or propulsion system elements. Such requirements may reasonably be considered structure or control system design criteria, since good engineering practice dictates consideration of and/or elimination of the identified conditions in the development of those subsystems. The requirements are included here, however, to ensure that such multi-disciplinary interactions are captured in the design space for launch vehicles (LV), spacecraft (SC), launch abort vehicles (LAV), or other crewed systems which may experience atmospheric flight.

The requirements in this document are focused on analyses to be performed to develop data needed to support structural verification. As described in JSC 65828, Structural Design Requirements and Factors of Safety for Spaceflight Hardware, implementation of the structural verification requirements is expected to be described in a Structural Verification Plan (SVP), which should describe the verification of each structural item for the applicable requirements. The requirement for and expected contents of the SVP are defined in JSC 65828. The SVP may also document unique verifications that meet or exceed these requirements with Technical Authority approval.

1.2 SCOPE

This document includes requirements governing

a. the analytical approaches and criteria for the development of structural design loads and dynamic environments,

b. the verification approach applicable to the mathematical models used for loads development,

c. the transfer/delivery of models and forcing functions, environments, results data, and test documentation,

d. the considerations of phenomena associated with the interaction of system structural dynamics and environments and vehicle subsystems.

This document is intended to cover analyses representing all phases of spaceflight hardware life cycles, including pre-flight, post-flight, and abort activities. The requirements herein represent the minimum set of conditions necessary to ensure proper identification of bounding loads and loading conditions and, in turn, contribute to a structural design solution which is adequate to maintain structural integrity and the required degree of functionality during all phases of the expected hardware life cycle. However, this document cannot cover all possible designs and situations, so it is not a substitute for sound engineering judgment in design, analysis, and test.

The definition of natural environments to be used for design loads derivation is out of scope of this document.

1.3 APPLICABILITY

This document establishes requirements for the loads and dynamics technical discipline and provides guidelines and good design practices identified by the NASA loads and dynamics technical community. It is applicable to both NASA and commercial launch vehicles, spacecraft, modules, in-space habitats, lunar/planetary surface assets, and other flight hardware. This document contains requirements that hardware developers can choose to either adopt as written or propose an alternate. Hardware developers are allowed to propose alternate requirements and standards that they consider to meet or exceed the requirements listed herein.

The NASA Program for which hardware is developed will charter a Loads and Structures Panel (LSP) or equivalent body for reviewing and approving the implementation of the requirements of this document. The LSP will serve as the responsible Technical Authority for structural design limit loads and environments. The Technical Authority will evaluate the equivalency of any alternate requirements proposed by the hardware developers. It will be the responsibility of the hardware developers to demonstrate to the NASA TA that a proposed alternate requirement fully meets the intent of the requirements of this document and to obtain formal NASA approval of the alternate requirement(s). When consensus cannot be reached on the resolution of an issue, the TA will bring forward the issue with a recommendation to the appropriate Program Board, along with the organizational team members presenting their conflicting positions.

These requirements are applicable to all flight hardware for crewed spaceflight missions, including Government Furnished Equipment, as well as all related contractor, subcontractor and commercial efforts. These requirements are not imposed on systems other than flight hardware. These requirements do not apply to non-flight systems such as ground test articles, but they may be tailored for use in specific cases where it is prudent to do so, such as for personnel safety or when assets are at risk.

1.4 ROLES AND RESPONSIBILITIES

The extent to which hardware developers may take an active role in development of loads/environments will vary, depending on structure and scope of the Program/Project for which the hardware will be procured and the type of hardware (launch vehicle, crewed vehicle, module/element, in-space habitat or transportation system, lunar/planetary surface asset, etc.).

For some or all mission phases, hardware developers may receive loads, environments, and forcing functions from external organizations, which may include other commercial entities or NASA. In such cases, hardware developers will be required to provide structural models, supporting documentation, and other data or information to the organization responsible for performing the relevant analyses to generate loads and dynamic environments. The hardware developer will then be responsible for performing detailed assessments to propagate the effects of those loads and environments through their system to develop design loads and local environments during those mission phases for the complete set of hardware primary structure, subsystems, and components. Timely transfer of models, forcing functions, environment data, and results is crucial to continued progress of design and development efforts.

As an example, if a hardware developer will obtain launch/delivery services from an external commercial entity, the launch vehicle provider will be responsible for analysis of mission phases and events (handling and integration with the launch vehicle, rollout, erection, pad stay, launch, ascent, and, possibly, on-orbit delivery) and development of loads and induced environments (ignition overpressure, liftoff acoustics, thrust build-up, steady burn, and tail-off, buffet, ascent acoustics, random vibration, sine vibration, shock, thermal, pressure, blast overpressure, blast debris, etc.) up to the point of spacecraft/payload separation. The resulting loads, environments, and forcing functions will be provided to the hardware developer. Note that this division of responsibility will also necessitate launch vehicle provider generation of both nominal and applicable abort/escape quasi-static and dynamic initial conditions and induced environments for spacecraft/payload separation analyses and delivery of these data to the hardware developer.

The hardware developer will then bear responsibility for analyses and definition of loads and induced environments (nominal separation motor or abort/escape motor ignition overpressure, thrust build-up, steady burn, and tail-off, nominal separation motor, abort/escape motor, and on-orbit maneuvering thruster plume flowfield pressure, heating and contamination, crew activity, acoustics, random vibration, sine vibration, shock, thermal effects, pressure effects, etc.) for the hardware during and after spacecraft/payload separation from the launch or transport vehicle and during in-space operations, such as rendezvous proximity operations, and docking, departure from Low Earth Orbit (LEO) destinations, lunar or planetary landing, surface operations, and ascent, terrestrial entry, descent, landing, and recovery, and applicable mission aborts/escapes.

If the hardware developer in this example will provide launch/delivery services, the hardware developer will be responsible for development of loads and induced environments during all mission phases over the hardware life cycle.

A similar situation exists for the case of a crewed spacecraft performing rendezvous, proximity operations, docking, and joined operations with a spacecraft or space habitat developed under a different Program or by a different commercial entity.

In all instances, however, it is expected that the NASA TA will maintain a significant technical insight/oversight responsibility and IV&V role, analogous to the procedures established for launch vehicles by NPD 8610.23, sufficient to substantiate the accuracy and adequacy of the results of any loads analysis performed under the Program/Project governing development and operation of the spaceflight hardware for which this document is applicable.

1.5 DOCUMENT STRUCTURE

The convention used in this document to distinguish between requirements and goals is as follows:

a. “shall” - Used to indicate requirements that must be implemented and verified

b. “should” - Used to indicate goals that must be addressed but do not need to be verified.

c. “will” - Used to indicate a statement of fact or declaration of purpose on the part of the government that is reflective of decisions or realities that exist and are to be taken as a given and not open to debate or discussion.

“Shall” requirements in this document are denoted by [**LDR-xxx**], where xxx is a unique numerical identifier. Requirements are accompanied by rationale and other explanatory text and implementation guidance in italics.

Rationale statements are intended to indicate why each requirement is needed, to describe the basis for its inclusion in this requirements document, and to provide context and examples to stakeholders. It is important to note that the rationale statements, explanatory text, and guidance are not binding and only provide supporting information. In the event that there is an inconsistency between a requirement and its rationale, the requirement always takes precedence.

Appendix B consists primarily of material from the Loads Control Plan developed for the Constellation Program and provides an example of a framework for expected loading events to be addressed in hardware developer’s Loads Control Plans.

Appendix C provides top-level guidelines for the expected contents of a hardware developer’s Loads Control Plan

Appendix D provides traceability between the requirements in JSC 65829 Revision A and the tailored requirements in this document.

Appendix E provides traceability between NASA-STD-5002A and the tailored requirements in this document. While NASA-STD-5002A is not called out in HEOMD-003, this matrix is provided for reference and to demonstrate that the current document offers coverage for all requirements in NASA-STD-5002A, as well as the previous version of JSC 65829.

1.5.1 A Note on Requirement Numbering

The requirements in this document are not numbered sequentially. This is to ensure commonality and backwards-traceability to the requirement numberings in tailorings of earlier versions of JSC 65829 for the Gateway, Human Landing System, and Extravehicular Activity and Human Surface Mobility Programs.

One of the motivations for creating this revision of JSC 65829 was to ensure a uniform requirement set for the loads and dynamics discipline across current and future NASA crewed spaceflight Programs and Projects. A common requirement numbering scheme will facilitate that goal.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

No other documents are cited as applicable in this requirement set.

2.2 REFERENCE DOCUMENTS

The following documents contain supplemental information to aid the user in the understanding and application of this document. Where a specific revision is not identified, use of the current version is assumed.

TABLE 1.5.1-1 REFERENCE DOCUMENTS

Document Number	Document Revision	Document Title
EHP-10028		Exploration EVA System Compatibility Standards
ELVL-2001-0002834	A	Guidance on the Number of Coupled Loads Analysis Cycles Required for a NASA ELV Mission
GSFC-STD-7000		General Environmental Verification Standard (GEVS)
HEOMD-003		Crewed Deep Space Systems Human Rating Certification Requirements and Standards for NASA Missions
JPL-D-5882		Mass Acceleration Curve for Spacecraft Structural Design
JSC 65828	B	Structural Design Requirements and Factors of Safety for Spaceflight Hardware

Document Number	Document Revision	Document Title
MIL-STD-810	H Change 1 (change incorporated) 18 May 2022	Environmental Engineering Considerations and Laboratory Tests
MSFC-RQMT-3019		Launch Vehicle Qualification Requirements
NACA TN-3030		A Method for Calculating the Subsonic Steady-state Loading on an Airplane with a Wing of Arbitrary Plan Form and Stiffness
NASA-HDBK-7004		Force Limited Vibration Testing
NASA-HDBK-7005		Dynamic Environmental Criteria
NASA-HDBK-7008		Spacecraft Dynamic Environments Testing
NASA-HDBK-7009		NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009
NASA-HDBK-7010		Direct Field Acoustic Testing (DFAT)
NPD 8610.23		Launch Vehicle Technical Oversight Policy
NASA SP-8003		Flutter, Buzz and Divergence
NASA SP-8004	Revised, June 1972	Panel Flutter
NASA SP-8031		Slosh Suppression
NASA SP-8055		Prevention of Coupled Structure-Propulsion Instability (Pogo)
NASA SP-8072		Acoustic Loads Generated by the Propulsion System
NASA SP-8077		Transportation and Handling Loads
NASA-SP-8099		Combining Ascent Loads
NASA-STD-3001 Volume 2	C	NASA Space Flight Human System Standard Volume 2: Human Factors, Habitability, and Environmental Health
NASA-STD-5002	A	Load Analyses of Spacecraft and Payloads
NASA-STD-5020		Requirements for Threaded Fastening Systems in Spaceflight Hardware
NASA-STD-7001		Payload Vibroacoustic Test Criteria
NASA-STD-7002		Payload Test Requirements
NASA-STD-7003		Pyroshock Test Criteria
NASA-TM-X-73305		Astronautic Structures Manual, volume 1
SMC-S-016	5 September 2014	Test Requirements for Launch, Upper-Stage and Space Vehicles

2.3 ORDER OF PRECEDENCE

In the case of conflict, where this document is adopted or imposed by contract on a Program or Project, the technical guidelines of this document take precedence over the technical guidelines related to loads and dynamics cited in other referenced documents.

3.0 DEFINITIONS

For the purposes of this document, the following definitions shall apply:

Abort: A launch phase process to protect and extract the crew from a failing launch vehicle and get them safely to the surface of the earth or to orbit.

Blast Overpressure: The airborne shock wave or acoustic transient generated by an explosion.

Blast Debris: The debris field generated by an explosion, where debris is defined as any external broken and/or scattered remains emanating from the element(s) of any flight or ground systems.

Buzz: A control-surface phenomenon; a type of flutter including only one degree of freedom. Buzz is usually a pure rotational oscillation of a control surface, but may appear as a torsional "windup" oscillation if the surface is restrained near one end. It generally occurs in regions of transonic flow.

Component: An equipment item that is part of a spacecraft and is treated as an entity for purposes of load analysis (examples are electronic boxes, batteries, electromechanical devices, and scientific instruments or experiments).

Crewed Space Systems: A crewed space system (CSS) consists of all the system elements that are occupied by the crew/passengers during a space mission and provide life support functions for the crew/passengers (i.e., the crewed elements). The CSS also includes all elements physically attached to the crewed element during the mission. The CSS is part of the larger space system used to conduct the mission.

Divergence: A non-oscillatory instability which occurs when the external aerodynamic upsetting moments exceed the internal structural restoring moments within a system.

Factor of Safety (FOS): A multiplying factor to be applied to limit loads or stresses for purposes of analytical assessment (design factors) or test verification (test factors) of design adequacy in strength or stability. Factors of safety are empirically based and are necessary to assure no failures due to uncertainties that result from the design process, manufacturing process, and the loading environment.

Fatigue Equivalent Duration: The length of time at the maximum environment achieved during the service life that produces the same fatigue damage potential as application of all time-varying acoustic or vibration environments that make up the full service life.

Flight Vehicle: The combination of elements of a launch system that is flown to orbit (e.g., the launch vehicle, spacecraft, and payloads) and/or reenters and lands or other hardware which experiences atmospheric flight. Also a spacecraft or assembly of elements/spacecraft with a control system and liquid or solid propulsion systems.

Flutter: A self-excited oscillatory instability caused and maintained by the aerodynamic, inertia, and elastic forces in the structural system of a vehicle that could lead to catastrophic structural failure.

Launch Abort Vehicle (LAV): The specific vehicle configuration that is used to fly the crew to safety in the event of an abort.

Launch Vehicle (LV): One or more of the stages of a flight vehicle capable of launching a spacecraft into a suborbital or orbital trajectory. Upper-stages used to inject a spacecraft into orbit from a suborbital trajectory and fairings used to protect the spacecraft during ascent, unless provided by the spacecraft, are considered part of the launch vehicle for the purposes of this requirements document.

Limit Load: The maximum load or combination of loads which a vehicle or its structural elements may be expected to encounter during its design service life. May also be referred to as "design-to load". Uncertainty factors associated with model uncertainty or forcing function uncertainty may be incorporated into the limit load as reported. Factors of safety are not included in the limit load.

Load Indicator: An approximate definition of the state of load or stress within a critical vehicle element structural substructure or part that can be evaluated directly at the external loads level of analysis. Although some indicators can exactly replicate the state of stress in a part if the loading and structural capability is simple, most load indicators are approximations. To be "evaluated directly at the external loads level" means that all inputs to the indicator are available in external loads databases, which are normally coarser approximations of loads than are used during the element stress evaluation. It should be noted that different load regimes (e.g., liftoff and maximum dynamic pressure) have different critical load paths and structures and, therefore, require different load indicators. Load indicators are valid only for the conditions used in developing the equations which define the load indicator.

Maximum Predicted Environment (MPE): The environment for random vibration, acoustics, and shock defined using a P95/50 normal tolerance limit, which is the level greater than 95% of the peak events with 50% statistical confidence or the environment for sine vibration defined using a P97.72 normal tolerance limit, which is the level greater than 97.72% of the peak events with 50% statistical confidence.

Pogo: A self-excited longitudinal vibration resulting from the coupling between liquid propellant rocket engines and the vehicle structural dynamics. This coupling will cause the continuous increase in the magnitude of the engine thrust oscillations and propellant flow rate oscillation, which manifests itself as an instability that could lead to catastrophic structural failure.

Primary Structure: That part of flight hardware which sustains the significant applied loads and provides main load paths for distributing reactions to applied loads. Because these structures redistribute loads from one part to another, they experience loads in excess of the loading created by its own mass. Also the main structure which is required to sustain the significant applied loads, including pressure and thermal loads, and which if it fails creates a catastrophic hazard. If a component is small enough and in an environment where no serious threat is imposed if it breaks, then it is not primary structure.

Random Vibration: The non-deterministic oscillatory response of a structure caused by acoustical and/or mechanical forcing functions. The magnitude and spectral content of random vibration is known only in terms of statistical average properties.

Redlines: Limits provided for load indicators or other vehicle element responses, primarily based on certification experience, used to determine the adequacy of the structure under the action of a particular load condition. Redlines represent the maximum allowable design load, whether or not there is additional margin in the structure that the load indicator or element response represents.

Secondary Structure: Ancillary or auxiliary internal or external structure which is used to attach small components, provide storage, and to make either an internal volume or external surface usable. Secondary structure attaches to and is supported by primary structure. Because secondary structures do not transfer or distribute loads between parts, their failure does not result in a catastrophic failure.

Spacecraft (SC): A self-contained/habitable vehicle or system, including, but not limited to, satellites, orbiters, capsules, modules, landers, transfer vehicles, rovers, extravehicular activity suits, and habitats, designed for travel or operation outside earth's atmosphere. A spacecraft can consist of a support structure onto which are attached scientific instruments and related systems for life support, communication, power, propulsion, and control. A spacecraft is a payload during the launch through payload separation phase.

Structure: All components or assemblies designed to sustain loads or pressures, provide stiffness and stability, or provide support or containment.

Twang: The loads induced on an LAV at separation from the LV while in unusual flight attitudes, with off-nominal bending, and under the influence of separation mechanism loads. The sudden release of stored elastic strain energy due to bending under these conditions results in a near-instantaneous step change in shear and bending loads at the LV to LAV interface. A similar twang effect occurs during liftoff.

Uncertainty Factor (UF): A value used to compensate for a deficiency in knowledge concerning the accuracy of analytical or test results. Such factors are used as a management tool, in a manner similar to weight growth margins, to manage the loads growth uncertainty and to ensure a robust design.

4.0 REQUIREMENTS

4.1 LOADS REQUIREMENTS

4.1.1 Loads Control Plan

[LDR-001] Loads Control Plan

At the Requirements Baseline Milestone (or equivalent program milestone review/project milestone review) and every project milestone thereafter, a Loads Control Plan shall be submitted for review and approval to NASA and/or other responsible Technical Authority that shows how the requirements herein are to be satisfied. Resubmission is not necessary if no updates to the Plan have been made since the prior milestone.

However, any time that planned activities covered by the Loads Control Plan are modified between project milestones, the modifications must be approved by the Technical Authority prior to implementation.

Rationale: A Loads Control Plan establishes a defined and approved agreement between the hardware developer and the responsible NASA Technical Authority. By agreeing to *the plan early in the design, there is reduced likelihood of disagreements over verification strategies.*

This requirement has no corresponding requirement in JSC 65829 Rev A *or* NASA-STD-5002A*. However, Appendix C is an example of the type of contents expected in a Loads Control Plan. In addition, Appendix B, consisting primarily of material based on the Loads Control Plan developed for the Constellation Program, provides an example of best practices and the scope of the analyses expected to be addressed. Further insight into the expectations regarding the content of the Loads Control Plan may also be obtained from the Notes column in the JSC 65829 Rev A Requirements Traceability Matrix in Appendix D of this document and the NASA-STD-5002A Requirements Traceability Matrix in Appendix E.*

The plan should explain the technical logic accounting for and assessing the operational environments and conditions to derive the design loads based on the loads requirements herein and the best practices detailed in Appendix B and NASA-STD-5002A*.*

The plan should also document organization-specific processes for definition of maximum predicted environments for dynamic environments such as random vibration, sinusoidal vibration, acoustics, and shock, descriptions of and sources for other forcing functions and environments (e.g. winds, engine ignition transients, external/internal acoustic environments, plume pressure fields, etc.) which will be used for loads calculations, and methodologies for combination of loads from various sources which might occur simultaneously.

As noted in Section 1.4 Roles and Responsibilities, depending on the type of hardware being developed, some or all of these design loads and environments and forcing functions for certain mission phases may be developed and provided by external organizations. In such cases, a description of the source, methods of data transfer, and configuration control of deliverables should be included in the hardware developer's Loads Control Plan.

In addition, the plan should describe plans, strategies, and goals for modal survey tests to be used in development of validated structural dynamics models to be used in loads analyses and plans for validation of forcing functions and environments, regardless of whether those data are developed internally to the Program or provided by external organizations, Programs, or Projects.

To facilitate Technical Authority evaluation, the hardware developer's Loads Control Plan should provide a mapping between its contents and the requirements herein.

4.1.2 Reuse

[LDR-029] Reuse

Where flight hardware reuse or life extension is planned or anticipated, flight instrumentation sufficient to measure and/or reconstruct flight loads and dynamic environments shall exist.

Rationale: The life remaining for reused and long-life hardware can only be evaluated with insight into the cumulative effects of loads and environments experienced on previous flights in comparison with certified structural life. Without valid measurements to anchor life usage estimates throughout the service life of the hardware, elevated risk exists in any decision regarding continued use as-is.

This requirement has no corresponding requirement in JSC 65829 Rev A *or* NASA-STD-5002A*. It has been added in response to reuse of currently-operating flight vehicles and plans to do so for other vehicles in development and to the tendency to remove instrumentation present in initial flights of new vehicles. This requirement addresses the fact that no analysis with presumed environments can assess real-life exposure.*

Because of the broad frequency range of loads-producing dynamic environments, any instrument suite chosen must include both low frequency sensors and high frequency sensors. Any suite of operational flight instrumentation which may be used to support extension of service life beyond that for which hardware was initially certified should be documented in the hardware developer's Loads Control Plan, along with rationale for why it is sufficient for that purpose.

Data obtained because of this requirement may at some point prove valuable for anomaly investigation and potentially offer evidence and rationale to support deferral of the requirement for modal testing of new hardware of similar design (see [LDR-014]*).*

4.1.3 Development of Limit Loads

[LDR-002] Hardware Life Cycle Phases

All anticipated static and dynamic loading events over all phases of flight hardware life cycles shall be assessed to establish limit loads, accelerations, deflections, and induced environments.

Rationale: Complete coverage of the hardware life cycle is necessary to ensure that bounding load cases are identified. Spaceflight hardware must be designed to ensure adequate structural strength under all static and dynamic load environments and combinations of loads that are expected to occur during all phases of fabrication, testing, transportation, handling, assembly, erection, checkout, launch, ascent, abort/escape, in-space operations, lunar or planetary landing and surface operations, terrestrial entry, descent, landing, and recovery (if applicable).

Limit loads represent the maximum loads or combination of loads which a vehicle or its structural elements may be expected to encounter during its design service life. Uncertainty factors associated with model uncertainty or forcing function and environment uncertainty may be incorporated into the limit loads as reported. Any uncertainty factors applied by the hardware developers should be documented in the hardware developer's Loads Control Plan. Factors of safety are not included in the limit load values.

Note that for certain failure modes (e.g. creep, stress rupture, thermo-mechanical fatigue) other factors such as the duration at load (e.g. hold time) or loading rate may be of significance. In such instances, it may be necessary to provide this type of information, in addition to the values of the limit loads.

All aspects of the hardware development should be considered for the potential to provide mechanical or thermal loads. This includes manufacturing or assembly-induced loads, loads due to transportation and handling of components or assemblies, loads induced during qualification or acceptance tests, operational conditions (for example, ascent, docking, mated on-orbit conditions, intravehicular or extravehicular crew activities, flow induced vibration in bellows systems, non-terrestrial landing and surface operations, terrestrial entry, descent, and landing, etc.) and applicable abort/escape conditions.

As noted in Section 1.4 Roles and Responsibilities, depending on the type of hardware being developed, some or all of these loads, environments, and forcing functions for certain mission phases may be developed and provided by external organizations. In such cases, a description of the source, methods of data transfer, and configuration control of deliverables should be included in the hardware developer's Loads Control Plan.

Section 2 of Appendix B and Appendix B of NASA-STD-5002A *provide guidelines for considerations in and recommended approaches to the assessment of key events over typical flight hardware life cycles.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0001] *and* NASA-STD-5002A *requirements* [LAR 2], [LAR 3], *and* [LAR 10].

[LDR-003] Sources of Loading

Each source of loading within each flight hardware mission phase shall be assessed and load sources which can occur simultaneously shall be combined in a rational manner.

Rationale: In cases where loads produced by different environments can occur simultaneously, these loads must be combined in a rational manner to define the limit load for that flight event.

Flight hardware is subjected to a broad array of loads and environments over the course of its mission profile. Some non-comprehensive examples include, but are not limited to:

- *Liftoff release and acoustics*
- *Ascent static, gust, buffet, and engine tones*
- *On-orbit docking/berthing, intravehicular activity, extravehicular activity, jet thruster firings, robotic operations, internal pressure, temperature, and vibrations from components (e.g., pumps, fans, flow-induced vibrations in bellows)*
- *Thruster plume impingement from other vehicles during joint in-space operations and docking-induced loads*
- *Pressurization, venting*

In circumstances where pressure loads have a relieving or stabilizing effect on structural load capability, the minimum value of such relieving loads should be used. There may be a range of pressure load magnitudes which are relieving or stabilizing to the structure. In order to ensure that lowest structural margin is calculated, the minimum value of the relieving pressure load should be used.

As noted in Section 1.4 Roles and Responsibilities, depending on the type of hardware being developed, for some mission phases external organizations may be responsible for developing combined loads due to effects of simultaneous or near-simultaneous load sources. In such cases, a description of the source, methods of data transfer, and configuration control of deliverables should be included in the hardware developer's Loads Control Plan.

Section 4.1 of Appendix B and Appendix B of NASA-STD-5002A *provide examples and guidelines for considerations in combination of loading sources for key events over typical flight hardware life cycles.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0002] *and* NASA-STD-5002A *requirements* [LAR 10], [LAR 12], [LAR 41], [LAR 42], [LAR 43] *and* [LAR 48].

[LDR-004] Configuration Changes

Load conditions shall be identified and assessed for each configuration of flight hardware structure that will have multiple configurations during a mission.

Rationale: Maximum loads for deployable items or hardware which is reconfigured in space may not be caused by flight events which occur when the hardware is in a stowed configuration. Evaluation of hardware in all of its deployed or operating configurations is vital to ensure proper identification of the bounding load cases.

Approaching vehicle thruster plume impingement on the deployed solar arrays of a target vehicle is one example of a potential design load condition not captured by loads analysis of the target vehicle in a configuration with the arrays stowed. Fairing jettison on ascent, sequential deployment of drogue and main parachutes and forward and/or base heat shield jettison during reentry are also configuration changes which result in load path changes and may cause variations in dynamic response.

Another example of a structure with multiple configurations is a habitable module with hatches which can be opened and closed, either to the external environment or to adjacent structure.

Other examples of a structure with multiple configurations include structure or components which can be deployed, extended, assembled, or otherwise un-stowed to a configuration, or sealed or vented components that are depressurized or pressurized, either nominally or inadvertently due to failure (structural, mechanical, or other credible failure). In such cases, redistributed loads should be defined after one credible system failure.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0003] *and* NASA-STD-5002A *requirement* [LAR 11].

[LDR-005] Load Dispersions

Analyses performed to develop flight hardware design limit loads shall include system dispersions.

Rationale: Possible dispersions in environments, vehicle performance, forcing functions, etc. must be accounted for to ensure that bounding load cases are captured. Confidence in limit load predictions can only be achieved by identifying and considering variability in all input conditions which can affect vehicle responses.

Appendix B and NASA-STD-5002A *provide guidelines for dispersions which should be included in the assessment of key events over typical flight hardware life cycles.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0004] *and* NASA-STD-5002A *requirements* [LAR 33] *and* [LAR 34].

[LDR-026] Non-deterministic Loads

For random vibration and vibroacoustic loads analysis, peak responses shall be used for the limit loads.

Rationale: In analyses of environments or excitations that are considered to be random in nature, where the analysis predicts average response (e.g. Statistical Energy Analysis (SEA)) rather than peak response, the results need to be converted to a peak response, (e.g., 3 - 4 decibels (dB) average-to-peak ratio) to ensure adequate statistical enclosure.

This requirement encompasses NASA-STD-5002A *requirement* [LAR 9]*. There is no corresponding requirement in* JSC 65829 Rev A.

[LDR-024] Standard for Damping

Damping used for flight hardware dynamic response analysis shall be less than or equal to 1% of critical unless data or experience demonstrates a more appropriate value.

Rationale: Ideally, damping should be based on test measurements of the actual structure, at amplitude levels that are representative of actual flight environments, or on experience with similar types of structures whenever possible. Truly reliable estimates of damping may only be obtained based on measurements of response for the actual structure. In practice, 1% is a value typically used for loads and dynamics analysis of aerospace structures because it has been shown to be a slightly conservative estimate.

The value(s) of damping used in various types of analyses and rationale (if necessary) for a chosen value is recommended content for a Loads Control Plan.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0041] *and* NASA-STD-5002A *requirement* [LAR 36].

[LDR-025] Intravehicular Activity (IVA) Inadvertent Contact Loads

Flight hardware which will be occupied by crew at any point shall be designed to the limit load for crew inadvertent contact of 154 lbf (685 N), applied as a uniform pressure load over a 4" by 4" (10.16 cm by 10.16 cm) area. If this area is unavailable to inadvertent contact, the load will be applied to the available contact area.

Table 4.1.3-1 Likelihood/Consequence-Based IVA Crew Inadvertent Contact Limit Loads may be used to define lower design load values for hardware items on a case-by-case basis, based on an assessment of the likelihood of inadvertent contact and the consequences of failure of that hardware. Rationale and justification for use of a lower design load for a particular hardware item must be approved by the appropriate Program control board, as well as documented in the hardware developer's Loads Control Plan. Previous design requirements are not sufficient justification for use of this exception. Analyses and assessments justifying use of Table 4.1.3-1 should consider the risk of damage to the hardware and consequence(s) to crew or mission. To mitigate likelihood and/or consequences, hardware and equipment may be protected by covering, locating to prevent contact (e.g. recessing), mounting so as to safely absorb impact (e.g., movable pedestal, break away connector/mounting), or designing to be durable to crew loads.

TABLE 4.1.3-1 LIKELIHOOD/CONSEQUENCE-BASED IVA CREW INADVERTENT CONTACT LIMIT LOADS

Hardware Location (Likelihood of Contact)	Consequence of Damage is…		
	Minor	Critical	Catastrophic
	Alternative Design Load for Hardware is…		
IVA, in translation path	369N (83lbf)	556.4N (125lbf)	685N (154lbf)
IVA, behind closeouts, etc.*	165N (37lbf)	556.4N (125lbf)	685N (154lbf)

*IVA, behind closeout, etc. options:

- Either the hardware or the closeout panels/enclosure can be used as the solution for load requirements when using this table.
- If utilizing the closeout panel/enclosure concept, the closeout panel/enclosure can be designed to either:
    - Take the full required load (preferred)
      OR
    - Fail or deform under the required load, and then the underlying hardware should be able to withstand the resulting load. Note: The deformation/failure of the closeout panel/enclosure should not result in other hazardous consequences.
- Additionally, if utilizing the closeout panel/enclosure concept, the operational concept (and operational controls, if required) must ensure that the hardware remains protected by the closeout panel/enclosure, and the hardware must still meet minimum IVA crew loads (see, for example, NASA-STD-3001, Volume 2, Rev C, Appendix F, Section F.7). When closeout panels/enclosures are opened or removed, the hardware that was behind/inside the closeout panels/enclosures must be 'crew managed'. This hardware will not be left in an untended state until closeout panels/enclosures are back in place with the hardware secured behind it.

<u>Catastrophic Consequence</u> - (1) Fatal injury to personnel, and/or loss of one or more major elements of the flight vehicle or ground facility. (2) Death or permanently disabling injury, major system or facility destruction on the ground, or loss of crew, major systems, or vehicle during the mission. (NPR 8715.3D)

<u>Critical Consequence</u> - Severe injury or occupational illness, or major property damage to facilities, systems, or flight hardware. (NPR 8715.3D)

<u>Minor Consequence</u> - Minor injury not requiring first aid treatment, minor discomfort, or minor damage to non-essential flight/ground assets. (Artemis Campaign Development Risk Scorecard Rev A draft 2022-10-31)

and

165N (37lbf) design load represents 0.8413 probability of no exceedance, with 50% confidence.

369N (83lbf) design load represents 0.9772 probability of no exceedance, with 50% confidence.

556.4N (125lbf) design load represents 0.9959 probability of no exceedance, with 50% confidence.

685N (154lbf) design load represents 0.9987 probability of no exceedance, with 50% confidence.

Rationale: The load values in [LDR-025] *were derived based on on-orbit data taken during crew activities while unsuited in a microgravity environment on the Space Shuttle and the Russian Mir space station. A July 12, 2023 Johnson Space Center Structural Engineering Division (ES) Loads and Structural Dynamics Branch (ES6) Loads*

Panel review of data obtained from the ES passive gravity offload test rig concluded that they are also valid bounding values for unsuited partial gravity operations. While the data set was limited, the unanimous judgment of the Panel members was that there is very low risk of these loads being exceeded by loads resulting from inadvertent contact in a microgravity environment.

This inadvertent load assumes that the crewmember is unsuited in a microgravity or partial gravity environment. This requirement does not apply to vehicle primary structure or extra-vehicular hardware and equipment during suited operations. Unintentional damage can occur if crewmembers inadvertently exert loads that exceed the design loads for hardware or equipment. Inadvertent loads can occur when crew push or kick off equipment or exert excessive force when performing an operation (such as turning a control during an emergency situation). This requirement is specific to unsuited IVA and does not cover loads in the EVA pressurized suited configuration. Pressurized suited load conditions for internal/external hardware that will be near or come in contact with an EVA crewmember are found in EHP-10028*,* Exploration EVA System Compatibility Standards*.*

Note that this requirement is not a comprehensive coverage of all IVA-induced loads. Other design load conditions for hardware with which the IVA crew may interact are found in NASA-STD-3001*,* Volume 2, Revision C*, in* Appendix F*,* Section F.7.1 *Withstand (Maximum Strength) Crew Loads. The IVA Inadvertent Contact Load covered by* [LDR-025] *is related to the "Durability is applicable to structural integrity of hardware due to non-intentional crew forces" consideration mentioned in the last sentence of the first paragraph of Section F.7 Crewmember Strength.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0033]. *There is no corresponding requirement in* NASA-STD-5002A*.*

[LDR-045] Crash Safety Loads for Horizontal Landing

Items within the crew compartment of lifting-body or other aircraft-like spacecraft which land horizontally shall not break loose from their mounting locations and pose a risk to the crew or prevent egress from the vehicle when subject to the load factors defined in Table 4.1.3-2

TABLE 4.1.3-2 CRASH SAFETY LOAD FACTORS FOR HORIZONTAL LANDING

Longitudinal (g)	Lateral (g)	Vertical (g)
+ 20/-3.3	±3	+10/-4.4

NOTES:
1. The positive Longitudinal axis is parallel to the landing surface and directed opposite to the vehicle's horizontal velocity. The positive Vertical axis is normal to the landing surface and directed up (i.e. opposite the gravity vector). The Lateral axis completes the right-handed frame.
2. Load factors act independently
3. The longitudinal load factors shall be directed in all directions within a 20° cone about the longitudinal axis.
4. The load factor is equivalent to the total externally applied load on the component divided by the component weight and is shown in the direction of the acceleration.

Rationale: *"Horizontal landing" indicates the situation where the component of a vehicle's velocity parallel to the landing surface is, by design, larger than the component of velocity normal to the surface. This is typically the case for vehicles which rely on forward motion to generate lift during descent and landing operations.*

The values in Table 4.1.3-2 are taken from Space Shuttle Orbiter crash safety load requirements. In reality, crash load factors are directly related to vehicle kinetic energy. Vehicles with lower approach/landing speeds than the Orbiter may reasonably be expected to see lower crash loads. Federal Aviation Administration airworthiness standards for transport aircraft stipulate +9/-1.5 g, ±4 g, and +6/-3 g longitudinally, laterally, and vertically, respectively. Until further details of spacecraft configuration and operations are defined, the values in Table 4.1.3-2 are recommended.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0032]. *There is no corresponding requirement in* NASA-STD-5002A*.*

4.1.4 Statistical Enclosure for Design Limit Loads

[LDR-006] Statistical Enclosure for Limit Loads

Limit loads for flight hardware primary structure shall be determined which encompasses at least a 0.9987 probability of no exceedance, with 50-percent confidence.

Rationale: *Design loads must be established at levels which envelope flight experience and minimize the likelihood of experiencing higher loads during operation of the vehicle, while simultaneously avoiding over-conservatism which may preclude achieving a design which will close and still meet performance requirements. The so-called "3-sigma" probability of 0.9987 with 50-percent confidence is traditionally used for crewed aerospace structure.*

Note that some structures will be subjected to static, quasi-static, acoustic, sinusoidal, transient, and random vibration loads. When loads produced by different environments or flight events can occur simultaneously, these loads must be combined, as applicable, in a rational manner to define the limit load for that flight, before using them in a strength or life assessment. (Explanatory text under [LDR-003] *offers a list of representative examples). Input values/ranges of parameters for loads analyses should be defined that produce loads that statistically meet the defined probability levels.*

All aspects of the hardware development should be considered for the potential to provide mechanical or thermal loads. This includes loads due to manufacturing, assembly, transportation and handling of components or assemblies, qualification or acceptance tests, and operational conditions (for example liftoff, ascent, docking, mated on-orbit conditions, intravehicular or extravehicular crew induced, flow induced vibration in bellows systems, landing, surface operations).

Some loads which are not dynamic in nature may not be adequately addressed with a 0.9987 probability and 0.50 confidence (P99.87/50) limit. In such cases, an equivalent derivation of the appropriate load should be conducted.

An example of a load which is not dynamic in nature but is subject to this requirement is preload of fasteners due to applied torque. In such cases, the processes of NASA-STD-5020 *can be used to establish nominal preload, minimum and maximum preload, and the preload variation.*

Note that for certain failure modes (e.g. creep, stress rupture, thermo-mechanical fatigue) other factors such as the duration at load (e.g. hold time) or loading rate may be of significance. In such instances, it may be necessary to provide this type of information, in addition to the values of the limit loads.

Commercial launch vehicle developers typically use a 0.99 probability of no exceedance with 90-percent confidence (P99/90) statistical enclosure for design loads. While the record of successful flights of multiple uncrewed and crewed vehicles designed using this value demonstrates the adequacy of this approach, a numerical disconnect between that value and the P99.87/50 value in the requirement remains.

The issue was identified in the Commercial Crew Program. While a blanket exception to the required enclosure was rejected, a methodology for evaluating the sufficiency of design-to loads with P99/90 enclosure to “meet the intent” of the requirement from a safety and reliability perspective was developed:

> *Accepting the change to a P99/90 statistical enclosure will be addressed per loading event, with each requested change supported by at least one of the following technical justifications:*
>
> 1. *The Provider can show that the calculation of the P99/90 enclosure, taking into account the sample size or probability distribution function, meets or exceeds the required P99.87/50 statistical enclosure.*
> 2. *The Provider has documented relevant historical flight data and post-flight reconstructions and flight margins to demonstrate that sufficient margin exists to exceed the analytical statistical difference.*

3. *The Provider has documented an engineering assessment that additional conservatism exists in this specific loads analysis to cover this shortfall.*
4. *A recognized technical entity (Provider, IV&V Contractor, or NASA TA) has estimated the potential loads shortfall and performed one of the following actions:*
    a. *Evaluated structure against this increase and confirmed that positive margins still exist (resolution may include stating that the structure is designed by other loading conditions and not affected), or*
    b. *Factored the potential shortfall for this loading condition into the overall Loss of Crew/Loss of Mission estimates*

Commercial providers will assemble supporting evidence for flight hardware designed to P99/90 in preparation for negotiations with the Program and document such evidence in the provider's Loads Control Plan.

Guidance on the derivation of design loads is found in Appendix B and NASA-STD-5002A*.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0005] *and* NASA-STD-5002A *requirements* [LAR 5] *and* [LAR 44]*.*

[LDR-028] Statistical Enclosure for Abort/Escape or Contingency Loads

For major independent system failures, limit loads shall be determined which encompass at least a 0.9772 probability of no exceedance, with 50-percent confidence.

Rationale: Sizing structure for extreme off-nominal conditions with full statistical enclosure can lead to excessive weight and penalize nominal performance for conditions with relatively low likelihood of occurrence. The so-called "2-sigma" probability of 0.9772 with 50-percent confidence has been adopted in past NASA crewed flight programs, including the Space Shuttle, International Space Station, Orion, and Commercial Crew Programs.

Note that hardware and systems that are classified as "must function" in an abort/escape or contingency should also be able to withstand an additional failure (1 fault tolerant to aborts), in addition to nominal flight fault tolerance requirements. It is not recommended to consider two faults once an abort has been declared, as the original fault that instigated the abort should be counted in the overall fault tolerance and the likelihood of multiple faults after abort should be remote.

Off-nominal situations such as launch vehicle departure from a nominal ascent trajectory with excessive rates and/or angles of attack, loss or premature shutdown of ascent vehicle engines, loss of a parachute during descent, etc. can expose spacecraft to extreme conditions and environments. While crew safety considerations dictate that these events must be considered in the design of spaceflight hardware, holding to the full statistical enclosure of [LDR-006] *would potentially size the entire vehicle(s) and disproportionately penalize nominal operations. Although a hardware developer may choose to not design the entire vehicle to abort/contingency loads, the ability of the launch abort vehicle to maintain structural integrity under abort/contingency load conditions must be assessed to properly quantify crew risk.*

To ensure a valid assessment of abort scenarios, benign scenarios must not be combined with more critical scenarios to achieve a statistical advantage. For example, for coverage of ascent abort/escape, results for the more benign pad abort/escape should not be statistically combined with results for the more serious transonic abort/escape.

A complete set of significant contributors to vehicle loads and environments for the off-nominal condition under consideration must be identified and included. Loads analyses should be conducted using fully-dispersed conditions representing the state of the vehicle(s) at the time of and following the off-nominal situation. Ascent aborts arising from contingencies when a launch vehicle is within nominal attitude and rate limits (e.g. loss of an engine without loss of control) will skew P97.72/50 abort loads analysis results to lower values and may result in under-design of the vehicle.

Conversely, some failures cannot be included in this statistical assessment due to time-to-effect reasons, and are evaluated as straight to Loss of Crew/Loss of Mission. For those cases, consideration of whether the remaining contributors to the off-nominal conditions constitute sufficient independent failure modes for the statistics to be valid.

Statistical enclosure for abort/contingency loads should focus on the abort/contingency phases and events which produce high loading within those phases. For ascent abort/escape specifically, analyses should be performed at 10-second intervals during the ascent, with statistical load estimates produced for each, and the results enveloped to develop design-to ascent abort loads.

Ascent abort/escape analyses to develop loads, forcing functions, and induced environments should consider, as a minimum:

- *a) the initial conditions at the initiation of the abort, especially the stored strain energy prior to separation*
- *b) the abort trajectory, including the effects of dispersions*
- *c) the characteristics of the abort motor*
- *d) human g-load limits*
- *e) characteristics of the landing deceleration system*
- *f) the engine ignition overpressure environment, if applicable at the time of abort*
- *g) the blast overpressure and debris environments resulting from possible launch vehicle catastrophic failure*
- *h) the characteristics of the upper stage engine(s) including start-up and shutdown transients and propellant loading*
- *i) launch vehicle credible failure scenarios, for example including engine gimbal failure in place, hard-over, and failure to null, engine-out conditions (if applicable), etc.*
- *j) abort entry, descent, and landing*

Subsystems and electronic equipment which must survive and function during and after an abort should be designed and qualified for abort dynamic environments developed in accordance with Section 4.1.7, at the full statistical enclosure represented by [LDR-006] and [LDR-007]. However durations for environmental qualification testing of such items may be reduced, as the durations of maximum dynamic environments during an abort are typically very *brief. Subsystems and electronic equipment which do not need to survive and/or function during or after an abort may be designed and qualified to nominal flight levels and durations. In either instance, support structure for these items should be sized for and qualified to abort levels.*

Guidance on the derivation of abort or contingency loads is found in Section 2.6 of Appendix B.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0025] *through* [LD0027]*. There is no corresponding requirement in* NASA-STD-5002A*.*

4.1.5 Combining Low Frequency and Random Loads for Components and Attachments

[LDR-007] Combination of Low Frequency and Random Loads for Components and Secondary Structure Attachments

Quasi-static loads, low frequency transient loads, and random vibro-acoustic loads for flight hardware components and secondary structure shall be combined in a rational manner consistent with the statistical enclosure requirements of [LDR-006] to determine the total loads environment for these items.

Rationale: The source of structural loading can be from multiple simultaneous phenomena, and simultaneous phenomena experienced in service should be accounted for in the certification.

Combined loads for components must encompass at least a 0.9987 probability of no exceedance, with 50-percent confidence, in each of three orthogonal axes. Off-axis components of the combined load which are applied simultaneously may have less statistical enclosure.

In addition to the quasi-static inertial loading due to vehicle acceleration in response to thrust loads and other steady forces, three basic types of flight environments generate dynamic loads on flight hardware components and component attachments:

1. *Low-frequency dynamic response, typically from 0 to 100 Hertz (Hz), of the launch vehicle/spacecraft/payload system to transient flight events.*
2. *High-frequency random vibration environment, which typically has significant energy in the frequency range from 20 Hz to 2000 Hz, transmitted from the launch vehicle to the spacecraft at the launch vehicle/spacecraft interface and propagated to items attached to or within the spacecraft.*
3. *High frequency acoustic pressure environment, typically 31 Hz to 10,000 Hz, inside a launch vehicle or spacecraft compartment. The payload compartment acoustic pressure environment generates dynamic loads on components in two ways: (1) by direct impingement on the surfaces of exposed components, and (2) by the acoustic pressure impingement upon the component mounting structures, which induces random vibrations that are mechanically transmitted to the components.*

Combinations of these loads occur at different times in flight and should be examined for each mission event. For components weighing less than 500 kg, the appropriate method of load combination is dependent on how the low frequency and the random vibration/acoustic design environments of the event are specified. Typically, the maximum levels are defined as requirements for a flight event, such as liftoff, even if these maxima do not necessarily occur at the same time. The relative timing of the transient and random vibration environments is unique *for each launch vehicle, but simultaneous occurrence of maximum low frequency transient and maximum random vibration load is improbable. Therefore, a Root Sum Squared approach is acceptable for combining the maximum low frequency and maximum random vibration loads for the liftoff flight event. When the low frequency transient and random vibration environments are specified in a time correlated manner, a time consistent approach is also acceptable for combining the low frequency transient loads and the random vibration loads.*

For preliminary design, sufficient details of either the component hardware, support structure, or design environments - or all of these - may not be available. In such circumstances, preliminary limit load factors for components may be defined based on a mass acceleration curve (MAC) or table that specifies load factors as a function of component weight, frequency range, structural support type, or other variables. Typically, a MAC is based on previous experience with particular launch vehicles and a variety of spacecraft, and, if possible, incorporates results from previous transient and random vibration analyses, as well as any available flight data. The MAC is derived to represent a combined load factor for component low frequency and random vibration loads. The MAC should not be considered as a substitute for final loads definition. Additional information on the mass acceleration curve can be found in NASA-HDBK-7005 *Dynamic Environmental Criteria and* JPL-D-5882 *Mass Acceleration Curve for Spacecraft Structural Design.*

In a situation where some details of the component hardware and/or support structure may be known but design environments are unspecified, GSFC-STD-7000 *General Environmental Verification Standard (GEVS) is often used as a source for preliminary design environments.*

Section 1.5.3 of Appendix B and NASA-STD-5002A *contain examples of recommended techniques for developing combined loading environments for flight hardware components.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0006] *and* NASA-STD-5002A *requirements* [LAR 45], [LAR 18], [LAR 46], [LAR 47], *and* [LAR 48].

4.1.6 Loads Analysis Cycles

[LDR-008] Verification Loads Analysis

The Verification Loads Analysis shall be performed using verified math models, environments, and forcing functions.

Rationale: The verification loads analysis cycle is so called because all models should be verified and therefore provide results that can be trusted as reliable. Similarly, forcing functions and environments used in the verification cycle should be anchored to test data and/or flight experience.

Flight hardware is subjected to a broad array of loads and environments over the course of its mission profile. Depending on the event, maximum responses may be driven by environments spanning a wide, and possibly varying, frequency range. A variety of analytical approaches and modeling techniques may therefore be required to ensure that bounding-case design loads are appropriately identified.

The verification loads analysis cycle is used to confirm that positive margins exist for all load events. Displacement output from the analysis is also used by the launch vehicle, spacecraft, *and in-space habitat organizations for the loss of clearance analysis. The modes of vibration from the load analysis cycle structural models are also used by launch vehicle, spacecraft, and in-space habitat organizations in controls analyses.*

The term "models" encompasses more than the structural dynamic math models used for coupled loads analysis and other types of models used for non-deterministic high frequency analyses. Examples of other models include, but are not limited to:

- *Engine thrust models - build up, steady burn, and shut down*
- *Aerodynamic models, total vehicle coefficients, running load distributions, and pressure distributions*
- *Wind models of both ground winds and ascent winds*
- *Models of thruster exhaust plume gas dynamics*
- *Models of vehicle/surface interaction forces during lunar or planetary surface operations.*

Forcing function and environment models may be verified in any combination of test and analysis which meets uncertainty requirements. Verification by analysis is more appropriate for models of forcing functions and environments for vehicles with significant flight history and less so for new vehicles/spacecraft with little or no flight experience. Structural dynamics math models should be verified by test (see [LDR-014]*.*

Section 5.2 of Appendix B and NASA-STD-5002A *provide guidelines for math model verification.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0008] *and* NASA-STD-5002A *requirements* [LAR 1] *and* [LAR 4].

4.1.7 Maximum Predicted Environment (MPE) Requirements and Guidance

[LDR-016] Maximum Predicted Environment for Random Vibration, Acoustics, and Shock

MPE for random vibration, acoustic, and shock environments shall be defined using a P95/50 normal tolerance limit based on:

a. The use of actual flight data scaled, if necessary, for differences in structure and acoustic environment and/or
b. Ground test data, scaled if necessary, and/or
c. Analytical predictions

Rationale: The P95/50 normal tolerance limit is the level enveloping greater than 95% of the peak events with 50% statistical confidence. This statistical coverage is standard NASA and industry practice, balancing the need for definition of an environment with a low probability of exceedance with the inherent limitations on allowable conservatism in optimized aerospace structures.

The MPE should be statistically based and calculated using an appropriate distribution and sample size. Unless a measured data set is available that dictates the use of a specific distribution, random vibrations (in g^2/Hz) and shock (g's) should be treated as log-normally *distributed, while acoustic sound pressure level environments should be treated as normally distributed when expressed in dB.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0010] *and* NASA-STD-5002A *requirement* [LAR 30].

[LDR-017] Maximum Predicted Environment for Sine Vibration

MPE for sine vibration environments shall be defined using a P97.72/50 normal tolerance limit based on:

a. The use of actual flight data scaled, if necessary, for differences in structure and acoustic environment and/or
b. Ground test, data scaled if necessary, and/or
c. Analytical predictions

Note that if an approved approach to develop sine vibration test parameters is linked to a different MPE definition, then that MPE may be used to develop test environments (e.g. SMC-S-016).

Rationale: The P97.72/50 normal tolerance limit is the level enveloping greater than 97.72% of the peak events with 50% statistical confidence. This statistical coverage is standard NASA and industry practice for launch vehicle sine vibration, balancing the need for definition of an environment with a low probability of exceedance with the inherent limitations on allowable conservatism in optimized aerospace structures. However, the intent of this requirement is not to define a test margin and should not be used to limit a user's choice of test criteria.

The MPE should be statistically based and calculated using an appropriate distribution and sample size.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0011] *and* NASA-STD-5002A *requirement* [LAR 30].

[LDR-020] Amplitude, Frequency Range and/or Resolution Bandwidth of MPE

The amplitude, frequency range and/or resolution bandwidth of the MPE shall be based on the following, as a minimum:

a. The acoustic environment shall be expressed by a 1/3-octave-band pressure spectrum in dB (reference 20 micropascal) for center frequencies spanning a range of at least 20 to 8,000 Hz, unless unique environmental or hardware response characteristics dictate an alternative range.
b. The random vibration environment Power Spectral Density (PSD) shall be defined over the frequency range of 20 to 2000 Hz, unless unique environmental or hardware response characteristics dictate an alternative range, with a resolution bandwidth of the PSD of 1/6 octave.

c. The shock environment shall be expressed as the derived Shock Response Spectrum (SRS) in g's, based upon the maximum absolute equivalent static acceleration induced in an ideal, viscously damped, single-degree-of-freedom system. For pyroshock or comparable disturbance, he SRS shall span the frequency range from at least 100 Hz to 10,000 Hz, at bandwidths of no greater than 1/6 octave, unless unique environmental or hardware response characteristics dictate a finer resolution. For non-pyrotechnic shocks, such as impacts or other mechanical shocks, the range will be determined by the character of the event. In the absence of other information, the SRS dynamic amplification factor, Q, shall be chosen as Q=10.

d. The sinusoidal vibration environment shall be expressed as an acceleration amplitude in g's with resolution bandwidth sufficient to accurately capture the narrow-band peaks, but no greater than 10% of the sinusoidal frequency.

Rationale: The minimum frequency range, bandwidth requirements and amplitude calculation methodologies values are standard NASA and industry practice. The magnitude of the resulting environments can vary significantly based on assumptions in these parameters. The standard ensures consistent methodologies that balance the need for definition of an environment with a low probability of exceedance with the inherent limitations of allowable conservatism in aerospace structures.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0013] *and* NASA-STD-5002A *requirement* [LAR 30].

[LDR-021] Durations for Maximum Predicted Environment

The MPE duration for acoustic and random vibration events shall be defined as the fatigue equivalent duration.

Rationale: The magnitude and duration of random vibration and acoustic environments vary significantly during the various events that encompass the service life. The fatigue equivalent duration ensures that sufficient fatigue damage potential is included in test environments and loads spectra. The fatigue equivalent duration should be calculated per the methodology defined in Section 2.2 of Annex A to Method 514.8 in MIL-STD-810 *or equivalent as approved by the Technical Authority.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0014]. *There is no corresponding requirement in* NASA-STD-5002A*.*

4.1.8 Fatigue Loads Spectra Development

[LDR-009] Fatigue Load Spectra

Cyclic loading spectra shall be derived for all applicable mechanical loading events for the lifetime of flight hardware primary structure and for components and secondary structure for which fatigue and/or fracture analysis are required.

Rationale: Structural strength and life assessments must consider fatigue crack propagation to ensure that flight hardware safely meets all performance objectives. Accurate and adequate characterization of anticipated cyclic loading is required to perform such assessments correctly. Note that development of load spectra may also be required *for non-primary structure if such items are determined to be sensitive to fatigue and/or fracture.*

Recommendations on fatigue loads spectra development, including treatment of Ground-Air-Ground (GAG) cycles and combination of transient, pressure, and thermal load cycles, are provided in Section 4.2 of Appendix B. The loads spectra should consider all relevant events that can induce load on the structure, such as

- *Transportation (ground, air, sea)*
- *Ground tests*
- *Flight integration operations, including crane operations, roll-out, erection, and roll-back events*
- *Flight operations (ascent, docking, mated operations, crew induced, entry, descent, landing, surface operations)*
- *Recovery (if applicable)*

While the complete definition of fatigue spectra must include cyclic thermal and pressurization contributions, determination of those are out of scope for the loads and dynamics discipline.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0015]. *There is no corresponding requirement in* NASA-STD-5002A*.*

4.1.9 Consideration of Gapping at Interfaces

[LDR-022] Interface Gapping

For flight hardware interfaces which exhibit gapping at less than limit load, loads and dynamic analyses shall be supported by non-linear analysis or test data to demonstrate that the non-linearities do not invalidate the documented loads or dynamic products.

Rationale: The majority of analyses typically performed to develop design limit loads assume linearity. A joint which exhibits a separation, or gapping, at an interface under an applied load violates that assumption of linearity, as the effective stiffness at the interface is changed. If this separation occurs below the limit load predicted using a linear analysis, the assumptions used to derive that limit load are, therefore, no longer valid. In addition, the changed stiffness resulting from a separated interface will result in changes in system frequencies and mode shapes which, in turn, may impact designs for other technical disciplines such as Guidance, Navigation, and Control (GN&C). Non-linear analysis or testing is necessary in this case to properly quantify the effects of the gapped interface on loads and structural dynamics.

Because bolted joint analysis has considerable scatter in the calculation of the preload even for assumed linear behavior, NASA-STD-5020 *recommends a bounding analysis that calculates the maximum expected preload and the minimum expected preload. The maximum preload is used to evaluate joint capability (margin) while the minimum preload is used in assessment of joint gapping. In cases where joint gapping is predicted, a bolt-bending nonlinear analysis should be performed. It is recommended that this nonlinear analysis also be performed with maximum and minimum properties to bracket the possible outcomes, as traditionally* *conservative assumptions for strength analyses are not always conservative for frequency and loads prediction.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0016]. *There is no corresponding requirement in* NASA-STD-5002A*.*

5.0 MODEL, FORCING FUNCTION, AND DATA REQUIREMENTS

5.1 MATH MODEL REQUIREMENTS

5.1.1 Dynamic Model Requirements and Guidance

[LDR-027] Models for Loads Analyses

Flight hardware providers shall develop a sufficient set of models, of appropriate types, to permit analysis using forcing functions and environments covering applicable frequency ranges for all loading events over the hardware life cycle.

Rationale: Flight hardware is subjected to a broad array of loads and environments over the course of its mission profile. Depending on the event, maximum responses may be driven by environments spanning a wide, and possibly varying, frequency range. A variety of analytical approaches and modeling techniques (e.g. Finite Element Analysis (FEA), Boundary Element Analysis (BEA), Statistical Energy Analysis (SEA), etc.) may be required to ensure that bounding-case design loads are appropriately identified. For reference, the section titled Model Delivery Requirements for Vibroacoustic Criteria Development in Section 5.4 of Appendix B contains guidelines applicable to SEA and BEA model development.

All loads and environments must be derived based on some model. The choice of the appropriate type of model to be used for a particular analysis depends on the frequency content of the environment or forcing function being assessed. Depending on the load regime, models may take the form of empirical models, rigid body models, kinematic models of mechanisms, finite element models, and/or boundary element models.

For example, a launch abort vehicle (LAV) may take on several configurations during abort flight and each must be assessed to assure functionality and crew survivability. The loads on the LAV are significant and of a wide frequency range. It may therefore be necessary to develop distinct models of the LAV which are applicable to the frequency ranges of the environments which the LAV will encounter during aborts/escapes. Complete analytical coverage will likely require the use of distinct models with different frequency applicability (e.g. FEA, BEA, SEA).

Section 5 of Appendix B of and NASA-STD-5002A *provide guidelines for format and content of models for use in coupled loads analyses.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0034] *and* NASA-STD-5002A *requirements* [LAR 19], [LAR 20], [LAR 21]*, and* [LAR 24].

[LDR-012] Finite Element Models for Loads Analyses

Flight hardware finite element mathematical models shall be developed for use in coupled loads analysis and other loads analyses.

Rationale: Finite element models are based on nominal structural properties and geometry. The model may be a reduced version of a finite element model developed for stress analysis or may be a model developed specifically for loads analysis. Regardless of the source, the modeling approach should be aimed at producing accurate dynamic predictions.

Models may encompass the range from detailed component/subsystem models to individual models, elements, or spacecraft to integrated launch vehicle/spacecraft/payload or integrated on-orbit structures comprised of multiple sub-element or segment models and attached appendages.

Section 5 of Appendix B and NASA-STD-5002A *provide guidelines for format and content of finite element models for use in coupled loads analyses.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0038] *and* NASA-STD-5002A *requirements* [LAR 19], [LAR 20], *and* [LAR 21].

[LDR-023] Model Resolution

Flight hardware models for dynamic analyses shall be of sufficient resolution and fidelity to represent subsystem and vehicle responses over the analysis frequency range of interest.

a. Finite element models for coupled loads analysis shall be of sufficient resolution and fidelity to represent subsystem and system resonances up to at least 1.1 times the upper bound of the range of frequency content of the forcing functions for all load events to be analyzed.
b. Finite element models for random vibration and acoustic analyses shall have both mesh density and the forcing function patch density sufficiently detailed to produce results in the frequency range of interest for the analysis.

Rationale: The value of 1.1 in a. is chosen to ensure that any dynamic content in the system just above the response upper bound is included. Also, this prevents frequencies just above the response upper bound from coming in and out of the limit with each new analysis. Random vibration and acoustic model development requirements depend on the analysis method and tools (and based on load regime and frequency of interest). In all cases, the frequency range for the dynamic loads analysis coupled to the resolution and fidelity of the hardware models and forcing functions. The modeling approach should be aimed at producing accurate dynamic predictions over the excitation frequency ranges in forcing functions and environments.

Part a. of this requirement applies for models used in a system-level analysis, where environments and forcing functions are applied to the model. Here "system" could be a stand-alone model of a spacecraft or free-flying payload or a combination of multiple models representing, for example, a transport vehicle plus a module, an integrated launch vehicle+spacecraft or launch vehicle+payload, or a complex on-orbit assemblage of multiple *modules. In all such cases, the model should accurately represent responses up to 1.1 times the highest frequency present in forcing functions and environments to which it is subjected. Note that a value of 1.1 is not sufficient for the separate element models combined to make an integrated system model, if those separate models are reduced prior to integration (see* [LDR-013]*).*

Section 5 of Appendix B and NASA-STD-5002A *provide guidelines for considerations in and recommended approaches to model development and frequency content needed for the assessment of key events over typical flight hardware life cycles.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0039] *and* NASA-STD-5002A *requirements* [LAR 8], [LAR 24], and [LAR 25].

[LDR-013] Upper Bound Frequency for Reduced Models

Flight hardware finite element models developed and reduced as sub-component models for integration into a larger integrated system model for coupled loads analysis shall be of sufficient resolution and fidelity to represent subsystem and integrated system resonances up to a model upper bound frequency of no less than 1.5 (with 2.0 being a recommended best practice) times the cutoff frequency of the next higher level of assembly.

Rationale: Sub-models integrated into a system model must retain a frequency content greater than that which will be used for integrated system response analysis.

In the event that multi-level reductions are performed prior to integration into a system model, this 1.5 times factor is multiplicative until the final assembly level is reached. For example, if models A and B are reduced and combined to create model C, which is then combined with other models to form a system-level model, then the sub-models A and B must include frequencies 2.25-4.0 higher than that of the system model cutoff frequency as defined in [LDR-023].

Section 5 of Appendix B and NASA-STD-5002A *provide guidelines for considerations in and recommended approaches to model development and frequency content needed for the assessment of key events over typical flight hardware life cycles.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0040] *and* NASA-STD-5002A *requirement* [LAR 25], [LAR 26], *and* [LAR 27].

5.1.2 Loads Model Verification

[LDR-014] Modal Survey Test

Flight hardware models developed for loads analysis shall be verified by modal survey tests, with the appropriate boundary conditions, to ensure the model is sufficiently accurate for load and deflection predictions.

Rationale: To enable reliable prediction of structural responses during operations over the hardware lifetime, dynamic models used to make those predictions must represent the response of the actual hardware to a specified level of accuracy. Modal survey *testing advances this goal by enabling tuning of structural dynamics models to measured response of hardware under controlled conditions.*

Model verification may be accomplished by a combination of spacecraft or element level and component level (if needed) modal survey tests. In some cases, additional verification tests may be required due to the non-linear nature of the dynamic response. Verification of spacecraft dynamic models may require off-loading systems that simulate the free-free boundary conditions of the spacecraft. Test configuration determination should consider the boundary configurations for driving phases of flight (e.g., constrained for liftoff and ascent, free for abort).

While modal tests are strongly preferred, other appropriate structural test and/or flight data may be utilized to demonstrate that models of the hardware in question satisfy [LDR-014] *without dedicated modal testing. This data may be from prior modal tests of similar hardware, sufficiently instrumented vibration tests, static/stiffness tests, mass properties measurements, instrumented ground transportation tests, or flight tests. In such cases, the approach to be taken and relevant supporting data should be clearly and thoroughly described in the hardware developer's Loads Control Plan as described in* [LDR-001]*. Alternates to modal testing should include sufficient instrumentation to capture all required primary modes needed for GN&C and loads capability analyses.*

Verification must include characterization of load paths which exist in in-space and/or non-terrestrial surface configurations which do not exist in a terrestrial launch configuration. One example is a forward interface of a module element launched as a free interface within a launch vehicle payload fairing, but which will transfer loading when joined to other elements in space.

For on-orbit configuration component models, the preferred method to verify the stiffness of the on-orbit attachment points of the structure is by mass loading these areas to exercise sufficient strain energy in the regions of the structure which are critical for the on-orbit configuration. Stiffness simulators and appropriate mass loading of adjacent structure for each phase of flight should be included. Consumables tanks, if present, should include representations of fluid mass in both full and empty configurations. Finally, test fixtures that have significant dynamic motion within the frequency range of the test should be dynamically characterized prior to the testing and be instrumented during the test.

When mass loading of on-orbit interfaces is not used to correlate the on-orbit model with ground modal tests, additional ground test data such as static deflection tests and/or strain data may be used to supplement the verification. Static testing must obtain static influence coefficients for any single point interfaces.

Section 5.2 of Appendix B and NASA-STD-5002A *provide guidelines on loads model verification, including recommendations on mass representation, treatment of boundary conditions, correlation accuracy, treatment of uncertainty, simplified approaches, etc.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0047] *and* NASA-STD-5002A *requirements* [LAR 49], [LAR 52], and [LAR 53].

[LDR-015] Loads Model Verification - Target Modes

Test data and/or flight data used for model verification shall measure and correlate frequency and mode shape for all significant modes below the model upper bound frequency per [LDR-023] and [LDR-013], consistent with the model resolution and fidelity guidelines within those requirements and other requirements in Section 5.1.1 Dynamic Model Requirements and Guidance.

Rationale: Models used to predict flight hardware structural responses must be verified to be accurate over a range of frequencies which encompass the forcing functions and environments to which the hardware will be exposed over its operational lifetime. Within that frequency range, structural modes which contribute most strongly to responses of interest must be identified and prioritized for increased focus and scrutiny.

Significant modes may be selected based on an effective mass calculation, grid point kinetic energy, strain energy distribution, or other criteria, but this set should be augmented by modes which are critical for specific loads and deflections and component interface modes. If effective mass is used as a selection criterion, significant modes should include all modes with greater than 5% modal effective mass and the summation of all test target mode modal effective mass should be greater than 80% of the test article structural mass in each of the 6 orthogonal directions. Regardless of selection method, all modes within the frequency range of the test should be identified and measured, if at all practical.

Verification must include characterization of load paths which exist in in-space and/or non-terrestrial surface configurations which do not exist in a terrestrial launch configuration. One example is a forward interface of a module element launched as a free interface within a launch vehicle payload fairing, but which will transfer loading when joined to other elements in space.

Note that this requirement is only applicable for models used in lower-frequency analyses, not analyses that depend on an ensemble of uncertain modes of higher frequency, such as vibroacoustics. For such analyses, the section titled Model Delivery Requirements for Vibroacoustic Criteria Development in Section 5.4 of Appendix B contains guidelines for model quality assurance.

Section 5.2 of Appendix B and NASA-STD-5002A *provide guidelines on target mode identification, including recommendations on correlation accuracy goals.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0048] *and* NASA-STD-5002A *requirement* [LAR 50].

5.2 DATA DELIVERABLE REQUIREMENTS

5.2.1 Models and Forcing Functions

[LDR-011] Dynamic Models for Loads Analysis

Dynamic models and associated data shall be made available (delivered or onsite) to NASA and/or the responsible Technical Authority for review. Where such models are used in integrated loads analyses performed by a third party, the Technical Authority approval shall also be required. Dynamic model deliveries will be accompanied with the following information:

1. Dynamic models for all mission phases
2. Output requests for all mission phases
3. Load indicators and redlines for all mission phases

4. Output transformation matrices for all mission phases
5. Forcing functions for all mission phases
6. Dynamic environments for all mission phases
7. Model documentation for all mission phases
8. Model checkout documentation and test cases (if applicable)

Rationale: Delivery of models and forcing function, environment, and output request data will support any necessary independent verification and validation activities which may be necessary and facilitate timely response in the event of any flight anomalies which may occur.

This requirement applies to flight hardware analysis models to support all integrated or stand-alone loads analyses. During certain mission phases (for example, launch/ascent or rendezvous/proximity operations/docking/mated operations with in-space habitats or spacecraft), external organizations may have unique model delivery requirements.

When a reduced model is provided, it is preferred that a non-reduced bulk data version of the model be provided along with the reduced model, if possible, to enable greater insight into dynamic response or facilitate debugging of any issues which might arise during use of the reduced model.

Reduced models should retain any grids representing interface locations at which the model may be integrated into a larger system model in the physical boundary set, as well as locations at which external loads may be directly applied. For example, a model of a habitable module payload provided for launch/ascent and/or on-orbit coupled loads analysis should retain physical boundary grids at docking ports or robotic interfaces which will be connected to other structure in orbit, even if those grids are not connected during launch and ascent, grids within the pressurized volume for application of loads from crew activities, and sets of grids distributed across the module surface for application of plume impingement loading. Grids for application of loads applied during transportation, ground handling, testing, and integration should also be retained.

As noted under [LDR-008]*, the term "models" encompasses more than the structural dynamic math models used for coupled loads analysis and other types of models used for non-deterministic high frequency analyses. Representations of forcing functions and dynamic environments are also to be included in the deliveries.*

This requirement encompasses JSC 65829 Rev A *requirements* [LD0051] *through* [LD0069] *and* NASA-STD-5002A *requirements* [LAR 29]*,* [LAR 31]*, and* [LAR 63].

5.2.2 Documentation

[LDR-010] Documentation Related to Dynamics Tests

Dynamic test documentation and data used to support verification of the requirements in this document shall be made available (delivered or onsite) to NASA and/or the responsible Technical Authority for review and approval. The provided data should include, but is not limited to, the following:

1. Pre-test analyses prior to the start of the test
2. Test plans prior to the start of the test
3. Test procedures prior to the start of the test
4. Test documentation files
5. Test Analysis Models
6. General test data
7. Qualification, proto-qualification, and acceptance test summaries
8. Test logs
9. Test discrepancy reports
10. Test mode quality checks (self-orthogonality to ensure discrimination between test modes)

Rationale: Documentation related to testing of systems is critical for proper certification of flight hardware.

Reference document SMC-S-016 provides guidance on the nature and scope of contents required for each of these deliverable items, as follows:

1. *Test plans - SMC-S-016 Section 4.8.1*
2. *Test procedures - SMC-S-016 Section 4.8.2*
3. *Test documentation files - SMC-S-016 Section 4.9.1*
4. *General test data - SMC-S-016 Section 4.9.2*
5. *Qualification, proto-qualification, and acceptance test summaries - SMC-S-016 Section 4.9.3*
6. *Test logs - SMC-S-016 Section 4.9.4*
7. *Test discrepancy reports - SMC-S-016 Section 4.9.5*

This requirement applies for modal survey testing, as described in [LDR-014]*, other testing used to support model validation, and dynamic environment testing required to certify hardware for flight, as well as other tests performed to support verification of the requirements in this document. In addition to the documentation identified, unique requirements associated with dynamic model verification reports are defined in* [LDR-018]*.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0049]*. There is no corresponding requirement in* NASA-STD-5002A*.*

[LDR-018] Model Verification Reports

Analysis model to dynamic test correlation reports shall be made available (delivered or onsite) to NASA and/or the responsible Technical Authority for review and approval with the following information:

1. A description of the baseline (pre-test) dynamic math model.

2. A description of the test article, test boundary conditions, and available test data for the correlation.
3. A comparison of test and analytical dynamic parameters (e.g., frequencies, mode shapes, orthogonality, etc.) of significant modes relative to correlation goals and requirements of [LDR-014] and [LDR-015] for both pre- and post-test correlation. Any deviations from correlation requirements and goals are to be explained with technical rationale and engineering judgment that justifies that the test/math model correlation is sufficient.
4. A description of the changes made to pre-test math models to improve the dynamic math model correlation.

Rationale: This requirement establishes the means by which flight hardware model correlation efforts will be captured. Specific correlation goals are to be provided in the Loads Control Plan required for all flight hardware.

Guidelines for model correlation can be found in Section 5.2 of Appendix B and NASA-STD-5002A*.*

This requirement encompasses JSC 65829 Rev A *requirements* [LD0049] *and* NASA-STD-5002A *requirements* [LAR 51] *and* [LAR 54] *through* [LAR 62]*.*

6.0 DYNAMIC COUPLING REQUIREMENTS

This section establishes a set of requirements covering coupling phenomena or other interactions between structural dynamics and aerodynamic environments, vehicle control systems, or propulsion system elements. Such requirements encompass multiple design criteria including structures, propulsion, aerodynamic, and control system architecture. However, the coupling of these aspects with structural dynamics dictates that these requirements be included herein, to ensure that such multi-disciplinary interactions are not overlooked in the design space for NASA and commercial launch vehicles spacecraft, launch abort vehicles, or other crewed systems which may experience atmospheric flight.

Because of the cross-discipline, multi-discipline nature of these requirements, they are largely transferred directly from JSC 65829 Rev A and not entirely subjected to the less-prescriptive tailoring applied for other requirements in this document. This was done to avoid inadvertent exclusion of aspects captured in the requirements which might be critical to the interests of other disciplines.

In the requirements in Sections 6.1, 6.2, 6.3, and 6.4, “Flight Vehicles” applies to any crewed spaceflight hardware exposed to external aerodynamic environments during launch, ascent, entry, descent, and landing, whether terrestrial or non-terrestrial.

6.1 AEROELASTICITY

[LDR-030] Consideration of Limit Conditions and Environments

Flight Vehicles shall account for static and dynamic structural deformations and responses including the effect of aeroelasticity under all limit conditions and environments in the structural design of said vehicles.

Rationale: Combined effects of aerodynamic loading and structural response must be accounted for in vehicles which perform atmospheric flight. The vehicle structure must be stiff enough to ensure that static elastic deflection will not cause structural failure or detrimental deformation or degrade stability and control below specified levels.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0077]*. There is no corresponding requirement in* NASA-STD-5002A*.*

[LDR-031] Preclude Adverse Aeroelastic Effects

Static and dynamic structural deformations and responses including the effect of aeroelasticity under all limit conditions and environments shall not cause a system malfunction, preclude the stable control of the Flight Vehicles, or cause unintentional contact between adjacent bodies.

Rationale: Combined effects of aerodynamic loading and structural response must be accounted for in vehicles which perform atmospheric flight. The vehicle structure must be stiff enough to ensure that static elastic deflection will not cause structural failure or detrimental deformation or degrade stability and control below specified levels.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0078]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.2 STATIC AEROELASTICITY

6.2.1 Divergence

[LDR-032] Preclude Divergence

Flight Vehicles shall be free from divergence at dynamic pressures up to: (1) 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent and entry design trajectories; (2) the maximum dynamic pressure expected along the dispersed abort trajectories; or (3) 1.32 times the maximum dynamic pressure expected at any point during atmospheric flight, with or without control surfaces activated.

Rationale: Divergence will result in loss of vehicle structural integrity and loss of crew. Therefore, flight vehicle design should preclude the possibility of divergence.

Dynamic-pressure margins for divergence for Flight Vehicles should be determined separately at constant density and at constant Mach number for all points within the atmospheric flight envelope, with or without control surfaces activated. The divergence evaluation should include, as appropriate, such factors as static and transient thermal effects on distortion and stiffness, loading magnitudes and distributions for all critical conditions, stiffness characteristics of the control-surface actuator system, system tolerances, misalignments, and mechanical play. For recommended practices, refer to NASA SP-8003.

This requirement encompasses JSC 65829 Rev A *requirements* [LD0079] *and* [LD0080]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.2.2 Control System Reversal

[LDR-033] Preclude Control System Reversal

Active aerodynamic control surfaces of Flight Vehicles shall not exhibit reversal up to the maximum dynamic pressure expected at any Mach number within the dispersed flight envelope for any given flight regime.

Rationale: Control reversal may lead to loss of control of the flight vehicle and loss of crew. Therefore, flight vehicle design should preclude control system reversal. For recommended practices, refer to NACA TN-3030. During an aborted flight, sufficient control effectiveness should be retained to permit the safe return of the vehicle and personnel.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0081]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.3 DYNAMIC AEROELASTICITY

6.3.1 Flutter

[LDR-034] Preclude Flutter

Flight Vehicles shall be free from flutter at dynamic pressures up to: (1) 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent and entry design trajectories; (2) the maximum dynamic pressure expected at any point along the dispersed abort trajectory; or (3) 1.32 times the maximum dynamic pressure expected at any point during atmospheric flight, with or without control surfaces activated.

Rationale: Flutter produces sustained-amplitude oscillations or diverging oscillations leading to structural failure. Sustained-amplitude oscillations can produce fatigue failures. In either situation, loss of crew is a significant possibility. Therefore, flight vehicle design should preclude flutter. For further information, refer to NASA SP-8003.

Dynamic-pressure margins for flutter for Flight Vehicles should be determined separately at constant density and at constant Mach number for all points within the atmospheric flight envelope, with or without control surfaces activated. The evaluation should account for all pertinent aerodynamic, elastic, inertial, and damping parameters, and coupling mechanisms (e.g., mechanical, elastic and aerodynamic), as well as the effects of control-system characteristics and mechanical play, misalignments, interface stiffnesses, and degrees of freedom of the cryogenic tank-support structure. If staging can occur in the atmosphere, the changes in vibration-mode characteristics and in the characteristics of the newly activated control surfaces should be accounted for, as well as the location of the lifting or control surfaces on the separating stages. For recommended practices, refer to NASA SP-8003.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0082] *and* [LD0083]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.3.2 Panel Flutter

[LDR-035] Preclude Panel Flutter

Flight Vehicle external surfaces shall be free of panel flutter at all dynamic pressures up to: (1) 1.5 times the local dynamic pressure expected at any Mach number along the dispersed ascent and entry design trajectories; (2) 1.5 times the maximum dynamic pressure expected at any point during atmospheric flight; and (3) the maximum dynamic pressure expected for the dispersed abort trajectories.

Rationale: Panel flutter results in sustained oscillations in thin plate- or shell-like elements of a vehicle which can cause 1) structural failure of the panel or supporting structure, 2) functional failure of equipment attached to the structure, or 3) excessive noise levels in space vehicle compartments near the fluttering panel. Panel flutter may be destructive, potentially leading to loss of vehicle structural integrity and loss of crew. Therefore, flight vehicle design should preclude panel flutter. For further information, refer to NASA SP-8004.

Dynamic-pressure margins for panel flutter for Flight Vehicles should be determined separately at constant density and at constant Mach number for all points within the atmospheric flight envelope. However, maximum nominal dynamic pressure for environmental and system dispersions used in panel flutter margin determinations for Flight Vehicles should not exceed dispersed dynamic pressure used for the structural design or ascent stability constraints.

The structural design of panel configurations for flutter prevention should be based upon consideration of the following parameters: panel stiffness, edge constraints, panel-support-structure stiffness, midplane stresses, thermal environment, local dynamic pressure and Mach number, differential pressure (including the effects of venting), and direction of flow. Panel flutter should be prevented in all modes including the first-vibration mode and in traveling-wave and standing-wave phenomena. NASA SP-8004 may be used as a guideline for designing panel surfaces.

This requirement encompasses JSC 65829 Rev A *requirements* [LD0084], [LD0085], *and* [LD0086]. *There is no corresponding requirement in* NASA-STD-5002A.

6.3.3 Stall Flutter

[LDR-036] Preclude Stall Flutter

Flight Vehicles shall be free of stall flutter at 1.32 times the dynamic pressure expected for high angle-of-attack maneuvers.

Rationale: Stall flutter can result in loss of vehicle control and/or produces sustained-amplitude or diverging oscillations which lead structural failure. In either situation, loss of crew is a significant possibility. Therefore, flight vehicle design should preclude stall flutter.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0087]. *There is no corresponding requirement in* NASA-STD-5002A.

[LDR-037] Preclude Structural Failure or Loss of Control at High Angle-of-Attack

Separated aerodynamic-flow effects associated with lifting and stabilizing surfaces in high angle-of-attack maneuvers shall not result in structural failure or loss of control.

Rationale: A parametric evaluation of vehicle stall-flutter characteristics should be conducted to determine the aeroelastic characteristics necessary to avoid limit-cycle amplitude responses that could induce adverse loads on the structure. The evaluation should consider:

1. *Separated-flow characteristics under all anticipated conditions of angle of attack and speed.*
2. *Stiffness, inertia, and damping characteristics of the aerodynamic surfaces.*
3. *All significant degrees of freedom.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0088]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.3.4 Control Surface Buzz

[LDR-038] Preclude Control Surface Buzz

Flight Vehicles, with or without control surfaces activated, shall be free of control-surface buzz at dynamic pressures up to: (1) 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent and entry design trajectories; and (2) 1.32 times the maximum dynamic pressure expected at any point during atmospheric flight.

Rationale: Control surface buzz can produce sustained-amplitude oscillations of control surface. Such oscillations can impair vehicle control system performance, leading to loss of control and/or can produce fatigue failures in control surfaces and actuators. In either situation, loss of crew is a significant possibility. Therefore, flight vehicle design should preclude control surface buzz. For further information, refer to NASA SP-8003.

Dynamic-pressure margins for control surface buzz for Flight Vehicles should be determined separately at constant density and at constant Mach number for all points within the atmospheric flight envelope.

Flight Vehicle control surfaces must not exhibit sufficient buzz to cause structural failure, loss of control of the vehicle, or otherwise prevent the safe return of personnel at the maximum dynamic pressure or at any Mach number along dispersed abort trajectories. The following considerations should be reflected in the design:

1. *Aerodynamic configurations should be carefully selected so that flow-separation positions minimize the onset of buzz.*
2. *High torsional and rotational rigidity should be provided to ensure the highest practical rotational frequency.*
3. *The design should incorporate close tolerance bearings, actuator linkage, and attachments to minimize mechanical play.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0089] *and* [LD0090]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.4 INTERACTIONS BETWEEN VEHICLE FLIGHT CONTROL SYSTEM AND ELASTIC MODES

[LDR-039] Preclude Control/Structure Interaction

Flight Vehicles shall be free of instability or other interactions of the control system with the elastic modes which could impair flightworthiness.

Rationale: Unstable interaction between vehicle structural dynamics and flight control system can lead to catastrophic failure of the vehicle and loss of crew. The vehicle structure interfacing with the guidance and control system should be designed so that the excitations from the vehicle do not impair the performance of the guidance and control system or produce unacceptable error drift.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0091]*. There is no corresponding requirement in* NASA-STD-5002A*.*

[LDR-040] Control/Structure Interaction Analysis Model Detail

Structural characteristics of Flight Vehicles shall be modeled in sufficient detail to permit analytical prediction of interactions of the control system with elastic modes.

Rationale: Accurate modeling of structures and structural dynamics is necessary to correctly analyze the interaction of vehicle control/structure interaction.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0092]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.5 POGO DESIGN AND ANALYSIS REQUIREMENTS

[LDR-041] Preclude Pogo

Flight Vehicle design shall not permit unstable coupling of the structure with the liquid-propulsion system for all mission configurations.

Rationale: Unstable interaction between vehicle structural dynamics and liquid propulsion system can lead to catastrophic failure of the vehicle and loss of crew. For recommended practices, refer to NASA SP-8055.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0093]*. There is no corresponding requirement in* NASA-STD-5002A*.*

[LDR-042] Pogo Analysis Coverage

Uncertainties in the parametric values shall be accounted for by appropriate statistical means for establishing that the probability of a pogo instability during a vehicle flight is sufficiently small.

As a minimum requirement, the nominal coupled system shall be stable at all times of flight for the following two conditions imposed separately: (1) the damping of all structural modes is halved simultaneously (this corresponds to a damping gain margin of at least 6 dB), and (2) any phase shift up to -/+30 degrees is applied simultaneously to all the structural modes (this corresponds to a structural phase margin of 30 degrees). When possible, the stability analysis shall be checked by a comparative analysis of the stability characteristics of closely related vehicles that have flown.

*Rationale: Adequate coverage of system response variability as a function of parametric uncertainties must be assured. A minimum criteria for pogo stability must be defined and verified. NASA SP-80*55 *may be used as a guideline for* pogo stability analyses*.*

This requirement encompasses JSC 65829 Rev A *requirement* [LD0094]*. There is no corresponding requirement in* NASA-STD-5002A*.*

6.6 SLOSH

[LDR-043] Determine Need for Slosh-Suppression Devices

The need for slosh-suppression devices for Flight Vehicles shall be determined on the basis of dynamic analyses which consider the impact of slosh damping on overall vehicle loads, propellant tank local loads, control-system effectiveness, and overall vehicle stability.

Rationale: Slosh has the potential to drive structural design and negatively impact vehicle flight control system performance. Typically, the need for slosh suppression is driven by a propellant slosh mode damping level required for control system stability. For recommended practices, refer to NASA SP-8031.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0095]*. There is no corresponding requirement in* NASA-STD-5002A*.*

[LDR-044] Slosh-Suppression Device Design

Flight Vehicle slosh-suppression devices shall be designed to provide the specified levels of slosh damping, to function compatibly with all other systems in the vehicle, and to maintain their structural integrity under all applied loads.

Rationale: Slosh has the potential to drive primary structure design and negatively impact vehicle flight control system performance. Typically, the need for slosh suppression is driven by a propellant slosh mode damping level required for control system stability. NASA SP-8031 may be used as a guideline for design of slosh-suppression devices.

This requirement encompasses JSC 65829 Rev A *requirement* [LD0096]*. There is no corresponding requirement in* NASA-STD-5002A*.*

APPENDIX A
ACRONYMS AND ABBREVIATIONS

BEA	Boundary Element Analysis
cm	Centimeter
dB	Decibels
EVA	Extravehicular Activity
FEA	Finite Element Analysis
FIP	Failure in Place
FTN	Failure to Null
g	Unit gravitational acceleration
GAG	Ground-Air-Ground
GEVS	General Environmental Verification Standard (GSFC-STD-7000)
GN&C	Guidance, Navigation and Control
HO	Hardover
Hz	Hertz
ISS	International Space Station
IVA	Intravehicular Activity
IV&V	Independent Verification and Validation
LAV	Launch Abort Vehicle
lbf	Pound (force)
LEO	Low Earth Orbit
LV	Launch Vehicle
MAC	Mass Acceleration Curve
N	Newton
PSD	Power Spectral Density
RSS	Root Sum Squared
SC	Spacecraft
SEA	Statistical Energy Analysis
SPL	Sound Pressure Level
SRS	Shock Response Spectrum
STM	Stress Transformation Matrix
SVP	Structural Verification Plan
TA	Technical Authority

APPENDIX B
GUIDELINES FOR LOADS ANALYSIS OF SPECIFIC FLIGHT PHASES

This Appendix provides recommended guidelines for developing structural design limit loads and load spectra for spaceflight hardware. Considerations which should be taken into account in the assessment of the key events in typical vehicle life cycles are identified and some recommendations regarding analysis methodologies are offered. Also provided are some suggested guidelines for mathematical models developed for structural loads analysis and vibroacoustic analysis. The contents of Appendix B are not formal requirements. Rather, they reflect experience gained and best practices developed over a history of NASA spaceflight hardware design and development.

Guidelines for Loads Analysis of Specific Flight Phases

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APPENDICES

1.0 LOADS MANAGEMENT PLAN

1.1 LOADS AND DYNAMICS TEAM RESPONSIBILITIES

Programs and Projects should identify and establish an organization which has ultimate technical authority (TA) over the development and definition of structural design loads requirements. The TA should have the responsibility to manage, make decisions, provide direction, review, resolve issues, and provide integration across all engineering disciplines in the areas of loads and structures activities, both as an integrated vehicle and as separate systems within a Program/Project.

TA team membership should be composed of representatives from NASA and contractors from the various system developers responsible for deriving design loads. The team would provide a technical forum for identification and resolution of loads integration issues. The team members will

a. develop loads criteria and coordinate math model requirements and load case definition, loads data output requests, and delivery schedules,

b. define analysis plans and tasks and track them to completion,

c. identify technical issues and provide technical review to reach a consensus, if possible, on recommendations to resolve these issues,

d. define Verification and Validation (V&V) requirements for math models and forcing functions used in loads derivation, and

e. provide a single forum to coordinate resolution of loads integration issues.

1.2 DESIGN LOADS ANALYSIS CYCLES

Design loads should be developed to support major milestones, including the Design and Analysis Cycles (DACs) and Verification Analysis Cycles (VACs). The VAC must use test verified models and forcing functions to support Flight Readiness Reviews.

1.3 LOADS ANALYSIS DOCUMENTATION

Formal documentation of loads analysis results should, at a minimum, capture

a. major interface loads between systems,

b. a comparison of major interface loads and selected structural design loads with the analysis results of each load cycle,

c. a description of the analysis methodology and assumptions used in each loads cycle, and

d. descriptions of the integrated models and forcing functions used in the analysis, including model checkout results that validate the model for use in that loads cycle.

A good practice is to provide a configuration-managed math model database for version-controlled loads models and forcing functions used in critical structural loads development.

1.4 FREQUENCY SEPARATION

Good design practice for primary integrated structure design should be to ensure adequate frequency separation from the known significant forcing functions on the vehicle to avoid tuning. Hardware designer groups should interact closely with the loads and dynamics group to determine the primary frequencies to avoid.

Good design practice for the secondary structure is to design the secondary structure to be decoupled from the interfacing primary structure frequencies. A recommended practice is to use a secondary structure fundamental frequency of at least a factor of 1.5 times the fundamental interfacing primary structural frequencies. The fundamental interfacing primary structural frequencies are defined as modes below 50 Hz with modal effective mass (MEM) > 5 percent. The designer should interact closely with the loads and dynamics group (at the next higher level of integration) to determine these fundamental interfacing primary structural frequencies.

The Definition of Vehicle Dynamics Criteria section provides additional guidelines for design of components and secondary structure.

1.5 LIMIT LOADS

Flight hardware structures must be designed to meet their performance requirements when exposed to all limit static, transient, and random loads; pressure; and thermal effects for all phases of hardware service life, considering, when applicable, combined loading effects. Analysis should be performed for all anticipated loading events to establish limit loads. Input values/ranges of parameters for the loads analysis should be defined that produce loads that statistically meet the Program- or Project-mandated probability levels.

Recommended criteria for establishing limit loads are provided below:

a. Limit loads should be developed that encompass at least a 0.9987 probability of no exceedance, with 50-percent confidence, for time-consistent loads (i.e., P (limit load > flight load) $\geq$ 0.9987).

b. When time consistency is unknown, individual loading conditions (e.g. static aeroelastic, gust, buffet, and propulsion induced oscillations during ascent) should be combined to develop an event-consistent load. Event-consistent limit loads should encompass at least a 0.9987 probability of no exceedance, with 50-percent confidence. Event-consistency can be developed via loads combination equations, Monte Carlo, or other suitable methods.

c. Loads resulting from the application of environments or excitations that are considered to be random in nature should be developed that encompass at least a 0.9987 probability of no exceedance, with 50-percent confidence, by flight loads arising from such environments/excitations.

1.5.1 Integrated Loads

For vehicles, spacecraft, or modules/elements which may change configuration during a mission, all integrated configurations should be considered for integrated loads. For integrated vehicle flight, systems should be designed to maintain required functionality and positive margins for all induced loads and deformations, including dynamic interactions between mated stages or elements and thermal environments. Verification of integrated loads may be performed by integrated analysis and/or test.

1.5.2 Load Combination Restrictions

Guidelines for combining mechanical loads may be found in NASA-TM-X-73305, Astronautic Structures Manual.

1.5.3 Combining Low Frequency and Random Loads for Components and Attachments

The effects of low frequency transient loads and random vibration/acoustic loads should be combined in a rational manner to determine the total load environment. Programs and/or Projects typically define criteria for combining loads from these different sources. Time-consistent loads may also be considered in the final loads cycle.

Three basic types of flight environments generate dynamic loads on flight vehicle components:

a. Low-frequency dynamic response, typically from 0 to 50 Hertz (Hz), of the launch vehicle/spacecraft system to transient flight events.

b. High-frequency random vibration environment, which typically has significant energy in the frequency range from 20 Hz to 2000 Hz, transmitted from the launch vehicle to the spacecraft at the launch vehicle/spacecraft interfaces.

c. High frequency acoustic pressure environment, typically 31 Hz to 10,000 Hz, inside the launch vehicle or spacecraft compartment. The payload compartment acoustic pressure environment generates dynamic loads on components in two ways: (1) by direct impingement on the surfaces of exposed components, and (2) by the acoustic pressure impingement upon the component mounting structures, which induces random vibrations that are mechanically transmitted to the components.

Combinations of these loads occur at different times in flight and should be examined for each flight event. For components weighing less than 500 kg, the appropriate method of load combination is dependent on how the low frequency and the random vibration/acoustic design environments of the event are specified. Typically, the maximum levels are defined as requirements for a flight event, such as liftoff, even if these maxima do not necessarily occur at the same time. The relative timing of the transient and random vibration environments is unique for each launch vehicle, but simultaneous occurrence of maximum low frequency transient and maximum random vibration load is improbable. Therefore, an RSS approach is acceptable for combining the maximum low frequency and maximum random vibration loads for the liftoff flight event. When the low frequency transient and random vibration environments are specified in a time correlated manner, a time consistent approach is also acceptable for combining the low frequency transient loads and the random vibration loads.

Table 1.5.3-1 provides one recommended combination approach. V1, V2, and V3 represent the orthogonal directions of a coordinate reference frame for the component in question. The axes may or may not align with the vehicle reference frame. Care must be taken to ensure that the three combined load sources are appropriately defined with respect to the reference frame used.

TABLE 1.5.3-1 LOAD COMBINATION CRITERIA FOR COMPONENTS

Axis	**Steady State Load (Limit)**	**Low Frequency Transient Load[1,2]**	**Random Load[3]**
V_i	QS_i	$\pm S_i$	$\pm R_i$
Combined Loads: Loads in Each Axis Acting Simultaneously[4]			
Load Set	V_1 Axis	V_2 Axis	V_3 Axis
1	$QS_1 \pm (S_1^2 + R_1^2)^{1/2}$	$QS_2 \pm (S_2^2 + (R_2/3)^2)^{1/2}$	$QS_3 \pm (S_3^2 + (R_3/3)^2)^{1/2}$
2	$QS_1 \pm (S_1^2 + (R_1/3)^2)^{1/2}$	$QS_2 \pm (S_2^2 + R_2^2)^{1/2}$	$QS_3 \pm (S_3^2 + (R_3/3)^2)^{1/2}$
3	$QS_1 \pm (S_1^2 + (R_1/3)^2)^{1/2}$	$QS_2 \pm (S_2^2 + (R_2/3)^2)^{1/2}$	$QS_3 \pm (S_3^2 + R_3^2)^{1/2}$

NOTES:
1. Quasi-static portion removed
2. Based on three-sigma predictions and case-consistent, when available
3. Three-sigma Gaussian random load
4. The off-axis contribution of random vibro-acoustics in each load set may be eliminated with approval of the NASA Technical Authority. This approach will be limited to cases where sufficient rationale is developed to ensure statistical coverage of combined flight loads.

1.6 DEFINITION OF VEHICLE DYNAMICS CRITERIA

A vehicle dynamics criteria spectrum should be defined to cover the frequency range from 0.5 –50 Hz. The criteria may be a simplified envelope based on vehicle response from coupled loads assessments, evaluated using spectral lines spaced at a maximum of 1 Hz from 0–10 Hz and 1/6th octave from 10–50 Hz. Sine sweep vehicle dynamics test criteria should be defined for a frequency band from 5-40 Hz at a minimum.

The set of vehicle response data used to assess each vibration zone should include the following:

a. Vehicle centerline response for each station.

b. Base input response at secondary structure/vehicle interfaces and/or component/vehicle interfaces on the vehicle side of the interface for secondary structure/component subsystems that have a fundamental interfacing primary structural frequency less than or equal to 50 Hz. (For example, if an isolator is present with the secondary structure/component subsystem, then provide the response on the vehicle side of the isolator.)

An example of a good practice that meets or exceeds the guidelines above can include:

a. Process the transient response data using a shock response spectrum (SRS) analyzer with a dynamic amplification factor (Q) of 10.

b. Normalize the results (i.e., divide by Q).

c. Evaluate each SRS using the following spectral lines: 0.5, 0.6, 0.7, 0.8, 0.9, 1.0–50 Hz by 1 Hz.

d. Envelope the results for each vehicle equipment mounting zone.

e. Evaluate the uncertainties and add margin to envelopes, if necessary.

2.0 LOADS DEVELOPMENT METHODOLOGY

Loads should be developed for all phases of hardware service life. Some recommendations on methodologies for assessing the many load events and environments over the lifetime of a flight vehicle are provided in the following sections.

2.1 TRANSPORTATION AND GROUND HANDLING ENVIRONMENTS

"Transportation" in this context includes transportation of vehicle elements as well as transport of vehicle sub-assemblies, stages, spacecraft, or other major components. It does not include rollout from the vehicle integration facility to the launch pad.

Ground handling operations include loading flight articles in and out of trucks, onto railroad cars or barges and into cargo planes, installing and removing fight articles into test fixtures, and lifting them into place for integration with the launch vehicle. Ground handling also includes post-landing recovery and retrieval.

Loads induced during ground handling operations can typically be characterized with static loads and shock loads. Although the ground handling environment is relatively benign, special handling precautions are often taken if the damage potential is severe. Procedures should be developed to ensure that ground handling operations do not impart loads to the vehicle that exceed design load values. Loads imposed by the transportation and handling system may be predicted by one or more of the following analytical methods. NASA SP-8077, Transportation and Handling Loads, Prediction Methods for Transportation and Handling Loads section provides supplemental information of these approaches.

a. Limit load factors (constant "g") based on accumulated experience in transportation and handling are used as input to support points of the space vehicle.

b. Composite loads, synthesized from loads measured at the cargo load bed of the appropriate type of transport vehicle during previous shipments with many types of cargo, are used as forcing-function inputs to a mathematical model of the space vehicle and that portion of the transportation or handling system between the space vehicle and the transport vehicle cargo load bed.

c. Loads measured on a similar space vehicle during shipment or handling with the same or similar transportation or handling system are scaled or extrapolated to the space vehicle of interest by an analysis using mathematical models of both systems.

d. Loads from the environment external to the transportation or handling system are used as forcing-function inputs to a mathematical model of the space vehicle and its entire transportation or handling systems.

2.1.1 Transportation and Handling Load Factors

Flight hardware may be shipped by aircraft, trains or trucks, hoisted by cranes, moved by dolly, or transported by watercraft. Quasi-static load factors for preliminary design should developed to account for all relevant shipping events.

The Transportation and Handling Limit Load Factors table below provides representative limit load accelerations for element hardware of all sizes. However, for items that weigh less than 136.08 kg (300 lb) with no isolation system, additional assessment of accelerations caused by random vibration and acoustics for certain modes of transportation should be considered.

If the loads in the Transportation and Handling Limit Load Factors table exceed design limits for the flight hardware to be transported, special care must be taken to ensure that the transportation or handling equipment will in no way impose excessive loads on the flight hardware. During shipping, the hardware should be appropriately instrumented to assure that the transportation environment is enveloped by these load factors.

Limit loads for jacking and hoisting flight hardware should be based on the maximum gross weight of the vehicle. The vertical jacking load should be assumed to act singly and in combination with the longitudinal and lateral loads. The horizontal loads at the jack points are to be reacted by inertia forces to prevent any change in the vertical loads at the jack point.

Hoisting loads should be applied to the vehicle in any direction within 20 degrees of the axis in which the hoist operation will occur.

TABLE 2.1.1-1 TRANSPORTATION AND HANDLING LIMIT LOAD FACTORS

Transportation Mode	Load Occurrence[2,3]	Fore/Aft (g)	Lateral (g)	Vertical[1] (g)
Water Craft	S	±0.75	±1.0	+2.5, -0.5
NASA Barge (MAF to KSC)	S	±0.75	±1.0	+2.25, -0.25 [8]
NASA Barge (Inland Waterway)	S	±0.5	±0.5	+1.4, +0.6
Airplane[5]	S	±3.0	±1.5	+3.0, -1.0
Crash Landing[5]	I	+3.0, -1.5	±1.5	+4.5, -2.0
Ground:				
Truck or Air Ride Trailer	I	±2.0	±2.0	+3.0, -1.0
Rail (Humping)	S	±30.0	±5.0	±15.0
Rail (Normal Operation)	S	±3.0	±1.5	+3.0, -1.0
Dolly (Max Velocity, 2.24 m/s [5 mph])	I	±1.0	±0.75	+1.5, +0.5
Forklift	S	±1.0	±0.5	+2.0, 0.0
Hoist	S	0	0	+1.33[9]

NOTES:

1. Vertical (+) acceleration is up, vertical (-) acceleration is down. (+) acceleration means the force (barge deck, truck bed, etc.) is pushing up on the GSE and flight hardware. To properly apply these (+) load factors using Finite Element Analyses, the GSE/Flight Hardware is constrained at the barge/truck/train interface, and a gravity load equal to the (+) vertical load factor is applied down in the direction of gravity.
2. S = Loads occur simultaneously in each of the three directions.
3. I = Loads occur independently in each of the three directions. Except that gravity (vertical) is always +1G for fore/aft and lateral load cases.
4. Load factors are to be applied at logical center-of-gravity locations, including all mass in the load path, depending on what is being analyzed. The following is an example: an engine is being shipped in a container on a truck, and the engine is supported within the container by a support structure. Loads factors are applied at the engine and support structure Center of Gravity (CG) when analyzing the support structure to container interfaces. Load factors are applied to the engine/support structure/container CG when analyzing the container to truck interfaces.
5. Airplane load factors envelope the NASA Super Guppy and C17 operational loads. Crash loads are to be assessed independently in the three orthogonal directions except gravity; Vertical gravity load of 1.0g must be applied simultaneously with longitudinal and lateral crash loads. The crash load case is an ultimate load case and no additional factor of safety should be applied to these values when used to derive loads to be used in a stress analysis or to such derived loads when used in a stress analysis.
6. For ground transportation, the support structure/carrier vehicle should be designed for the occurrence of a 15.43 m/s (30-knot) wind in combination with the load factors. Others external loads may need to be considered.
6. Cargo must be restricted from sliding or tipping during transportations. Restraints must be capable of withstanding cargo loads show in this table.
7. Loads were modified for Michoud Assembly Facility (MAF) to Kennedy Space Center (KSC) trips based on review of data from instrumented NASA Barge trips.
9. KSC uses hoist factor of 1.0 for assessment of GSE, and hoist factor of 1.33 for assessment of flight hardware.
10. Provide, if possible, a determinate interface between the GSE and the Truck, Train, Barge, Etc. to prevent deflections from driving load into the flight hardware. If this is not possible, deflection loads must be fully assessed.
11. Values in this table are based on research/analysis performed by Marshall Space Flight Center in support of the Constellation Program and are documented in memo ER41(08-030). These values differ from and represent an update to similar data contained in NASA-SP-8077, Transportation and Handling Loads.

2.1.2 Vehicle Assembly at the Launch Site

Vehicle assembly loads should be enveloped by vehicle design loads. The loads analysis should include both static and dynamic analysis with max weight, alignment tolerances, gravity effects, and operationally-induced loads imparted during the assembly operation. If elements are assembled that are fueled, propellant slosh loads and weights must be taken into account during assembly. Load assessment techniques are similar to those described in the Transportation and Handling Load Factors section.

2.1.3 Spacecraft Transportation at the Launch Site

Loads induced due to the transfer of vehicle stages, spacecraft or major components around the launch site in preparation for or during assembly should be assessed to verify that they are enveloped by the design loads. Load assessment techniques are similar to those described in the Transportation and Handling Load Factors section.

2.2 ROLLOUT TO PAD

2.2.1 Launch Vehicle/Launch Platform Rollout Loads

A pathfinder rollout should be performed for each unique launch configuration to validate that rollout loads are enveloped by vehicle design loads and to provide data to support life assessments for vehicle and launcher hardware.

Launch vehicle/launch platform rollout loads calculations should include the following considerations, vehicle rollout speeds, maximum wind effects, wind direction, and Wind Induced Oscillations (WIOs) for all unique vehicle configurations and constraints. In addition to the static axial load due to the weight of the stack, changing gravity moments resulting from the motion of structure mass items during a dynamic event should be considered. If a structural tie-off or damper to a launch support structure is used to help withstand wind or other forces imposed on the vehicle for rollout, the loads at the vehicle attachments must be included in the determination of the total vehicle loads.

If a vehicle is fueled during rollout, the effect of propellant slosh must be included in the system load calculation. Propellant slosh loads should be accurately determined for individual tank and baffle elements and should include, at a minimum, the effects of the physical properties of the fluid, the fluid level, and acceleration. The dynamic response of the vehicles to liquid sloshing can be calculated if an equivalent mechanical system is used to represent the liquid dynamics. Such mechanical systems are composed of fixed masses and oscillating masses connected to the tank by springs and dashpots or pendulums and dashpots, designed so that they have the same resultant pressure force, moment, damping, and frequency as the actual system.

The rollout loads assessment should also include emergency braking and turning, if applicable. The only dynamics in the problem are associated with the rise rate of applying or releasing the brakes. For turning, a rotational rate and centripetal acceleration appropriate to the means of transporting the vehicle should be included in the loads assessment.

2.2.2 Ground Wind Loads During Rollout

For each unique launch configuration, ground wind velocity and direction constraints for rollout should be developed and assessed. Ground wind speeds for rollout should be defined per Program-/Project-specific requirements. Wind directions should be considered at a minimum of every 30 degrees clocking, including the worst-case azimuth based on vehicle configuration. In addition to ground wind velocities, gusts, vortex shedding and local shielding, and amplifying effects of support structure or tower and umbilicals should be included in the loads assessment.

Ground wind effects are difficult to quantify. Subscale ground wind testing should be performed for each unique launch configuration, including significant launch pad structure and any dampers used to attenuate ground wind loads, and surrounding terrain. Such tests would validate that predicted ground wind loads represent enveloping design loads. The criteria for combining the vortex-shedding induced loads with the ground wind loads should also be developed based on this testing.

2.2.2.1 Steady-State Wind and Gust Loads

Appropriate combinations of steady-state wind, spectral turbulence/gust environments, and discrete (1-minus-cosine) gust environments should be considered.

2.2.2.2 Vortex Shedding or Wind Induced Oscillation (WIO) Loads

Vortex shedding or WIO effects can be represented by several methods:

2.2.2.2.1 Static Preliminary Design Analysis

a. Per NASA SP-8008, Prelaunch Ground Wind Loads, a combined wind and WIO load can be represented by a 1.5 factor on static ground wind forces applied as a single-direction load. These wind forces should be derived from the appropriate peak winds per Program/Project requirements for ground wind environments. These forces are applied along several possible clocking directions per the Ground Wind Loads During Rollout section. A drag coefficient of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test.

b. Alternately, the static peak wind forces with a 1.0 factor can be combined with a perpendicular static force equal to the static peak wind forces with a 1.5 factor. These wind forces should be derived from the appropriate peak winds per Program/Project requirements for ground wind environments. The force combinations should be applied along several possible clocking directions per the Ground Wind Loads During Rollout section. A drag coefficient for the longitudinal, or along wind, direction of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test. A lift coefficient for the lateral direction, or perpendicular wind, of 0.75 for single cylinder or 1.125 for multi-cylinder vehicles should be used unless more appropriate values are available from test.

2.2.2.2.2 Dynamic Preliminary Design Analysis

The following method should be used for preliminary design analyses, such as liftoff or initial stabilizer design, where dynamics are important. The longitudinal, or along, wind should be modeled as a static peak wind force with a 1.0 factor. The perpendicular WIO wind should be modeled as a 1-cosine wave with the peak-to-peak amplitude equal to the static peak wind forces with a 1.5 factor. The wavelength of the cosine wave should be tuned to the first cantilevered bending frequencies of the vehicle on the pad. For liftoff analyses, this wave should be timed such that the release occurs at either the maximum vehicle tip deflection or the maximum vehicle tip velocity. At release, the perpendicular WIO force is removed, while the longitudinal wind force continues.

These wind forces should be derived from the appropriate peak winds per Program/Project requirements for ground wind environments. These force combinations are applied along several possible clocking directions per the Ground Winds at Lift-off section. A drag coefficient for the longitudinal, or along wind, direction of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test. A lift coefficient for the lateral direction, or perpendicular wind, of 0.75 for single cylinder or 1.125 for multi-cylinder vehicles should be used unless more appropriate values are available from test.

2.2.2.2.3 Post-PDR Design Analysis

A lateral dynamic force should be combined with a longitudinal main wind direction steady state force. The lateral force should be a lateral WIO force predicted using rigorous load/structure interaction dynamics analysis methodology, tools, and test data, when available. These wind forces should be derived from the appropriate steady-state winds per Program/Project requirements for ground winds. Vortex shedding frequency lock-in with structural frequencies should be evaluated for the first four bending frequencies in any given direction of the vehicle on the pad.

These force combinations should be applied along several possible clocking directions per the Ground Winds at Lift-off section. A drag coefficient for the longitudinal, or along wind, direction of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test. A lift coefficient for the lateral direction, or perpendicular wind, of 0.6 for single cylinder or 0.9 for multi-cylinder vehicles should be used until more appropriate values are available from test.

2.2.2.3 Umbilical Loads

Loads induced on the launch vehicle due to the launch pad umbilicals and loads on the umbilicals should be developed by analysis supported by wind tunnel testing. Each unique launch configuration should be considered. The analysis should include the effects of umbilical configuration, method of attachment, method of disconnect, feed-line pressures, and wind loads.

2.2.2.4 Stabilization/Damper System Loads

Loads induced on the launch vehicle due to the stabilization/damper configuration, method of attachment, and method of disconnect should be developed by analysis.

2.2.2.5 Crew Access Arm Loads

Loads induced on the launch vehicle due to the crew access arm and loads on the crew access arm should be developed by analysis.

2.2.2.6 Ground Wind Fatigue Spectra

Ground wind fatigue load spectra should be developed for each unique launch configuration using the peak ground wind speed and frequency of occurrence probability distributions as provided in Program/Project requirements for ground winds environments. From these data, mean wind speed and gust values should be estimated and used to generate fatigue spectra loads. Wind induced oscillation must be included in the loads spectra, if significant.

2.3 LAUNCH PAD OPERATIONS

Vehicle and launch support structure loads arising during the period in which the vehicle is on the launch pad prior to launch must be evaluated. Loads can be induced on the stack and pad by natural environments such as seismic activity and ground winds and by pre-launch operations such as loading of cryogenic liquid commodities for the propulsion system and engine hot-fire tests.

2.3.1 Seismic Loads During Pre-launch

Depending on the location of the launch facility, earthquakes may be an important consideration. Although the probability is very small that an earthquake with a potentially damaging magnitude will occur during the relatively short time interval between the installation of a space vehicle on the launch pad and its launch, the possibility of such an occurrence must be considered. Of primary concern are the lateral loads that would be introduced at the base of the space vehicle by seismic induced horizontal motions of the launch pad, as well as those loads applied to a variety of ground support equipment and flight elements prior to launch, e.g., vehicle hardware in nearby storage.

If the launch pad is supported by a hard rock site, a conventional dynamic analysis of the vehicle on its pad may be performed to determine vehicle loads and deflections during an earthquake. However, if a softer site is utilized, soil-structure interaction must be considered. Soft soil supporting the pad can be expected to permit an excess of translational and especially rotational motion at the pad/vehicle interface, causing a reduction of the system natural frequencies, an increase in the relative displacements between vehicle and elements of the launch support structure, and sometimes an increase in the vehicle loads. On the other hand, system damping is greatly increased due to the response-induced generation of seismic waves back into the soil.

2.3.2 Static Launch Vehicle/Pad Pre-loads

For each unique launch configuration, static hold-down loads due to any constraint device must be developed, if applicable. If a structural tie-off or damper to a launch support structure is used to help withstand wind or other forces imposed on the vehicle for rollout, the loads at the vehicle attachments must be included in the determination of the total vehicle loads.

2.3.3 Pre-Launch Ground Wind Loads at the Launch Pad

Static and dynamic loads resulting from winds and gusts (and resultant vortex shedding) during pre-launch should be analyzed. Loads assessments should include, at a minimum, the effects of

a. the forward profile shape for the vehicle (e.g., vehicle nose);

b. vehicle mass, stiffness, propellant loads, and tank pressurization conditions;

c. protuberances and surface roughness;

d. proximity and shapes of umbilical masts; and

e. other large structures.

The resultant elastic vehicle static and dynamic loads should be obtained by suitable combination of the turbulence loads and steady loads, together with the periodic vortex-shedding loads calculated from the peak wind profile.

For each unique launch configuration, ground wind velocity and direction constraints for pre-launch operations at the launch pad should be developed and assessed. Ground wind speeds for pre-launch should be defined per Program-/Project-specific requirements. Wind directions should be considered at a minimum of every 30 degrees clocking, including the worst-case azimuth based on vehicle configuration. In addition to ground wind velocities, gusts, vortex shedding, and local shielding and amplifying effects of support structure or tower and umbilicals should be included in the loads assessment.

Ground wind effects are difficult to quantify. Subscale ground wind testing should be performed for each unique launch configuration, including significant launch pad structure and any dampers used to attenuate ground wind loads, and surrounding terrain to validate that predicted ground wind loads represent enveloping design loads. The criteria for combining the vortex-shedding induced loads with the ground wind loads should also be developed based on this testing.

2.3.3.1 Steady-State Wind and Gust Loads

Appropriate combinations of steady-state wind, spectral turbulence/gust environments, and discrete (1-minus-cosine) gust environments should be considered.

2.3.3.2 Vortex Shedding or Wind Induced Oscillation (WIO) Loads

Vortex shedding or WIO effects can be represented by several methods:

2.3.3.2.1 Static Preliminary Design Analysis

a. Per NASA SP-8008, Prelaunch Ground Wind Loads, a combined wind and WIO load can be represented by a 1.5 factor on static ground wind forces applied as a single-direction load. These wind forces should be derived from the appropriate peak winds per Program/Project requirements for ground wind environments. These forces are applied along several possible clocking directions per the Pre-Launch Ground Wind Loads at the Launch Pad section. A drag coefficient of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test.

b. Alternately, the static peak wind forces with a 1.0 factor can be combined with a perpendicular static force equal to the static peak wind forces with a 1.5 factor. These wind forces should be derived from the appropriate peak winds per Program/Project requirements for ground wind environments. The force combinations are applied along several possible clocking directions per the Pre-Launch Ground Wind Loads at the Launch Pad section. A drag coefficient for the longitudinal, or along wind, direction of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test. A lift coefficient for the lateral direction, or perpendicular wind, of 0.75 for single cylinder or 1.125 for multi-cylinder vehicles should be used unless more appropriate values are available from test.

2.3.3.2.2 Dynamic Preliminary Design Analysis

The following method should be used for preliminary design analyses, such as liftoff or initial stabilizer design, where dynamics are important. The longitudinal, or along, wind should be modeled as a static peak wind force with a 1.0 factor. The perpendicular WIO wind should be modeled as a 1-cosine wave with the peak-to-peak amplitude equal to the static peak wind forces with a 1.5 factor. The wavelength of the cosine wave should be tuned to the first cantilevered bending frequencies of the vehicle on the pad. For liftoff analyses, this wave should be timed such that the release occurs at either the maximum vehicle tip deflection or the maximum vehicle tip velocity. At release, the perpendicular WIO force is removed, while the longitudinal wind force continues.

These wind forces should be derived from the appropriate peak winds per Program/Project requirements for ground wind environments. These force combinations are applied along several possible clocking directions per the Ground Winds at Lift-off section. A drag coefficient for the longitudinal, or along wind, direction of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test. A lift coefficient for the lateral direction, or perpendicular wind, of 0.75 for single cylinder or 1.125 for multi-cylinder vehicles should be used unless more appropriate values are available from test.

2.3.3.2.3 Post-PDR Design Analysis

A lateral dynamic force should be combined with a longitudinal main wind direction steady state force. The lateral force should be a lateral WIO force predicted using rigorous load-structure interaction dynamics analysis methodology, tools, and test data when available. These wind forces should be derived from the appropriate steady-state winds per Program/Project requirements for ground winds. Vortex shedding frequency lock-in with structural frequencies should be evaluated for the first four bending frequencies in any given direction of the vehicle on the pad.

These force combinations should be applied along several possible clocking directions per the Pre-Launch Ground Wind Loads at the Launch Pad section. A drag coefficient for the longitudinal, or along wind, direction of 1.0 for single cylinder or 1.5 for multi-cylinder vehicles should be used unless more appropriate values are available from test. A lift coefficient for the lateral direction, or perpendicular wind, of 0.6 for single cylinder or 0.9 for multi-cylinder vehicles should be used until more appropriate values are available from test.

2.3.3.3 Umbilical Loads

Loads induced on the launch vehicle due to the launch pad umbilicals and loads on the umbilicals should be developed by analysis supported by wind tunnel testing. Each unique launch configuration should be considered. The analysis should include the effects of umbilical configuration, method of attachment, method of disconnect, feed-line pressures, and wind loads.

2.3.3.4 Stabilization/Damper System Loads

Loads induced on the launch vehicle due the stabilization/damper configuration, method of attachment, and method of disconnect should be developed by analysis. The analysis should make use of test-validated models accounting for the dynamics of those T-0 devices (e.g., speed of retraction, separation path, etc.).

2.3.3.5 Crew Access Arm Loads

Loads induced on the launch vehicle due to the crew access arm (CAA) and loads on the CAA should be developed by analysis. The analysis should use a test-correlated model of the CAA that accurately represents the CAA/vehicle physical attachment points, as well as forcing functions representing the effect of ground personnel and crewmembers walking inside the white room.

2.3.3.6 Ground Wind Fatigue Spectra

Ground wind fatigue load spectra should be developed for each unique launch configuration using the peak ground wind speed and frequency of occurrence probability distributions as provided in Program/Project requirements for ground winds environments. From these data, mean wind speed and gust values should be estimated and used to generate fatigue spectra loads. Wind induced oscillation must be included in the loads spectra, if significant.

2.3.4 Tanking-Induced Loads

Effects of loads due to filling of all liquid-fueled stages should be evaluated. Tank pressurization conditions should account for the venting system characteristics, including valve tolerances and setting for design ullage and vent pressure.

2.3.4.1 Operational Tanking Scenarios

Propellant mass, tank pressures, and temperatures can vary substantially during the tanking procedures. All possible tanking scenarios and partial fill conditions should be evaluated.

2.3.4.2 Cryogenic Shrinkage

Tanking loads due to cryogenic propellant must be included in the loads assessment. Cryogenic shrinkage occurs when the tanks are fueled and a thermal gradient is induced. The tanks contract and static preloads can be induced in all areas of the vehicle.

2.3.5 Ground-test Firing Loads

Loads induced on the launch vehicle during any ground test firing conducted at the launch pad should be considered.

2.3.5.1 Ignition Overpressure

Analysis, supported by ground and flight testing of each unique launch vehicle/payload and launch platform, pad, and surrounding area configuration, should be performed to determine ignition overpressure loads. Effects of any measures taken to mitigate ignition overpressure (e.g., water sound-suppression systems) should also be taken into account.

2.3.5.2 Thrust Buildup and Shutdown

Loads arising from engine thrust buildup and decay should be analyzed. Analysis should include the effects of deviations in engine start time in multi-engine configurations, unsymmetrical side loads on the engine nozzle(s), and engine rotations due to local deflections. Effects of engine-out or hard-over conditions should also be considered. Effects of ground winds (steady winds, gusts, turbulence, WIO) as described in the Pre-Launch Ground Wind Loads at the Launch Pad section must also be included.

2.4 LIFTOFF

2.4.1 Ignition Overpressure

Analysis, supported by ground and flight testing of each unique launch vehicle/payload and launch platform, pad, and surrounding area configuration, should be performed to determine ignition overpressure loads. Effects of any measures taken to mitigate ignition overpressure (e.g., water sound-suppression systems) should also be taken into account.

2.4.2 Thrust Buildup and Shutdown

First stage ignition transient loads should be developed and incorporated into the vehicle design. If solid motors are used, effects of first stage pressurization should be included, as well. The ignition transient loads analysis should evaluate both nominal and dispersed thrust performance and include effects of thrust vectoring and thrust misalignments. Multi-engine ignition sequencing, thrust buildup, and emergency shutdown transient loads should be developed and incorporated into the vehicle design. Effects of engine-out or hard-over conditions should also be taken into account.

2.4.3 Thrust Oscillations

Loads due to thrust oscillation during liftoff should be assessed for all vehicle configurations based on analysis and test data. Characterizations of the variation of thrust amplitudes with oscillations frequency should be obtained from motor test or flight performance data and evaluated to determine bounding vehicle loads responses.

2.4.4 Ground Winds at Lift-off

Static and dynamic loads from winds and gusts (and resultant vortex shedding) during liftoff should be analyzed. The liftoff ground wind environment should be defined per Program-/Project-specific requirements. Ground wind loads should be developed for each unique launch configuration. Wind directions should be considered at a minimum of every 30 degrees clocking, including the worst-case azimuth based on vehicle configuration. In addition to pad ground wind velocities, gusts, and vortex shedding induced loads should be included in the loads assessment.

Loads assessment should include but should not be limited to

a. the forward profile shape of the vehicle;

b. vehicle mass, stiffness, propellant loadings, and tank pressurization conditions;

c. protuberances and surface roughness;

d. proximity and shapes of umbilical masts; and

e. other large structures.

The resultant elastic vehicle static and dynamic loads should be obtained by suitable combination of the turbulence loads and steady loads, together with the periodic vortex-shedding loads calculated from the peak wind profile.

2.4.5 Lift-off Vortex Shedding

For each unique launch configuration, the effects of vortex shedding should be included in the ground wind loads calculation for the liftoff transient.

2.4.6 Pad Separation

For each unique launch configuration, the timing of the first stage engine(s) start-up and pad hold-down release, including uncertainties, must be developed.

The transient load (twang) caused by the launch vehicle separation from the pad should be determined by analysis for each launch configuration. Vehicle-to-pad re-contact loads must be considered, if applicable.

Depending on hold-down device design, stud hang-ups may be a credible failure. If the probability of occurrence is significantly large, stud hang-ups must be analyzed and incorporated into the design of each launch configuration.

Stud hang-ups are a credible failure that must be developed by analysis and incorporated into the design of each launch configuration if the probability of occurrence is greater than 0.0013. Shuttle stud hang-ups occur when the hold-down bolt shanks which attach the solid rocket booster aft skirt to the launch pad do not retract completely and do not permit a clean separation of the aft skirt and pad. Stud hang-ups can induce loads on the vehicle at pad separation.

2.4.6.1 Pyrotechnic Shock Loads

Pyrotechnic shock loads occurring during separation of the launch vehicle from the pad should be determined by component testing and analysis and the range of influence of the pyrotechnic shock environment should be ascertained. Sensitive components within the range of the shock event must be assessed for this environment.

2.4.6.2 Umbilical Separation

Any transient loads due to the separation of the umbilicals between the launch vehicle and the Mobile Launcher should be determined by analysis and included in the vehicle design.

2.4.7 Lift-off Transient Elastic Body Response

For the time period after liftoff, where the forces of ignition overpressure and ground winds, including the effects of vortex shedding, are applied to the launch vehicle, the elastic body response of each unique launch vehicle configuration should be determined by analysis. "Twang" due to release of stored elastic strain energy must be included in the analysis. Flight data may be used to validate the analytical predictions.

2.4.8 Lift-off External Acoustic Noise

The launch acoustic environment for each pad and vehicle configuration should be defined based on test data, subscale testing, and analysis of the pad and vehicle geometry. The predicted environment should then be compared with flight data subsequent to the first launch and refined, if necessary, as operational experience is gained. The vehicle and pad structures should be assessed for the loads induced by the acoustic environment.

2.4.9 Lift-off Random Vibration

The structure-borne random vibration and the acoustic environment at liftoff should be analyzed to determine the total random vibration environment to which both the launch vehicle and spacecraft/payload will be subjected. Each unique launch configuration should be analyzed.

2.4.10 Maneuvers

Loads induced by any roll heading or pad clearance (flyaway) maneuver performed during the transient liftoff event should be analyzed. Effects of thrust vector control and thrust misalignment should be included in the analysis.

2.4.11 Thrust Misalignment

The bounds of the total thrust vector misalignment should be established considering all motors and engines. Nozzle cant due to pressurization must be included in the analysis. A design solution that mitigates the nozzle cant effect is desirable. Loads due to the maximum predicted thrust misalignment should be developed by analysis supported by ground and flight testing. Loads should be developed for each unique launch vehicle first stage configuration.

2.4.12 Vehicle Quasi-Static Accelerations

Loads due to launch vehicle quasi-static accelerations should be developed for each unique launch configuration by analysis supported by ground and flight testing.

2.4.13 Venting

Venting loads should be considered for all launch vehicle volumes that execute a venting function during liftoff.

2.4.14 Pogo Dynamics

Pogo dynamics should be assessed by the appropriate combined Loads and Dynamics (L&D) and propulsion system team to determine if a pogo situation exists. If there is a potential for pogo, then this cross-discipline team must work with the other vehicle elements to mitigate the pogo phenomenon.

Consideration of all contributing factors is required for proper conduct of a pogo stability analysis. Since pogo is a self-excited phenomenon and the variation of response with frequency is highly non-linear, protection for modeling uncertainties relative to actual flight hardware characteristics must be maintained. Coupling of the flight vehicle structure with the liquid-propulsion system should be evaluated with the aid of a mathematical model that incorporates physical characteristics determined by experiment, where possible, and accounts for the following:

a. Elastic-mode coupling of the vehicle structure, propellant feedlines, and tank-fluid system.

b. Engine characteristics, including engine mounting flexibility, turbopump transfer functions, cavitation characteristics, and propellant flow rates.

c. Delivery-system characteristics, including flexible supports, accumulators, pressure-volume compensators, fluid or gas injection, fluid damping, and flow resistances.

Furthermore, vehicle structural dynamics vary over the course of the ascent flight profile. Coupling between propulsion system element frequencies and vehicle modes may occur at any point during ascent if propulsion system and body elastic modes converge. Therefore, the likelihood of pogo must be evaluated over the entire ascent and stability analysis should be performed for using mathematical models which cover the entire rocket-powered flight regime.

2.4.15 Over-Turning Moment (OTM)

The second order effect of Over-Turning Moment (OTM) must be included, if significant.

2.5 ASCENT

Ascent is defined as the period from initial pad separation to spacecraft or spacecraft plus upper stage separation. Ascent loads analysis should include, but should not be limited to, the effects of wind and gust loads at various altitudes, Static Aeroelastic (STEL) effects, trajectory variations (thrust dispersions, wind variations, vehicle weight variations, etc), thrust oscillations and misalignment; variations in aerodynamics (Mach, α, β, $C_{D,}$ etc.), buffet, and venting.

Ascent loads should also be determined for at least the following trajectory conditions:

a. Several points in the transonic-speed regime (0.8 < Mach < 1.2), including the point at which the free-stream Mach number is 1.0

b. Points of Maximum Dynamic Pressure (Max Q)

c. Points of maximum longitudinal acceleration and deceleration

d. Point(s) at which the product of the dynamic pressure and angle of attack is a maximum

e. Points where centers of pressure are at extreme locations

f. Points of maximum heating rate

g. Points of maximum temperature

h. Points of maximum and minimum inertial loading

i. Points of maximum differential pressure across the structure

j. At least one subsonic point (Mach < 0.8) below the transonic regime

k. Points of maximum and minimum pressure on compression and expansion surfaces

l. Points of maximum fluctuating pressure

m. Points of Maximum Combined Steady State and Thrust Oscillation Loading

Ascent loads must also address the applicable aborts.

Variations in dynamic model axial mode frequencies and uncertainties in damping of longitudinal modes must be included in the ascent loads assessment.

2.5.1 Wind and Gust Criteria

The shear buildup and gust methodology should include the analysis of each criterion separately, with their results combined in some rational manner. The equation

$$\text{ASCENT LOADS} = 1\ \text{STEL} + 1/3\ \text{GUST} + 0.335\ \text{BUFFET} + \text{MEAN TO} + \sqrt{(2/3\ \text{Gust})^2 + (0.665\ \text{Buffet})^2 + (\text{TO} - \text{Mean TO})^2}$$

represents one technique for achieving this combination. Note that this equation also accounts combines loads from buffet and thrust oscillation.

The shear buildup should be derived based on Monte Carlo ascent simulations using the Global Reference Atmospheric Model (GRAM), or other appropriate representation, which creates wind profiles for each case. Flight of the vehicle through these wind profiles should be simulated and static aeroelastic loads should be calculated for selected worst-case conditions. The gust analysis should include tuning gusts at various altitudes. In addition, a discrete (1-minus-cosine) gust environment should be considered.

2.5.1.1 Wind Persistence

The change in the ascent winds steady state, shears, and gusts should be included in the vehicle ascent loads predictions. Each unique vehicle configuration should be considered.

2.5.2 Static Aeroelastic Effects

Integrated dynamic analysis of ascent flight should be performed for each unique vehicle configuration to determine the contribution Static Aeroelastic (STEL) effects to ascent loads. STEL effects should be determined for selected points of the worst-case conditions from the Monte Carlo ascent simulations.

2.5.3 Aerodynamic Flutter- and Divergence-Induced Loads

Flutter- and divergence-induced phenomena should be considered. Flutter and divergence analyses should include all significant degrees of freedom, such as symmetric and anti-symmetric bending, torsion, and body bending and torsion. The preferred formulation of flutter analyses is to utilize vibration modes and frequencies, although a formulation using aerodynamic and structural influence coefficients is acceptable. Vibration modes can be either coupled modes or uncoupled or assumed modes. If uncoupled or assumed modes or an influence coefficient approach is used, the coupled vibration modes and frequencies at zero airspeed should be calculated from the flutter equations for correlation with measured modes and frequencies.

2.5.4 Ascent Acoustic Noise

For each unique vehicle configuration, the ascent acoustic noise environment should be determined by wind tunnel testing and extrapolation of data for similar Outer Mold Lines (OMLs) and supplemented by flight data. Ascent acoustic loads should be developed considering dispersions in the trajectory, atmosphere, and vehicle control system and for combinations of dynamic pressure, angle of attack and sideslip angle. The vehicle structure and systems should be assessed to this environment, which includes the effects of dispersions.

2.5.5 Venting

Venting loads must be considered for intertank and interstage volumes for each unique vehicle configuration during ascent. All compartments should be analyzed for proper venting. The venting model should be defined as to the connectivity between compartments and between compartments and vents. As a minimum, the following should be developed in an analysis:

a. The external flow field and its pressure, temperature and velocity over the vehicle surface.

b. Expected flight profiles and associated dispersions, with their resulting variations in Mach number, dynamic pressure, angle of attack and sideslip angle.

c. Characteristics and quantity of all internally produced gases (e.g., from venting of instrument compartments, reaction gases, outgassing of solid materials, from leaks and controlled venting of pressurized containers, and from propellant draining).

d. The flow characteristics of the compartment vents, including interactions between the external flow field and the vented fluid.

e. Ingesting of external atmosphere, including leakages through unplanned vents, such as joints, gaps, and seams, which may be aggravated by the influence of static or dynamic loads or heating.

f. Heat transfer into and within the fluid of the compartment.

g. Vent geometry (including effective discharge coefficient) and free volumes of the applicable regions.

2.5.6 Ascent Random Vibration

Random vibration environments during ascent should be determined by analysis using external aeroacoustic pressures that have been validated by wind tunnel testing, supplemented by analysis and flight data. Random load components occurring simultaneously with deterministic load components can be a significant contributor to the total loads. An acceptable method for developing internal component random vibration environments involves performing base drive analysis using nodal accelerations for transient events of interest from the launch vehicle dynamic model and combining the results with the higher frequency components of acceleration derived from the acoustic environment.

2.5.7 Ascent Aerobuffeting

Aerobuffeting environments may be derived based on wind tunnel test data and Computational Fluid Dynamics (CFD) analysis supplemented by flight test data. During preliminary design, historical data from previous launch vehicles can be used until test data or CFD analysis become available.

2.5.8 Ascent Aerodynamic Shock Loading

Aerodynamic shock loading environments should be determined by wind tunnel test data supplemented by CFD analysis and flight data. During preliminary design, historical data from previous launch vehicles can be used until test data or CFD analysis become available.

2.5.9 Steady-State Aerodynamic Loads

Steady-state aerodynamic loads should be developed considering dispersions in the trajectory; atmosphere and launch vehicle control system, and combinations of dynamic pressure, angle of attack, and sideslip angle.

2.5.10 Ascent Aerothermal Loading

Ascent aerothermal environments should be developed for the entire ascent profile and provided to the system developers for assessment of any thermally-induced loading effects on their hardware.

2.5.11 Stage Separation

Accelerations due to stage separation should be developed by analysis supplemented by flight test data. Events such as thrust tail off and termination, retrograde motor firings, separation devices, aero loads, thrust misalignments, fluid slosh, exhaust plume impingement from separation motors, and transient loads due to the removal of attach forces must be considered. In the absence of rational analyses of such effects, design factors may be chosen in a conservative manner and imposed on the corresponding loads.

2.5.12 Fairing Separation

Loads and accelerations produced during separation of vehicle fairings or shrouds should be evaluated. Loads induced by operation of separation devices and separation dynamics must be considered. Post-separation relative motion of the fairings/shrouds should be analyzed to evaluate and preclude the possibility for re-contact with the vehicle

2.5.13 Pyrotechnic Shock

Pyrotechnic shock loads due to separation of the ascent vehicle stages or jettison of fairings during ascent should be determined by component testing and analysis and the range of influence of the pyrotechnic shock environment should be ascertained. Sensitive components within the range of the shock event must be assessed for this environment.

2.5.14 Slosh

An assessment should be performed to determine that liquid slosh effects are mitigated by the design of all vehicle elements. Low frequency accelerations due to the liquid slosh should be determined for use for flight control system analyses. This assessment must also show that liquid slosh loads are not a significant contribution to the overall vehicle loads.

Propellant slosh loads should be accurately determined for individual tank and baffle elements. The lateral sloshing of liquid propellant in a tank results in a distributed pressure loading on the walls. Determination of the magnitude and frequency of propellant sloshing and of forces and moments acting on the vehicle must consider the following parameters:

a. Tank geometry

b. Propellant properties

c. Effective damping

d. Height of propellant in the tank

e. Acceleration field

f. Perturbing motion of the tank

The dynamic response of the vehicle(s) to liquid sloshing can be calculated if an equivalent mechanical system is used to represent the liquid dynamics. Such systems may include fixed masses and oscillating masses connected to the tank by springs and dashpots or pendulums, designed so that they have the same resultant pressure force, moment, damping and frequency of the actual system. A factor may be used to represent the effect of tank baffles on slosh. This factor may be determined from subsystem analyses or testing.

2.5.15 Reaction Control System Operation

Loads produced by operation of Reaction Control System (RCS) thrusters in roll control or any other capacity should be developed by analysis supported by engine thrust and flight test data.

2.5.16 Thrust Loads

Thrust loads for all vehicle configurations and number and type of motors and/or engines used during ascent must be developed based on analysis, ground testing, and flight data.

2.5.17 Thrust Misalignment

The bounds of the total thrust vector misalignment should be established considering all engines. Loads due to the maximum predicted thrust misalignment should be developed for each unique ascent vehicle stage configuration by analysis supported by ground and flight testing.

2.5.18 Engine Gimbal Effects

The variation in the thrust vector direction over the full range of engine gimbal motion and accuracy of the flight control system should be taken into account when developing the ascent loads.

2.5.19 Thrust Gimbal Hard-Over

If deemed a credible failure for the launch vehicle, loads due to a engine gimbal hard-over conditions should be developed by analysis and considered.

2.5.20 Engine-out Conditions

Effects on vehicle loads due to engine-out conditions for multi-engine configurations should be taken in to account in developing ascent loads.

2.5.21 Crew Escape System Jettison

Loads produced by nominal jettison of any crew escape system must be analyzed. The pyrotechnic shock environment induced by the separation system and any plume impingement from the jettison motors should be taken into account.

2.5.22 Environments for Spacecraft Cargo

The ascent acceleration environment, the internal interface loads, the random vibration environments, the shock environment, and the ballast requirements should be defined for any cargo carried by the spacecraft. In some cases, unique coupled, system level analyses may be required to derive environments for cargo.

2.5.23 Thrust Oscillation

An analysis should be performed to develop the loads induced by thrust oscillations for each unique ascent configuration. Characterizations of the variation of thrust amplitudes with oscillations frequency should be obtained from engine test or flight performance data and evaluated to determine bounding vehicle loads responses.

2.5.24 Vehicle Quasi-Static Accelerations

Loads due to launch vehicle quasi-static accelerations should be developed for each unique ascent configuration by analysis supported by ground and flight testing.

2.5.25 Separation Motors

Where separation motors are used to separate ascent vehicle components, the loads due to ignition and thrust of these motors should be developed by analysis supported by ground and flight test data and accounted for in the vehicle design.

2.5.26 Ullage-Induced Loads

Any contribution to loads due to the presence of propellant ullage should be developed by analysis and accounted for in the vehicle design.

2.5.27 Ignition Transient and Thrust Buildup

Loads due to ignition transients and thrust buildup due to vehicle stage engines that are started in-flight should be developed by analysis for the defined range of propellant loading, at all possible starts and cutoffs, supported by ground and flight test data and should be accounted for in the vehicle design.

2.5.28 Plume Loads Between Separated Stages

Loads due to the interaction of engine exhaust plumes between separated stages in-flight should be developed by analysis, supported by ground and flight test data, and accounted for in the vehicle design.

2.5.29 Self-Induced Mechanical Vibration

Any loads due to propulsion self-induced mechanical vibration that must be addressed should be developed by analysis based on ground testing and flight data. Pogo and flutter are two examples of self-induced vibration.

2.6 LAUNCH/ASCENT ABORTS

Each Program should define the abort scenarios for loads assessment. The launch vehicle developer should provide both loads up to the point of spacecraft separation and the initial conditions at spacecraft separation for each scenario. The spacecraft developer should develop loads for operations during and after separation. Typically, aborts will be initiated based on an exceedance of a pre-set value of critical vehicle parameters (i.e., attitude rates and attitude errors).

2.6.1 Pad Abort

Loads for the launch vehicle, spacecraft, and launch abort system (LAS) should be developed for pad abort scenarios based on the initial conditions at the initiation of the abort, the abort trajectory (including the effects of dispersions), the characteristics of the abort motor, and the configuration of the hardware. Analyses to develop pad abort loads should use the system dynamic math models, abort trajectories, human g-load limits, and the characteristics of the landing deceleration system. Blast overpressure resulting from possible launch vehicle catastrophic failure should also be assessed.

2.6.2 Liftoff Abort

Loads for the launch vehicle, spacecraft, and LAS should be developed for liftoff abort scenarios based on the initial conditions at the initiation of the abort, the abort trajectory (including the effects of dispersions), the characteristics of the abort motor, and the configuration of the hardware. Analyses to develop pad abort loads should use the system dynamic math models, abort trajectories, human g-load limits, and the characteristics of the landing deceleration system. Launch vehicle engine-out and engine gimbal failure cases, including Failure in Place (FIP), Hardover (HO), and Failure to Null (FTN) should be included in the loads assessment.

2.6.3 Ascent Abort

Loads for the launch vehicle, spacecraft, and LAS should be developed for ascent aborts based on the initial conditions at the initiation of the abort, the abort trajectory (including the effects of dispersions), the characteristics of the abort motor, and the configuration of the hardware. Analyses to develop pad abort loads should use the system dynamic math models, abort trajectories, human g-load limits, and the characteristics of the landing deceleration system. Launch vehicle engine-out and engine gimbal failure cases including, FIP, HO and FTN should also be included in the loads assessment.

2.6.3.1 Recommended Assessment Approach

To assess LAS ascent abort loads, the following procedure is recommended:

a. Use a minimum of 2,000 ascent trajectories for determining initial conditions for loads.

b. Include cases that are consistent with the load limits provided by loads team to the Guidance, Navigation, and Control (GN&C).

c. For each type of failure, calculate abort loads.

d. Use statistics and combine loads based on probability of occurrence

e. Define load indicators.

f. From statistics, obtain abort load values based on a 0.9773 probability of not being exceeded.

2.6.3.2 Aborts Involving the Upper Stage Engine

Loads for the upper stage(s) and spacecraft should be developed for abort scenarios involving an upper stage, or when the upper stage engine is used to perform an abort, based on the initial conditions at the initiation of the abort, the abort trajectory (including the effects of dispersions), the characteristics of the upper stage engine(s) including start-up and shutdown transients and propellant loading, and the configuration of the hardware. Analyses to develop pad abort loads should use the system dynamic math models, abort trajectories, human g-load limits, and the characteristics of the landing deceleration system.

2.6.3.3 Blast Overpressure

For abort scenarios where a blast overpressure occurs due to the detonation of launch vehicle propellants, the magnitude of the overpressure and its propagation characteristics over time should be defined based on Program-approved initial conditions for propellant characteristics, extent of mixing, and amount of warning between the detonation and the ignition of the abort motor. Although blast overpressure is often not a design requirement, it should - at a minimum - be assessed by the hardware developers.

2.6.4 Fragmentation Environment

For abort scenarios where a fragmentation environment occurs due to the breakup of the launch vehicle or detonation of launch vehicle propellants, the mass, velocity, impact angle, and distribution of debris should be defined and should be assessed by the hardware developers.

2.6.5 Crew Escape System Motor Ignition Overpressure

The ignition overpressure environment from any crew escape system motor should be defined and included in all abort scenarios assessments.

2.6.6 Crew Escape System Motor Plume Environment

The plume environment produced by any crew escape system motor when an abort is initiated should be evaluated by launch vehicle and spacecraft hardware developers to assure that no detrimental loading or other effects are produced.

2.7 IN-SPACE FREE-FLIGHT OPERATIONS

Once on-orbit, spacecraft typically undergo some sort of re-configuration, such as deployment of antennae, solar arrays, etc. Thus, they are in a different hardware configuration than they were during launch and ascent. Assessments must be performed for loading conditions which may occur during in-space operations, to ensure that bounding load cases for all hardware have been identified and that environments unique to micro-gravity operations have been evaluated.

2.7.1 Low Earth Orbit (LEO) Insertion Burn

The LEO insertion burn loads should be developed by analysis of all vehicle configurations which enter low earth orbit. Engine thrust data and launch vehicle and spacecraft dynamic models should be used in the analysis.

2.7.2 Loads on Deployable Structures

Loads on deployed or deployable structures which arise from on-orbit operations or the on-orbit environment should be developed using the spacecraft and appendage dynamic math models. The assessment should account for both mechanically transmitted structure-borne base excitation and direct loading from impingement, if any, of jet thruster plumes.

2.7.3 Velocity Change (delta-V) Maneuvers

Loads due to spacecraft primary engine and/or Reaction Control System (RCS) burns used to perform delta-V maneuvers such as orbital altitude adjustment/maintenance, rendezvous phasing, earth orbit departure, destination orbit insertion, etc. should be developed. Analysis should include engine thrust build-up, steady burn, and tail-off data, jet firing sequences, RCS thruster thrust data, and the spacecraft or spacecraft+payload dynamic math model.

If RCS thrusters are used to control spacecraft attitude and rate excursions during a primary engine burn, loads induced by RCS activity should be combined with loads induced by the primary engine burn in a rational manner.

2.7.4 Reaction Control System Operation

Loads due to RCS jet firing sequences used to perform either maneuvers or attitude correction should be developed. Analysis should include jet firing sequence and timing, RCS thruster thrust data, and the spacecraft dynamic math model. To protect for uncertainties in both structural resonances and control system operation, timing and spacing of RCS thrusters should be varied to sweep across a range of modal frequency uncertainty which is appropriate for the maturity of the hardware design.

2.7.5 Internal Compartment Pressure-Induced Loads

When developing on-orbit loads, loads due to the internal cabin pressure must be considered.

2.7.6 Intravehicular Activity (IVA) Crew Loads

Loads on the spacecraft arising from activities of the crew within the pressurized volume should be assessed. Crew/hardware interaction forces based on human factors and historical data for micro-gravity crew loading should be considered in the analysis. The time/frequency characteristics of any repetitive-motion crew activities such as exercise must be considered to evaluate the potential for tuning of the applied loads and spacecraft structure or appendages.

For exercise, forcing functions derived from ground or on-orbit measurements of loads from human-in-the-loop exercise using relevant exercise equipment should be the basis for the analysis. Forcing functions should account for the full range of crewmember mass and strength and represent both aerobic and resistive exercise and the exercise prescription stipulated by the Crew Health and Performance organization. Forcing function frequency content should be varied to sweep across a range corresponding to a range of modal frequency uncertainty which is appropriate for the maturity of the hardware design.

If exercise devices used for maintenance of crew health and conditioning are not isolated, structural loads induced by crew exercise may have significant impacts on structural fatigue life usage. Exercise forces are generally narrow-band in nature and tend to occur at frequencies which are in the range of resonant frequencies for typical spaceflight module clusters.

2.7.7 Extravehicular Activity (EVA) Crew Loads

Loads on the spacecraft arising from activities of pressure-suited crew outside the pressurized volume should be assessed. Crew/hardware interaction forces from EVA compatibility documents such as EHP-10028 *Exploration EVA System Compatibility Standards* should be considered in the analysis.

The time characteristics of any repetitive-motion EVA crew activities should be assessed to evaluate the potential for tuning between the frequency content of the applied loads and spacecraft structure or appendages. Use of time domain forcing function representations such as those used for the International Space Station (ISS) and Gateway Programs is recommended.

2.7.8 Venting

Venting dynamic pressures and loads on deployed appendages should be analyzed using vent plume flowfield models, vent characteristics, and venting forcing functions. Resultant vent net thrust forcing functions should be developed and assessed for impacts to spacecraft hardware and for impact to control system operations.

2.8 JOINT VEHICLE-TO-VEHICLE OPERATIONS

Once in space, spacecraft often conduct joint operations with other spacecraft. The operations may include, but are not limited to, extraction of payloads from upper stages of other launch vehicles, rendezvous/docking/mated activities with habitation complexes (also referred to as space stations) or deep space transportation systems, and rendezvous/docking with other crewed or uncrewed space transportation vehicles for crew and/or cargo transfer. Loads assessments must be performed for all loading conditions on both spacecraft to ensure that bounding load cases for all hardware have been identified and load limits for existing spacecraft are not exceeded.

Such operations may occur in LEO, cis-lunar space, lunar orbit, deep space, or in orbit around other planetary bodies. However, the analysis approach to assessment of these loads driving events in all scenarios is the same.

For the purposes of the subsections below, the “active” vehicle is the spacecraft responsible for controlling relative positions and closure rate between the two spacecraft during unmated operations. The “target” vehicle is the spacecraft which serves in a passive role in such operations, except for controlling its roll, pitch, and yaw attitudes to remain within pre-defined limits.

2.8.1 Vehicle Configuration Definition

For development of loads during spacecraft operations in proximity to and mated to other vehicles, all potential configurations of the spacecraft serving as the target vehicle should be assessed. All target vehicle configuration variants which include other visiting vehicles that may be present should be included.

After the active spacecraft is mated to the target spacecraft, the joined configuration may serve as the target vehicle for proximity operations performed by other visiting vehicles.

2.8.2 Rendezvous and Proximity Operations

Loads induced during spacecraft rendezvous and proximity operations should be developed based on relative attitudes and positions during the approach or departure of the spacecraft serving as the active vehicle. The assessment should be based on trajectories used by the active spacecraft, RCS jet firing schemes, active spacecraft and target spacecraft dynamic math models, and feathering angles of all articulating appendages of the target vehicle and other visiting vehicles which may already be present at the target spacecraft. Active spacecraft thruster plume flowfield models should be used along with active spacecraft/target spacecraft relative positions and orientations to predict dynamic pressures, loads, heating, and contamination arising from thruster plume impingement on target vehicle hardware.

If plume impingement from target spacecraft thruster firings for attitude control during active spacecraft approach or separation has the potential to affect active spacecraft loads or performance, target spacecraft thruster plume flowfield models and relative positions/attitudes should be used to predict dynamic pressures, loads, heating, and contamination on the active vehicle as well.

All nominal and contingency maneuvers during these operations should be considered to ensure identification of bounding loads for all credible cases.

2.8.3 Docking

Loads induced during spacecraft docking to other in-space assets should be developed using active spacecraft and target spacecraft dynamic math models and a test-verified model of the docking mechanism. Analyses to predict docking loads should consider the docking contact conditions (linear and angular rates and velocities at contact), active and target vehicle mass properties and dynamic characteristics, and effects of any active spacecraft thruster firings used to aid in ensuring capture. If either the active spacecraft or target spacecraft attitude control systems will be operational during docking contact, capture, and arrest of relative vehicle motion, effects of the control system response to the docking disturbance must be included in the analysis.

2.8.4 Mated Operations

During mated operations, the spacecraft responsible for orbit maintenance and attitude control of the mated configuration will perform the loads analyses for all operations. Loads will be calculated for the spacecraft-to-spacecraft interface, deployed appendages, and internal data recovery items requested for either vehicle. Data recovery requests should be negotiated between the providers of the non-controlling spacecraft and the organization performing the loads analyses. The organization performing the loads analyses will also provide forcing function time histories at the spacecraft-to-spacecraft interface, to enable the non-controlling spacecraft developer to recover internal loads independently, if desired. Operations or environments for which loads analyses will be performed include:

a. Attitude control events as described in Section 2.7.4

b. Delta-V maneuvers as described in Section 2.7.3

c. EVA loading events as described in Section 2.7.7

d. IVA crew loading events as described in Section 2.7.6

e. Controlling vehicle and visiting vehicle plume impingement events as described in Section 2.8.2

f. Visiting vehicle dockings as described in Section 2.8.3

g. Robotic operations, such as berthing of other visiting vehicles or components as described in Section 2.8.5

h. Venting as described in Section 2.7.8

i. Undocking as described in Section 2.8.8

2.8.5 Robotic Operations

Loads on the spacecraft arising from robotic activities should be assessed. Robotic operations involve extracting, translating, and re-installing large masses. Operations may also involve track-and-capture of free-flying vehicles.

During free-flying capture or emergency braking during translation of large masses, dynamic forces are imparted to the spacecraft hosting the robotic system. Such loads usually have a strong single-degree-of-freedom frequency content with the potential to tune to structural resonances, can be of high magnitude, and must be evaluated for effects on the robotic interface as well as hardware within the host spacecraft.

Similarly, berthing of robotically-manipulated objects imparts transient impact loads at the berthing interface. These must be used to assess effects on host spacecraft.

2.8.6 Thermally-induced Effects

Thermal effects on the spacecraft in the mated configuration should be analyzed for the induced environments and shadowing or differential temperature at the mated interface

2.8.7 Pressure-Induced Deformations and Loads

Pressure-induced deformations and loads for the case in which a pressurized spacecraft is mated to an unpressurized structure should be assessed. Similarly, pressure-induced deformations and loads for the case in which an unpressurized spacecraft is mated to a pressurized structure should be assessed, as should the case where spacecraft on both sides of the mated interface are unpressurized.

2.8.8 Undocking and Separation

Loads due to spacecraft undocking should be developed based on the characteristics of the separation mechanism, using both the target spacecraft and active spacecraft dynamic math models and mass properties.

Plume impingement effects during separation should be analyzed per Section 2.8.2

2.8.9 Expedited Separation

Loads for an expedited separation condition should be assessed. The assessment should consider worst-case mated configuration angular rates. If the separation will occur with some residual pressure in the vestibule between the spacecraft hatches on either side of the mated interface, the effect of the sudden pressure release on spacecraft loads and vehicle dynamics must also be considered.

2.9 LUNAR/PLANETARY MISSIONS

Many of the loading events which will occur during missions beyond LEO are operationally similar or identical to those outlined in other sections of this Appendix and may be analyzed as described in those sections. Where appropriate, assessment of the following events for lunar or planetary missions will refer to relevant sections/subsections to avoid unnecessary duplication of material.

2.9.1 Vehicle Configuration Definition

The vehicle travelling beyond LEO may include a combination of crewed spacecraft, launch vehicle upper stages, deep space propulsion or habitation elements, and landers. Landers may consist of separable descent and ascent stages. Vehicle configurations may vary for certain operations. All possible configurations of the integrated spacecraft, referred to as the “transit spacecraft” in the following sections, over the course of the lunar or planetary mission profile should be assessed to ensure identification of bounding loads for credible cases.

2.9.2 Earth Departure Burn

The delta-V maneuver to inject the transit spacecraft into a trajectory for lunar, deep space, or planetary missions should be analyzed according to Section 2.7.3. RCS activity concurrent with the burn should also be accounted for per Section 2.7.4.

2.9.2.1 Departure Stage Staging

If a launch vehicle upper stage or other separable module is used to perform the earth departure burn, loads produced by stage separation must be assessed. Contributors to loading such as thrust tail off and termination, retrograde motor firings, separation devices, thrust misalignments, fluid slosh, exhaust plume impingement from separation motors, and transient loads due to the removal of attach forces must be considered. In the absence of rational analyses of such effects, design factors may be chosen in a conservative manner and imposed on the corresponding loads.

2.9.3 In-transit Operations

In the period between earth departure and arrival at the destination, loading events experienced by the transit spacecraft will be analogous to those described in Section 2.8, with the possible exceptions of rendezvous and proximity operations/docking and robotic operations. If the mission concept of operations includes spacecraft repositioning or robotic relocation of modules/elements/payloads, however, those operations must be evaluated for induced loads.

2.9.3.1 Trajectory Correction Maneuvers

Trajectory correction maneuvers, whether performed by primary engine burns or RCS, are delta-V maneuvers and should be analyzed as described in Sections 2.7.3 and 2.7.4

2.9.3.2 Rendezvous, Proximity Operations, and Docking

Only needed if such operations during this mission phase are part of the overall mission concept of operations. If so, per Sections 2.8.2 and 2.8.3.

2.9.3.3 IVA Crew Loads

Per Section 2.7.6.

2.9.3.4 EVA Crew Loads

Per Section 2.7.7.

2.9.3.5 Robotic Operations

Only needed if robotics operations during this mission phase are part of the overall mission concept of operations. If so, per Section 2.8.5.

2.9.3.6 Thermally-Induced Effects

Per Section 2.8.6.

2.9.3.7 Pressure-Induced Deformations and Loads

Per Section 2.8.7.

2.9.3.8 Emergency Return Loads

Scenarios for emergency return from lunar, planetary, or deep space missions will depend on the specifics of those missions. At a top level, however, common elements will likely involve undocking and separation (Section 2.8.8), RCS operations (Section 2.7.4), and delta-V maneuvers (Section 2.7.3). Depending on urgency, expedited separation loading per Section 2.8.9 may also be applicable.

Other loading sources as defined earlier in this section will occur during transit for return to earth.

2.9.4 Destination Orbit Insertion Burn

The delta-V maneuver for destination orbit insertion should be analyzed according to Section 2.7.3. RCS activity concurrent with the burn should also be accounted for per Section 2.7.4.

2.9.5 Descent Vehicle Undocking and Separation

Undocking and separation of a lander, if present, should be analyzed for loads induced on the lander and the transit spacecraft. Undocking forces at the interface and plume impingement loading during separation should be developed as described in Sections 2.8.8 and 2.8.2, respectively, based on the characteristics of the separation mechanism, lander and transit spacecraft post-separation configuration dynamic math models and mass properties, and lander and transit spacecraft thruster plume flowfield models and relative positions and attitudes along the departure trajectory.

2.9.6 Lunar/Planetary Entry, Descent, and Landing

2.9.6.1 Entry and Descent

Missions to planetary destinations with measurable atmospheres should account for loading sources during atmospheric entry as described in Sections 2.10.1 and 2.10.2. For entry vehicles which use parachutes, Sections 2.10.2.1 , 2.10.2.2, and 2.10.2.3 should also be considered. Differences in atmospheric properties between the destination and earth must be factored into the assessment.

Regardless of the deceleration system used, if any, cabin pressure equalization loads and differential crush pressures as described in Sections 2.10.3 and 2.10.3.1 should be accounted for.

For descent to non-terrestrial destinations without an atmosphere, none of these loading events are applicable.

Descent engine operations should be assessed as delta-V maneuvers, per Section 2.7.3. In addition to engine thrust build-up, steady burn, and tail-off data, however, thrust variations due to engine throttling must be included.

2.9.6.1.1 Attitude Control During Descent

Attitude control during descent should be assessed for loads per Section 2.7.4.

2.9.6.2 Landing

Horizontal and vertical components of the lander velocity and accelerations, any angular rates and angular accelerations for dispersed surface wind conditions (for destinations with an atmosphere), and the terrain definition at touchdown as defined in Program-/Project-specific requirements should be defined for both nominal and off-nominal scenarios. This information should be used along with the lander dynamic model to develop touchdown forcing functions and loads. Structural loads will be developed using these forcing functions and lander dynamic math models.

Pressures, loads, acoustic effects, and heating due to reflection of engine exhaust plumes in the terminal phase of landing must be modeled and evaluated.

Engine burns and throttling during propulsive landing should be assessed as delta-V maneuvers per Section 2.7.3. Loading due to engine shutdown must also be included.

2.9.7 Surface Operations

2.9.7.1 Seismic Activity

Depending on the destination, seismic activity may be an important consideration, particularly for habitation and infrastructure hardware for extended surface operations. Of primary concern are the lateral loads that would be introduced at the base of the lander and surface assets by seismic induced horizontal motions.

If the destination surface site is hard rock, a conventional dynamic analysis of the surface hardware and lander may be performed to determine loads and deflections during seismic activity. However, if a softer site is utilized, soil-structure interaction must be considered. Soft soil supporting the lander and surface assets can be expected to permit an excess of translational and rotational motion at the hardware-to-surface interface, causing a reduction of the system natural frequencies, and an increase in lateral displacement. Conversely, system damping is greatly increased due to the response-induced generation of seismic waves back into the soil.

2.9.7.2 Surface Winds

For planetary destinations with measurable atmospheres, wind loading on the lander and surface assets must be assessed. Section 2.3.3 titled Pre-launch Ground Winds at the Launch Pad may be used as guidance for assessment of wind-induced loading at the destination.

2.9.7.3 Surface Transportation Vehicle (Rover) Operations

Loads for roving vehicles - either pressurized or unpressurized - will primarily be driven by the interaction of surface topography, operating speed, characteristics of the rover hardware interacting with the surface, and the rover suspension. Development of loads for rover operations should be based on Program/Project definition of the surface area over which the rover will be permitted to operate and dynamic math models of the rover and its suspension system. Models of wheel and/or track interaction with the surface should also be developed and verified by test.

In addition to hardware considerations, acceleration-based metrics for crew health and performance requirements must be computed and tracked during analysis of rover operations.

For rovers with attached robotic systems, loads induced on the rover during operation of these systems should be analyzed per Section 2.8.5.

2.9.7.4 Element-to-Element Interface Mating

For certain operations, such as unsuited crew transfer from a pressurized rover to a pressurized habitation element, an operation to create a pressurized transfer path will be necessary. This operation will require some to-be-determined means of interface connectivity. Until details of the hardware and operations are defined, loads for this operation should be analyzed as robotic berthing operations per Section 2.8.5.

2.9.7.5 IVA Crew Loads

For pressurized habitation elements and pressurized rovers in which crew will spend extended durations, IVA crew loading per Section 2.7.6 must be evaluated. Crew exercise loads may be of particular concern for pressurized rovers for, reasons noted in that section.

2.9.7.6 EVA Crew Loads

Loads on the lander and surface hardware arising from activities of pressure-suited crew outside pressurized volumes should be assessed. Crew/hardware interaction forces for partial-gravity operations in EVA compatibility documents such as EHP-10028 *Exploration EVA System Compatibility Standards* should be considered in the analysis.

2.9.7.7 Robotic Operations

Per Section 2.8.5

2.9.7.8 Thermally-Induced Effects

Per Section 2.8.6.

2.9.7.9 Pressure-Induced Deformations and Loads

Per Section 2.8.7.

2.9.8 Lunar/Planetary Launch and Ascent

Loads during lunar and planetary launch and ascent should be assessed in a manner analogous to terrestrial launch as described in Sections 2.4 and 2.5. Some loading events such as pad separation (2.4.6), fairing separation (2.5.11), crew escape system jettison (2.5.21), etc., will not be relevant. But on the whole, assessment of loads for these mission phases will be comparable.

Any assessment involving atmospheric phenomena (winds, vortex shedding, aerodynamic pressure, etc.) is not applicable for lunar missions or other destinations without a measurable atmosphere.

2.9.9 Ascent Vehicle Rendezvous, Proximity Operations, and Docking

Ascent vehicle proximity operations with and docking to the portion of the transit vehicle remaining in orbit, if any, should be assessed per Sections 2.8.2 and 2.8.3, based on use of a test-verified model of the docking mechanism, lander and transit spacecraft post-separation configuration dynamic math models and mass properties, and lander and transit spacecraft thruster plume flowfield models and relative positions and attitudes along the approach trajectory.

2.9.9.1 Ascent Vehicle Separation and Jettison

Loads for ascent vehicle separation and jettison, if performed, should be assessed per Section 2.8.8.

2.9.10 Trans-Earth Injection Burn

The delta-V maneuver to inject the returning spacecraft into an earth return trajectory should be analyzed according to Section 2.7.3. RCS activity concurrent with the burn should also be accounted for per Section 2.7.4.

2.10 EARTH ENTRY, DESCENT, AND LANDING

2.10.1 Re-entry Vehicle Entry Aerothermal and Aerodynamic Loads

2.10.1.1 Stage Separation

Staging/separation of a crewed re-entry vehicle, if performed, should be analyzed using separation mechanism characteristics, dynamic models of the flight hardware, and mass properties of the re-entry vehicle and separated stage.

2.10.1.2 Initial Conditions for Nominal Entry

The crewed re-entry vehicle developer should develop initial conditions for atmospheric entry considering dispersions including entry interface altitude, flight path angle, velocity, and atmospheric conditions for re-entry vehicle aerothermal and aerodynamic loads assessments.

2.10.1.3 Re-Entry Vehicle Entry Trajectories

The crewed re-entry vehicle developer should develop entry trajectories for aerothermal and aerodynamic loads assessments.

2.10.1.4 Aerodynamic Loads for Entry Outside the Nominal Entry Corridor

For off-nominal entry scenarios, the crewed re-entry vehicle developer should develop initial conditions considering dispersions including altitude, flight path angle, velocity, and atmospheric conditions and off-nominal trajectories for aerothermal and aerodynamic loads assessments.

2.10.2 Deceleration System Deployment

Guidelines below pertain to systems using parachutes for aerodynamic deceleration. However, other systems such as deployable lifting bodies, autorotation systems, etc. may also be used. For guidelines and recommendations on design and analysis of these types of devices, refer to NASA SP-8066, Deployable Aerodynamic Deceleration Systems.

2.10.2.1 Drogue Parachute Deployment

Loads for drogue parachute deployment should be developed based on entry trajectory initial conditions with dispersions considered, drop testing of the drogue chute and flight hardware system, and analysis.

2.10.2.2 Main Parachute Deployment

Loads for main parachute deployment should be based on the entry trajectory initial conditions with dispersions considered, drop testing of the of the parachute and flight hardware system, and analysis.

2.10.2.3 Off-nominal Drogue or Main Parachute Deployment

Loads for off-nominal drogue or main chute deployment scenarios should be developed considering dispersions based on the entry trajectory initial conditions, drop testing of the parachute and flight hardware system, and analysis.

2.10.3 Cabin Pressure Equalization Loads

Loads due to cabin pressure equalization following parachute deployment should be developed based on the spacecraft structural math models and pressure equalization scheme, including Program-defined failure scenarios.

2.10.3.1 Maximum Differential Crush Pressure

Based on the cabin pressure equalization scenario, the maximum crush pressure for the re-entry vehicle should be determined.

2.10.4 Land Landing

2.10.4.1.1 Loads for Heat Shield Separation

If required, loads should be developed for the heat shield separation event based on the characteristics of the separation mechanism and the crewed re-entry vehicle dynamic math models.

2.10.4.2 Land Landing Deceleration System

Loads should be developed for any land landing deceleration system employed in addition to parachutes, based on drop testing of the land landing deceleration and flight hardware system and analysis of the crewed re-entry vehicle dynamic model.

2.10.4.3 Horizontal/Vertical Velocity, Wind Conditions, and Terrain Conditions at Touchdown for Land Landing

Horizontal and vertical components of the re-entry vehicle velocity and accelerations, any angular rates and angular accelerations for surface wind conditions (including dispersions), and the terrain definition at touchdown as defined in Program-/Project-specific requirements should be defined for both nominal and off-nominal parachute deployment scenarios. This information is necessary for the purposes of developing touchdown forcing functions and loads.

2.10.4.4 Touchdown for Land Landing

Loads at touchdown should be developed for land landing based on the initial conditions at landing derived in the Horizontal/Vertical Velocity, Wind Conditions and Terrain Conditions at Touchdown for Land Landing section (2.10.4.3), drop testing of the re-entry vehicle, and analysis of the flight hardware dynamic model.

2.10.5 Water Landing Initial Conditions

2.10.5.1 Horizontal and Vertical Velocity, Wind Conditions and Sea State at Touchdown for Water Landing

Horizontal and vertical components of the re-entry vehicle velocity and accelerations, any angular rates and angular accelerations, the surface wind conditions (including dispersions) and the sea state definition as defined in Program-/Project-specific requirements at touchdown should be defined for both nominal and off-nominal parachute deployment scenarios. This information is necessary for the purposes of developing touchdown forcing functions and loads.

2.10.5.2 Touchdown for Water Landing

Loads at touchdown should be based on the initial conditions at water landing derived in the Horizontal and Vertical Velocity, Wind Conditions and Sea State at Touchdown for Water Landing section (2.10.5.1), drop testing of the Crew Module, and analysis of the spacecraft dynamic model.

2.10.6 Propulsive Entry and Landing

Engine operations during propulsive entry should be assessed as delta-V maneuvers, per Section 2.7.3. In addition to engine thrust build-up, steady burn, and tail-off data, however, thrust variations due to engine throttling must be included. Any concurrent RCS activity should be addressed per Section 2.7.4

Pressures, loads, acoustic effects, and heating due to reflection of engine exhaust plumes in the terminal phase of landing must be modeled and evaluated.

Engine burns and throttling during propulsive landing should be assessed as delta-V maneuvers per Section 2.7.3. Loading due to engine shutdown must also be included.

2.11 EARTH RECOVERY

2.11.1 Vehicle Hoisting and Handling

Loads during post-landing hardware recovery should be assessed for both land and water landing scenarios.

2.12 HUMAN ACCELERATION LIMITS

Human acceleration limits as defined for a Program or Project should be considered as constraints for all loads development and assessments.

3.0 UNCERTAINTY FACTORS/FACTORS OF SAFETY

3.1 TREATMENT OF MODEL/LOADS UNCERTAINTY FACTORS

Uncertainty Factors (UFs) for transient loading events may be incorporated into loads analyses to account for unknowns in forcing functions or environments and modeling fidelity and to protect for possible load and load path changes resulting from possible future design changes. Values often vary depending on design and operations maturity, typically decreasing with increased knowledge of expected operations, insight into environment and forcing function accuracy gained by testing, convergence of vehicle hardware and structural design, and hardware tests performed for model correlation. The uncertainties to use for each type of transient loading event should be rationally chosen, well understood, and defensible. Some examples of methodologies that could be implemented are listed below:

a. Option #1 - Uncertainties can be included by generating forcing functions for a range of frequencies appropriate to the uncertainties of each frequency with appropriate spacing and damping and then tuning the model to those forcing functions.

b. Option #2 - Uncertainties included as noted in option #1 but with interrogating the set of results of a Monte Carlo assessment to determine the 0.9987 probability of no exceedance value.

c. Option #3 - Uncertainty factors can be applied to calculations of transient dynamic loads appropriate to the maturity and verification level of structural models and forcing functions used to calculate the transient loads.

d. Option #4 - If there is not sufficient fidelity in the modeling of the loading environment or the processes involved, a combination of Option #1 and #3 could be implemented. The uncertainty factor can be used to address known shortcomings in the modeling that cannot be necessarily captured by simply sweeping through the large range of frequencies and damping and then tuning the model.

3.2 FACTORS OF SAFETY

Factors of safety are structural design considerations and should not be included in limit loads development.

4.0 LOADS AND LOAD SPECTRA COMBINATION

4.1 COMBINATION OF MECHANICAL LOADS

When loads produced by different environments or flight events can occur simultaneously, these loads must be combined, as applicable, in a rational manner to define the limit load for that event, prior to their use in strength or life assessments. Common types of load combinations include static pressure loading occurring at the same time as turbulent buffeting during atmospheric entry and thermal loads occurring at the same time as deployment release loads and/or end of travel loads. Input values/ranges of parameters for loads analyses should be defined that produce loads that statistically meet the Program-defined probability levels. Appropriate combinations of loading events throughout each vehicle's flight regime and ground processing should be defined to properly derive design limit loads.

Often, a Monte Carlo assessment is selected as the preferred method of choice. Alternative load combination approaches may also be used, including equations which combine peak loads from different loading sources to create an event-consistent limit load. A summary table should be developed that describes the selected methodology for the load combinations for all mission events.

4.1.1 Transportation and Ground Handling

A static analysis should be completed using maximum system gross weight as described in the Transportation and Handling Load Factors section. Jacking and hoisting loads should be applied as described in the Transportation and Handling Loads Factors section. A rationale scheme to combine loads for various events should be developed to properly evaluate transportation and ground handling loads.

4.1.2 Vehicle Assembly at Launch Site

Launch site vehicle assembly loads should be calculated based on the following considerations including maximum weight, propellant, alignment tolerances, gravity effects, etc. as described in the Vehicle Assembly at the Launch Site section. A means to combine loading from various events and sources should be developed.

Launch vehicle/mobile launcher rollout loads should be calculated based on the criteria defined in the Launch Vehicle/Mobile Launcher Rollout Loads section. The loads analysis should be based on a Monte Carlo approach to address variations in rollout speeds, and wind loads and should be completed for all potential configurations of vehicle and support structure configuration which may be used during rollout. Data should be recorded for each rollout to provide the required information for a structural life assessment.

4.1.3 Launch Pad Operations

Loads on the launch pad should be determined for both a fueled and unfueled vehicle and include tanking loads due to fueling, umbilicals, static hold-down loads, and effects from ground winds as defined Program-defined natural environment requirements. Directional winds, wind induced oscillations and local shielding should be considered. If a structural tie-off and/or damper to a launch support structure is used to help withstand wind or other forces imposed on the vehicle at the pad, the loads at the vehicle attachments should be included in the determination of the total vehicle loads.

4.1.3.1 Pad Abort

Pad abort loads analysis should be based on a Monte Carlo analysis of randomly selecting dispersions for abort trajectories, variations in wind velocities and characteristics of the LAS abort motor and blast pressure environment.

4.1.4 Combining Liftoff Loads

Liftoff loads analysis should include, but should not be limited to, the effects of engine thrust vector, variations in wind speed and direction, wind induced oscillations, gusts, thrust rise rate, magnitude and ignition timing, thrust vector misalignments, ignition overpressure, hold down loads due to variations in release timing and stud hang-ups, twang due to vehicle separation from the pad, umbilical separation, and t=0 separation, and launch support structure stiffness. The liftoff transient analysis should include a modal damping of 1 percent up to 50 Hz.

A loads analysis based on a Monte Carlo method of randomly selecting dispersions to the liftoff conditions for a dry (without water sound-suppression systems) vehicle is preferred. If the specified requirement includes a sound suppression system, then an inactive sound suppression system is a constraint to launch.

4.1.5 First Stage Ascent Loads

Ascent loads analysis should include the criteria defined in the Ascent Loads section, including static aeroelastic, gust, buffet, and Thrust Oscillation (TO) effects.

The loads combination for ascent loads is defined as:

$$\text{ASCENT LOADS} = 1\ \text{STEL} + 1/3\ \text{GUST} + 0.335\ \text{BUFFET} + \text{MEAN TO} + \sqrt{(2/3\ \text{Gust})^2 + (0.665\ \text{Buffet})^2 + (\text{TO - Mean TO})^2}$$

The loads generated using the equation above are subject to meeting a Program-mandated probability-of-no-exceedance requirements.

4.1.6 Stage Separation Loads

Stage separation loads should include, but should not be limited to, the effects of stage thrust decay characteristics, retro rocket firing, separation pyro shocks, separation mechanism (if any) operation, ullage (upper stage) motor, upper stage engine(s) start characteristics (buildup and thrust), motor exhaust plume impingement, and vehicle separation dynamics.

4.1.7 Second and Subsequent Stage Ascent Loads

Analysis for second stage ascent loads should include the effects of upper stage engine(s) thrust characteristics, thrust misalignment, and mass reduction (crew escape system jettison, fairing separation, etc.) for the maximum weight and for the maximum acceleration configurations. The analysis may be down-selected to the controlling configuration, if applicable. Second stage ascent loads must also address the applicable aborts.

4.1.8 Upper Stage Separation Loads

Upper stage separation loads should address the following effects:

a. Thrust decay characteristics of the upper stage engine(s)

b. Timing of separation devices

c. Allowable rotation rates at separation

Loads should also be determined for the applicable aborts.

4.1.9 Loads for Rendezvous, Proximity Operations, Docking and Undocking and Spacecraft Mated Operations

Combination of loads for Rendezvous, Proximity Operations, Docking and Undocking (RPODU) and mated operations with other spacecraft should be performed on an event-consistent basis, using peak loads from each individual event. Mechanical loads should be combined with thermal loads and pressure loads (for pressurized modules) to provide combined loads which meet a 0.9987 probability of no exceedance. An RSS combination may be used when it provides a conservative estimate for a 0.9987 probability of no exceedance value. Otherwise, a Monte Carlo analysis or other conservative load combination method may be used.

4.2 FATIGUE LOADS SPECTRA DEVELOPMENT

Mechanical, thermal and pressurization load spectra should be derived from the applicable loading events for the lifetime of each major flight hardware item. As a minimum, one Ground-Air-Ground (GAG) cycle, which is defined as the max value of all events and the min value of all events, should be included in the loads spectra for each mission. Load spectra for hardware which may be reused over multiple flights must account for the cumulative effects of cyclic loading experienced over its operational lifetime.

Load spectra cycle counting should consider transient load time histories developed for each significant load event for the life of the hardware. Both randomly distributed events and constant amplitude events must be included. Probability distributions may be applied to the peak load events for random distributions and scaled to create lower peak loads as defined by the probability distribution function. The Rainflow cycle counting method per ASTM E1049-85 (2005), Standard Practices for Cycle Counting in Fatigue Analysis, is the recommended method for determining load cycle counts within each amplitude range, but other methods may be employed.

4.3 COMBINATION OF TRANSIENT LOADS, PRESSURE AND THERMAL LOAD SPECTRA

Because transient loading events occur at extremely short time intervals compared to pressure and thermally induced loads, the pressure loads should be assumed to be at the normal operating mean pressure load at the time of the thermal or transient load event. Thermally-induced loads should be assumed to be at the mean of their cyclic load values at the occurrence of a transient or pressure cycle loading event. Transient, pressure and thermal load spectra specified for hardware should be combined as independent loading events.

5.0 STRUCTURAL DYNAMIC MATH MODEL GUIDELINES

Loads and deformations utilized in flight hardware verification should be based on verified structural math models as described in the Structural Math Model Verification section and/or test.

5.1 MODEL DELIVERY FOR LOADS DEVELOPMENT

5.1.1.1 Software

Models should be compatible with the NASA Structural Analysis Program (NASTRAN). Note that Programs/Projects may require use of specific versions of NASTRAN.

5.1.1.2 Model Interfaces

Grids at interfaces between flight vehicle elements should contain six Degrees of Freedom (DOF). DOF releases should be negotiated between interfacing vehicle elements and accounted for within the integrated models.

When using Multi-Point Constraints (MPCs) or Rigid Elements (e.g., RBEx, RTRPLT, etc.) at the vehicle element interfaces, DOFs which connect to other vehicle elements should be the independent DOFs.

5.1.1.3 Coordinate Systems

Flight vehicle element coordinate systems should reference a single, common coordinate system to facilitate the integration of the model in overall system models.

5.1.1.4 Unit System

Spacecraft models must be provided in the system of units specified in Program/Project requirements.

5.1.1.5 Mass Properties and Configurations

Spacecraft models must be provided with mass properties in the system of units specified in Program/Project requirements and represent all possible vehicle configurations for all mission phases..

5.1.1.6 Load Indicators

Each flight vehicle system developer should provide critical hardware element component load indicators and their associated redline values for launch and/or on-orbit design load case search. This information should be included in the system element component model delivery document.

5.1.1.7 Model Check-out Requirements

Prior to delivery, the flight vehicle models should undergo the Quality Assurance (QA) checks described below. The results of the QA check should be documented and delivered with the models:

a. Free-Free Mode Check: Modal frequencies of the unconstrained system should demonstrate applicable rigid-body modes with frequencies less than 1.0e-4 Hz. Element models must not contain additional rigid body modes that, when coupled into the vehicle, result in the vehicle having more than six rigid body modes.

b. Equilibrium Check: 1-g static loading of the constrained model in all three (3) translational axes should demonstrate that the Applied Loading (OLOAD) equals the summation of forces of Single Point Constraint (SPC) Forces.

c. Pressure Load Check: Unit pressure loading of the constrained model should show that the net OLOAD is equal to the SPC Force resultant. For tank models they both should be zero.

d. Determinate Constraint Thermal Check.

e. Strain-Energy Check: The unconstrained model should be subjected to an enforced unit displacement for all six DOFs. Displacements of all nodal DOF in the direction of the enforced displacement should be equal to it. Strain energies should be negligible or zero.

f. Mass Properties Check: Rigid body mass properties should be computed at the CG for the modeled configuration. Output should be compared to those specified in the appropriate vehicle’s mass property report. The overall system mass and CG location should compare within 1 percent. Moments of inertia should compare within 2 percent.

g. Element Quality Checks: Warping, distortion, and stretch of elements should be within those specified by NASTRAN for these parameters.

h. Element Free Edge Checks: The model should be checked to insure there are no unexpected free edges, or “cracks” in shell and solid meshes.

i. Element Coincident Nodes Checks: The model must be checked for coincident nodes. Coincident nodes used deliberately for modeling purposes should be documented.

j. Grid Point Singularities Check: There must be no unexplained Grid Point Singularities.

k. The model should be modal test correlated to ensure that it is representative of as-built flight or test article hardware with boundary constraints consistent with that expected in flight or test (per Correlation Requirements for Loads Model Verification section).

l. Step Transient Load Check: A free-free transient response analysis should be conducted to verify the appropriateness of requested responses to a known dynamic input load. Suggested loadings include the following:

   1. A unit step gravity load to exercise dynamic response as well as damp-out 1-G gravity results.

   2. An appropriate magnitude step loading of system element supplied forcing functions such as First Stage or J-2X thrust.

m. Grounding Check: The system element model stiffness should be Guyan-reduced to the interface boundaries and centerline DOFs and multiplied by a 6-DOF rigid body transformation. The 6-column output must be provided to the system model integrator for comparison.

5.1.1.8 Modal Content for Analysis Support

The flight vehicle models should directly support the following integrated system analyses. System element modal truncation should be at least 2.0 times the highest frequency of interest for each type of analysis.

a. Structural dynamic loading events such as pre-launch, liftoff, ascent, and staging

b. Structural dynamic characterization of guidance and control sensor mounting locations

c. Hydrodynamic characterization and fluid-structure coupling of significant liquid masses for use in structural loading and control interaction analysis

d. Thermal contraction effects

e. Pressure stiffening effects

f. Overall bending static aeroelastic effects

5.1.1.9 Data Recovery Requests

The flight vehicle models should indirectly support stress analysis and correlation to system level test and flight data (past, current, planned). Typical data recovery items should include the following:

a. Request lists of maximum and minimum accelerations, displacements, loads, stresses and pressures for the grid points and elements identified.

b. Acceleration, Displacement, Load, Stress, and Pressure Transformation Matrices (ATMs, DTMs, LTMs, STMs, PTMs), if a Craig-Bampton matrix model is provided

c. Displacement, Load, and Stress indicator equations

d. Nodes compatible with current stress input requirements

5.1.1.10 Damping

Damping used for dynamic response analysis should be based on test measurements of the actual structure, at amplitude levels that are representative of actual flight environments, or on experience with similar types of structures whenever possible. In the absence of measured damping data, a 1 percent critical modal damping is considered adequate for the transient response analysis.

5.1.1.10.1 Report Documentation

All element models and integrated system models should provide both adequate documentation and a configuration report, which should be submitted with the formal model delivery that should include as a minimum:

a. Report outline

b. Model usage for each applicable flight configuration

c. Mass property audit and traceability

d. Model QA checks

e. Model Pretest analysis

f. Post test / Model correlation report

5.1.1.10.2 Bulk Data Files

NASTRAN bulk data files submitted should contain, as a minimum:

a. Base model, empty tanks, no material definition

b. Material files: ambient and cryogenic properties

c. Ullage pressure unit loading

d. Temperature definition of the appropriate cryogenic fill level for points in the ascent flight profile at which analyses will be performed.

5.1.1.10.3 Hydroelastic Fluid Models

Any hydroelastic fluid models submitted should as a minimum contain:

a. Hydroelastic fluid models of the appropriate cryogenic fill level for the following flight conditions:

  1. Test firings
  2. Liftoff
  3. Maximum Dynamic Pressure (Max Q)
  4. Staging
  5. Spacecraft separation
  6. Strap-on booster separation (if any)
  7. Core stage firing
  8. Upper stage firing(s)

b. Original Hydro code input should be provided

c. Hydro models should be provided as NASTRAN DMIG cards, output four (.op4) files, output two (.op2) files, or NASTRAN database files with appropriate documentation for use.

d. Pogo fluid models: The method referenced in NASA-CR-193909, Modeling Dynamically Coupled Fluid-Duct Systems with Finite Line Elements, is acceptable.

e. Propellant Slosh: Modeled as a pendulum with its 1-g mode corresponding to the first natural frequency of the propellant slosh or other appropriate techniques.

5.1.1.10.4 Model Quality Assurance Checks

The NASTRAN analysis input files submitted for model Quality Assurance (QA) checks must as a minimum contain:

a. Case Control

b. Parameters

c. Bulk data include files

d. File assignment definition (if used)

5.2 STRUCTURAL MATH MODEL VERIFICATION

Structural math models provide the necessary accuracy for assessment of loads and flight performance. Correlation goals of math model to measured data are defined to ensure the accuracy of the structural models. If the defined goals are not met, this does not imply that the model is inadequate. Technical rationale and engineering judgment can be sufficient to justify use of the model. Additional effort such as additional testing, additional analyses, and/or application of a model uncertain factor for any significant mode, critical deflection and/or stress to all results obtained from the use of the math model may be used in the event that adequate model correlation is not achieved.

All static and dynamic math models that are used to develop design loads or to represent or certify individual or integrated flight vehicle structures generally require test validation. These tests should be performed at the flight vehicle level or at the component or subsystem level and the results combined.

5.2.1 Loads Model Verification

The loads model should be verified by modal survey tests with the appropriate boundary conditions to ensure the model is sufficiently accurate for load and deflection predictions. Model verification may be accomplished by a combination of spacecraft or element level and component level modal survey tests. In some cases, additional verification tests may be necessary due to the non-linear nature of the dynamic response, for example a spacecraft landing model which would require data from ground impact testing.

For on-orbit configuration component models, the preferred method to validate the stiffness of the on-orbit attachment points of the structure is by mass loading these areas to exercise sufficient strain energy in the regions of the structure which are critical for the on-orbit configuration. When mass loading of on-orbit interfaces is not used to correlate the on-orbit model with ground modal tests, additional ground test data such as static deflection tests and/or strain data may be used to supplement the validation.

5.2.1.1 Resolution and Fidelity for Loads Analysis

a. The frequency range for load analyses, as determined by the resolution and fidelity of the integrated vehicle models and forcing functions, should be up to 50 Hz.

b. The spacecraft, element or component dynamic model must have sufficient fidelity up to 100 Hz to capture the subject's dynamic behavior in this frequency range. This will support an integrated vehicle target modal cutoff of 50 Hz.

c. Subsystem resonances and overall spacecraft, element or component modes must be modeled up to a model upper bound frequency and have at least 1.5 times the cutoff frequency of the load analysis.

5.2.1.2 Modal Survey Test Requirements

a. The modal survey test should measure and correlate all significant modes below the model upper bound frequency, consistent with the model resolution requirement described in the Resolution and Fidelity for Loads Analysis section.

b. Significant modes may be selected based on an effective mass calculation, but this set should be augmented by modes which are critical for specific load, deflection definition and/or component interface modes. The selection of significant modes should be documented in the test plan.

c. Boundary interface degrees of freedom that carry loads in the flight configuration must be constrained in verification testing. Other constraint conditions, such as free-free modal testing may be employed if there is sufficient technical rationale.

d. If alternate boundary conditions are utilized, additional testing and analysis should be performed to verify effects of the alternate configuration.

e. The modal survey test must include appropriate techniques to identify nonlinearities and characterize their effects.

f. The test approach and technical rationale must be provided in the structural verification plan.

5.2.1.3 Mass Representation in the Modal Test

Accurate mass representation of the test article should be demonstrated with orthogonality checks using the analytical mass matrix $[M_A]$ and the test mode shapes $[\Phi_T]$.

a. The orthogonality matrix is computed as $[\Phi_T]^T[M_A][\Phi_T]$, where the analytical model mass matrix is reduced to retain the test instrumentation degrees of freedom.

b. Off-diagonal terms of the orthogonality matrix should be less than 0.1 for significant modes based on the diagonal terms normalized to 1.0.

5.2.1.4 Correlation Guidelines for Loads Model Verification

Evidence of successful correlation between verification test data and the test article math model should consist of frequency and mode shape comparisons.

a. Mode shape correlation should be demonstrated qualitatively with mode shape descriptions and mode shape deflection plot comparisons.

b. The goal for frequency correlation is less than ±5 percent differences on the significant modes and ±10 percent on higher order modes.

c. Quantitative mode shape comparisons should be provided via Modal Assurance Criteria (MAC) and Cross Orthogonality (XOR) checks using the test modes, the analytical modes, and the analytical mass matrix (for XOR). The MAC and XOR goals are the following:

   1. Diagonal terms greater than 0.9

   2. Off-diagonal terms less than 0.1 for modes critical to the integrated interface loads and system internal loads is the other goal.

d. Failure to satisfy the goals of items b and c must be accompanied by an assessment of the effects of model uncertainty on critical loads and documented as described in the Model Correlation Report section.

5.2.1.5 Simplified Loads Model Verification

Under certain conditions, simplified loads model verification by sinusoidal sweep test may be allowed if:

a. The natural frequencies of the spacecraft, element or component are calculated with the flight configuration boundary conditions fixed.

b. Components with significant modes have a minimum frequency higher than or equal to the model upper bound frequency per the Resolution and Fidelity for Loads Analysis section.

c. If the simplified method is applicable, mode shape correlation is not required.

5.3 MODEL CORRELATION REPORT

The loads model developer should develop a model correlation report. As a minimum, this report should contain:

a. A description of the baseline (pretest) dynamic math model

b. A description of the test article, test boundary conditions and available test data for the correlation

c. A comparison of test and analytical dynamic parameters, e.g., frequencies, mode shapes, orthogonality, etc. of significant modes relative to correlation goals and requirements in the Loads Model Verification section for both pre- and post-test correlation. Any deviations from correlation requirements and goals must be explained, with technical rationale and engineering judgment that justifies the test/math model correlation is sufficient.

d. A description of the changes made to pretest math model to improve the dynamic math model correlation

5.4 MODELING GUIDELINES FOR VIBROACOUSTIC CRITERIA DEVELOPMENT

In general, there are four typical procedures used to obtain vibroacoustic structural responses: classical normal mode analysis, modeling techniques, extrapolation, and direct measurements. Choosing which method to use will depend on design maturity, existing data, and frequency range of interest among other things. The NASA-HDBK-7005, Dynamic Environmental Criteria, provides an excellent overview of each of the methods. This section is currently written to provide guidance on the modeling techniques, particularly Statistical Energy Analysis (SEA), with the intent to add information on the other applicable techniques as it arises.

This section describes standard data distribution guidelines for vibroacoustic models. These guidelines provide a common distribution methodology applicable for Finite Element Analysis (FEA), SEA, and Boundary Element Analysis (BEA) model types. The guidelines apply to model documentation and source traceability. Detailed modeling techniques are not prescribed due to the complexity of potential modeling methods and modeler preferences.

The section contains five subsections describing

a. guidelines for model configuration control and data management,

b. guidelines for model inputs,

c. guidelines for model development and quality assurance,

d. guidelines for model outputs, and

e. guidelines for model validation and correlation with test results.

5.4.1 Configuration Control and Data Management

Adequate documentation of the origins of the model is critical and the process for delivery must be standard. Adequately documenting model origination (traceability) is critical and therefore the process for model delivery must be standardized. The SEA model may be created partially or directly from a FEM. Any item that is updated in the SEA model or is different from the original FEM should be logged in an electronic file. The bulk data file (.bdf) of the original FEM model used in the creation of the SEA model must be included in any model delivery. In addition, the documentation containing the updates from the original FEM must also be included in the delivery.

An emphasis is placed on using Computer Aided Design (CAD) files or images in the creation of critical parts of the model. Any CAD data used must be cited or supplied in the model delivery to ensure the proper configuration is modeled.

All other input data including but not limited to applied loads, damping data, absorption data, material properties, structural properties and sizing, and connection information should be documented and supplied in the delivery.

5.4.2 Vibroacoustic Model Inputs

As stated in the previous section, all modeling inputs should be documented and included in the model deliveries. There are some additional conditions, all described in the following sections, that are placed on these inputs with the purpose of assuring that all models are created similarly with common assumptions.

5.4.2.1 Applied Loads

The assumptions and methods describing the load types to their respective flight regimes must be thoroughly documented. The documentation should include relevant air properties, application zones, load parameter assessment, and any assumptions required to complete the analysis.

For flight load conditions requiring Diffuse Acoustic Field (DAF) source types, typically a blocked pressure is applied to models rather than a free field pressure. Therefore, it will be imperative to understand what types of pressures are stated in the environmental specification and, in turn, how to appropriately apply them.

Similarly for flight load conditions requiring Turbulent Boundary Layer (TBL) source types, application should have properly documented assumptions and parameters. The uncertainty of the input parameters should be addressed to ensure a reasonably conservative result is obtained. At the very least, a simple parameter study should be completed for the convection velocity and spatial correlation coefficients. If possible, a Monte Carlo analysis of the input can be completed, and a statistical approach can be used to achieve a reasonably conservative prediction.

5.4.2.2 Subsystem Parameters

The subsystem parameters, including material properties and sizing, need to maintain traceability back to a particular design or design change. A possible method to achieve this could be to keep a living spreadsheet with the model that tracks changes to the design after the model is originally built.

In a similar fashion, the material Damping Loss Factors (DLFs), Coupling Loss Factors (CLFs), and acoustic absorption properties must be documented and tracked as the design evolves. The source of the data used in the model should be included in the documentation. In addition, the process and plan for validation of the factors and properties should be included in the documentation.

If an equivalent material property is being used, the derivation of the material properties should be documented, such as in the cases of

a. using isotropic material to represent laminated composite material, and

b. smearing nonstructural mass to the attached panel.

5.4.3 Vibroacoustic Model Development and Quality Assurance

5.4.3.1 Subsystems

The model creation methods will depend on the analysts' preferences, as well as the construction of the vehicle. There may be multiple ways of defining subsystem in the models with each one providing unique results. Therefore, it is critical that major modeling decisions on subsystem types and subsystem options be justified with proper explanations and documentation. This should be completed for critical subsystems including, but not limited to, those used for direct loading or response recovery. For example, there should be a clear rationale for the modeling characteristics (i.e., size, type, analysis options, etc.) of the exterior skin of the fairing where the direct loading occurs.

5.4.3.2 Subsystem Connections

Typically, SEA software has options to automatically connect subsystems that are adjacent to each other. Such an option should be used wherever possible to minimize the excessive bookkeeping attributed with having many manual junctions. Wherever possible, the junctions that are provided by the software should be spot checked to ensure that they were connected as intended.

Manual junctions (such as manual point, line and area junction, double wall area junction, etc.) should be documented with their physical meanings and properties. To improve the model traceability and accuracy, manual junctions should be limited to situations where they are absolutely necessary.

Double wall area junctions must be added when the thickness of the middle cavity is small compared to the length and the width of the panels (plates or shells). Double-wall area junctions supplement ordinary area junctions by taking into account additional, indirect couplings between the nonadjacent acoustic and structural subsystems.

5.4.3.3 Quality Assurance

Imposing consistent quality assurance checks will be a step toward obtaining robust and reliable vibroacoustic models. The checks should be completed and documented for the model delivery. The SEA model quality assurance checks should at least include the following items:

a. Conduct a property comparison to the original FEM on a line by line basis.

b. Conduct a mass comparison to the original FEM and mass properties report with a description of any deviations.

c. Complete a visual free edge check looking for missing junctions.

d. Complete a symmetry check by placing a load or loads on a line of symmetry and inspect for a symmetrical response.

e. Perform a complete recovery of the dynamic loss factors and compare with the intended values.

f. Ensure that all subsystems respond when excited at single input subsystem. This ensures that all subsystems are connected. Plotting modal energy as colored fringe plot to demonstrate that energy flows to all visible subsystems is recommended.

5.4.3.4 Applicable Frequency Range

The applicable frequency range of the model should be justified, especially for the FEA, BEA, and SEA models. For FEA and BEA models, the size of the mesh should be justified to meet frequency requirements. For the BEA model, the acoustic impedance for acoustic treatment material should be documented.

5.4.3.5 Model Documentation

The model documentation supplied during the model delivery should include the following at a minimum:

a. Description of model construction of critical subsystems for each subsection

b. General modeling assumptions (i.e., property simplifications, structural simplifications, etc.)

c. Model geometry with source traceability

d. Cross-sectional and material property with source traceability

e. Damping loss factor and coupling loss factor assumptions and sources (i.e., connection information)

f. Applied loads descriptions

g. Data recovery descriptions

5.4.4 Vibroacoustic Model Outputs

The model output locations should be documented consistent to the component specification documentation. The subsystem names should have an identifier so that the environments in the specifications can easily be traced to the model. Relevant subsystem response should be recovered at the very least for each 1/3 octave band up to 2,000 Hz for vibration environments and up to 8,000 Hz for cavity sound pressure levels. For the Commercial Crew Transportation Services Program, system responses should be recovered in 1/6 octave bands.

Model outputs must be specified to indicate whether they are average response (i.e., both frequency band and spatial averages if SEA) or other type of response. If an alternative is used, the estimated frequency band where results are considered suitable must be provided.

5.4.4.1 Capturing Uncertainty

Generally, SEA software will include methods for calculating the statistical variance of the response prediction due to local modal properties. While the variations calculated in these modules are significant, they typically are only significant at the low frequencies where modal densities are low. Though this type of variance is important to quantify, it does not consider other types of potential variations incurred in the model building and substructuring process. These variations would include model substructures such as panels, materials, beams, and joint properties. Errors in these variables generally overshadow the error accounted for in the variance prediction and should be estimated. Critical subsystems include the recovery locations as well as the subsystems that are directly loaded.

In addition, uncertainty should account for variance in relative to spatial averaged results (see reference NASA-HDBK-7005). The SEA analysis software may account for spatial variance of response from location to location across subsystems.

Uncertainty should account for any flight–to-flight variation that is not covered by statistical enclosure of model excitation cases.

The following methods are suggested for estimating response variance incurred during the model building process:

a. For a statistical approach, it is suggested that a Monte Carlo method be applied to physical parameters that may have a significant impact on the model's results.

b. Provide an estimate of under/over conservatism due to the various model approximations.

c. Provide an estimate of low modal density issues and an estimate of how these affect the model responses.

d. Show predicted responses versus test data, technical literature, or theory: Are there any test data that support the modeling methods for this particular shape, size, and material?

Subsystem Risk Level: What is the risk level of over/under predicting the vibration environment, especially if the environment is solely dependent on one subsystem?

5.4.5 Model Correlation to Test/Flight Data

The SEA models must be validated by correlation to test and flight data. It is recommended that a model correlation plan for each of the vibroacoustic models be developed. The model correlation plan should include an integration timeline of all the acoustic tests and flight tests. Subsystem tests should be identified and incorporated into the correlation plan. Define what subsystems contribute the most uncertainty to the model predictions as a justification for the subsystem tests. Criteria could come from Monte Carlo runs, etc. In addition, any parameter testing that will improve the reliability of the model should also be included.

SEA model correlation tests should include, but not be limited to, component level development tests, system level ground test article (GTA) tests, and vehicle level flight tests, etc.

SEA model component level correlation may include the following:

a. Verify wave speed as a function of frequency. A simple tap test with damped edges to reduce the affect of reflected waves on the measured results is recommended. This test can be completed using test articles that have not been integrated with the rest of the vehicle.

b. Verify the subsystem damping spectrum. A free-free tap test is recommended. This test can be completed using test articles that have not been integrated with the rest of the vehicle.

c. Verify the integrated damping spectrum based on an integrated system test on the flight vehicle or a similar vehicle.

d. Conduct a Sound Transmission Loss (STL) Correlation Test. STL correlation for acoustic panels will be important for airborne response prediction. The modeling strategy for critical acoustic panels in the SEA model should be correlated using test data and literature data.

e. Measure sound absorption. The modeling strategy for acoustic material should be verified by test. The test should be performed using an impedance tube or in a small reverberation chamber.

f. Validate transmission through structural joint. Structural joint validation will be important for structure-borne response prediction. The correlation may be done for critical structural joints.

SEA model system level correlation should be conducted in an acoustic reverberation chamber and/or acoustic anechoic chamber using an ideal acoustic source.

The vehicle level flight tests data should be used to verify the loads definition and correlate the whole vehicle model.

APPENDIX 1
ACRONYMS AND ABBREVIATIONS
AND GLOSSARY OF TERMS

1.0 ACRONYMS AND ABBREVIATIONS

α	Angle of attack
AC	Assembly Complete
ASTM	American Society for Testing and Materials
ATM	Acceleration Transformation Matrix
ATV	Automated Transfer Vehicle
β	Sideslip angle
BEA	Boundary Element Analysis
CAA	Crew Access Arm
CAD	Computer Aided Design
CB	Craig-Bampton
CCDP	Commercial Crew Development Program
C_D	Drag coefficient
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CLF	Coupling Loss Factor
COTS	Commercial Orbital Transportation Services
CR	Change Request
DAC	Design Analysis Cycle
DAF	Diffuse Acoustic Field
DCR	Design Certification Review
dB	Decibel
DLF	Damping Loss Factor
DOF	Degrees of Freedom
DSNE	Design Specification for Natural Environments
DTM	Displacement Transformation Matrix
DUF	Dynamic Uncertainty Factor
EVA	Extravehicular Activity
FEA	Finite Element Analysis
FEM	Finite Element Model

FF	Forcing Function
FIP	Failure in Place
FTN	Failure to Null
g	gravity
GFE	Government-Furnished Equipment
GN&C	Guidance, Navigation, & Control
GRAM	Global Reference Atmospheric Model
GS	Ground Systems
GSE	Ground Support Equipment
GTA	Ground Test Article
HO	Hardover
HSIR	Human-Systems Integration Requirements
HTV	H-II Transfer Vehicle
ICD	Interface Control Document
ID	Identification
IEDS	Induced Environments Design Specification
ISS	International Space Station
IV&V	Independent Verification and Validation
IVA	Intravehicular Activity
LAS	Launch Abort System
lbf	pound force
lb	pounds
LC	Loads Cycle
L&D	Loads and Dynamics
LDB	Loads Data Book
LEO	Low Earth Orbit
LIDS	Low Impact Docking System
LIM	Load Indicator Metric
LOI	Lunar Orbit Insertion
LOX	Liquid Oxygen
LSAM	Lunar Surface Access Module
LSP	Loads and Structures Panel
LTM	Load Transformation Matrix
LV	Launch Vehicle
LVP	Launch Vehicle Provider
MAC	Modal Assurance Criteria

MAF	Michoud Assembly Facility
Max Q	Maximum Dynamic Pressure
MECO	Main Engine Cut-Off
MEFL	Maximum Expected Flight Level
MEM	Modal Effective Mass
ML	Mobile Launcher
MPC	Multi-Point Constraint
MPE	Maximum Predicted Environment
MR	Management Reserve
m/s	meters per second
NASTRAN	NASA Structural Analysis Program
OML	Outer Mold Line
OPR	Office of Primary Responsibility
OTM	Over-Turning Moment
PDR	Preliminary Design Review
PMP	Program Management Plan
PSD	Power Spectral Density
PTM	Pressure Transformation Matrix
Q	Dynamic Amplification Factor (when used in the context of shock response spectra)
Q	Dynamic Pressure (when used in the context of atmospheric flight)
QA	Quality Assurance
RCS	Reaction Control System
RPODU	Rendezvous, Proximity Operations, Docking and Undocking
RSS	Root-Sum-Squared
SDR	System Design Review
SDVR	Structural Design and Verification Requirements
SE&I	Systems Engineering and Integration
SEA	Statistical Energy Analysis
SM	Service Module
SC	Spacecraft
SCP	Spacecraft Provider
SPC	Single Point Constraint
SPL	Sound Pressure Level
SRD	System Requirements Document
SRR	System Requirements Review

SRS	Shock Response Spectrum
STEL	Static Aeroelastic
STL	Sound Transmission Loss
STM	Stress Transformation Matrix
T-	Time minus
TBL	Turbulent Boundary Layer
TEI	Trans-Earth Injection
TLI	Trans-Lunar Injection
TO	Thrust Oscillation
TVC	Thrust Vector Control
UF	Uncertainty Factor
V&V	Verification and Validation
VAC	Verification Analysis Cycle
VI	vehicle integration
WGA	Weight Growth Allowance
WIO	Wind Induced Oscillation
XOR	Cross Orthogonality

2.0 GLOSSARY OF TERMS

Term	Description
Active Vehicle	The spacecraft responsible for controlling relative positions and closure rate during rendezvous and proximity operations with another spacecraft.
Blast Overpressure	The airborne shock wave or acoustic transient generated by an explosion.
High Q (Hi-Q)	A region of high dynamic pressure that occurs during ascent flight.
Random Vibration	The oscillating haphazard motion of a structure caused by acoustical and/or mechanical forcing functions.
Target Vehicle	The spacecraft which serves as a passive vehicle, except for controlling its roll, pitch, and yaw attitudes to remain within pre-defined limits, while another vehicle conducts rendezvous and proximity operations.
Thrust Oscillation	A phenomenon in solid propellant in which the burning of fuel produces pressure oscillations that can tune with modes of the vehicle structure causing high vibration oscillations.
Transonic	A range of velocities just below and above the speed of sound (about Mach 0.8-1.2). It is defined as the range of speeds between the critical Mach number, when some parts of the airflow over a vehicle become supersonic, and a higher speed (i.e., Mach 1.2), when all the airflow is supersonic. Severe instability can occur at this speed range.
Transit Spacecraft	A vehicle which travels beyond low earth orbit to a lunar, planetary, or deep space destination. Transit spacecraft may be comprised of combination of crewed spacecraft, launch vehicle upper stages, deep space propulsion or habitation elements, and landers, which may consist of separable descent and ascent stages.
Vortex Shedding	An unsteady flow that takes place in the flow of fluid past objects. The airflow past the object cerates alternating low-pressure vortexes on the downwind side of the object.

APPENDIX C
GUIDELINES FOR LOADS CONTROL PLAN

This Appendix provides typical information expected in a Loads Control Plan. The contents of this Appendix are not formal requirements, but they reflect experience gained and best practices developed over a history of NASA spaceflight hardware design and development.

- Analysis cycles

Describes the planned analysis cycles for loads and environment development and would include the following information:

  - *Number of analysis cycles and their objectives*
  - *Type of analyses to be performed in each analysis cycle and their level of interface (e.g. element level, integrated level, etc.)*

- Loads and Maximum Predicted Environment (MPE) development

Describes the analysis methods for loads and MPE for each analysis cycle and would include the following information:

  - *Lifecycle loading events/regimes (e.g. transportation, liftoff, in-space, etc.) and expected loading sources for each loading event*
  - *Analyses being performed for each event and methodology to be employed*
  - *Expected forcing functions inputs, model inputs, damping, uncertainty factors, and load combinations of events and analysis results*

- Loads and MPE mathematical model development

Identifies the mathematical models to be developed/used for the loads and MPE and would include the following information:

  - *Type of mathematical model (e.g. empirical, NASTRAN, etc.)*
  - *Model configurations and boundary conditions*
  - *Version control*

- Loads and MPE model delivery requirements

Addresses model delivery requirements between internal and external organizations and would include the following information:

  - *Model units*

- *Model format (e.g. code type, full vs reduced, etc.)*
- *Model numbering scheme*
- *Model origin, coordinate system*
- *Model boundary/interface specifications/agreements*
- *Quality checks (i.e. minimum model checkouts and results)*

- Loads and MPE mathematical model verification and validation (V&V)

Describes planning for V&V of mathematical models used for loads and MPE prediction in each analysis cycle and would include the following information:

- *Testing to be performed and test objectives*
- *Test data-to-test model correlation requirements*
- *V&V assessments to be performed and objectives*

- Design loads and MPE verification and validation (V&V)

Describes planning for V&V of design loads and MPE results from each analysis cycle and would include the following information:

- *Testing to be performed and test objectives*
- *Test data-to-test model correlation requirements*
- *V&V assessments to be performed and objectives*

APPENDIX D
JSC 65829 REV A REQUIREMENTS TRACEABILITY MATRIX

This table shows the mapping of requirements in JSC 65829 Rev A to requirements in JSC 65829 Rev B. Where requirements in JSC 65829 Rev A were excluded from this document, rationale for their exclusion is provided in the Notes column.

JSC 65829 Rev A	JSC 65829 Rev B	Notes
LD0001	LDR-002	
LD0002	LDR-003	
LD0003	LDR-004	
LD0004	LDR-005	
LD0005	LDR-006	
LD0006	LDR-007	
LD0007	Covered by LDR-001	Should be addressed in the Loads Control Plan
LD0008	LDR-008	
LD0009	Covered by LDR-001, LDR-002, and LDR-003	Should be addressed in the Loads Control Plan
LD0010	LDR-016	
LD0011	LDR-017	
LD0012	Covered by LDR-016 and LDR-017	Should be addressed in the Loads Control Plan
LD0013	LDR-020	
LD0014	LDR-021	
LD0015	LDR-009	
LD0016	LDR-022	
LD0017	Covered by LDR-002 and LDR-003	Should be addressed in the Loads Control Plan
LD0018	Covered by LDR-002, LDR-003, LDR-016, LDR-017, LDR-019, LDR-020, and LDR-021	Should be addressed in the Loads Control Plan
LD0019	Covered by LDR-002	Should be addressed in the Loads Control Plan
LD0020	Covered by LDR-002	Should be addressed in the Loads Control Plan
LD0021	Covered by LDR-002 and LDR-003	Should be addressed in the Loads Control Plan

JSC 65829 Rev A	JSC 65829 Rev B	Notes
LD0022	Covered by LDR-002, LDR-003, LDR-016, LDR-017, LDR-019, LDR-020, and LDR-021	Should be addressed in the Loads Control Plan
LD0023	Covered by LDR-002 and LDR-003	Should be addressed in the Loads Control Plan
LD0024	Covered by LDR-002, LDR-003, LDR-016, LDR-017, LDR-019, LDR-020, and LDR-021	Should be addressed in the Loads Control Plan
LD0025	LDR-028	
LD0026	Covered by LDR-028	Should be addressed in the Loads Control Plan
LD0027	Covered by LDR-028	Should be addressed in the Loads Control Plan
LD0028	Covered by LDR-002	Should be addressed in the Loads Control Plan
LD0029	Covered by LDR-002	Should be addressed in the Loads Control Plan
LD0030	Covered by LDR-002	Should be addressed in the Loads Control Plan
LD0031	Covered by LDR-002	Should be addressed in the Loads Control Plan
LD0032	LDR-045	Should be addressed in the Loads Control Plan
LD0033	LDR-025	
LD0034	LDR-027	
LD0035	Covered by LDR-027	Should be addressed in the Loads Control Plan
LD0036	Covered by LDR-027	Should be addressed in the Loads Control Plan
LD0037		Guidance
LD0038	LDR-012	
LD0039	LDR-023	
LD0040	LDR-013	
LD0041	LDR-024	
LD0042	Covered by LDR-024	Should be addressed in the Loads Control Plan
LD0043	Covered by LDR-011	
LD0044	Covered by LDR-011	

JSC 65829 Rev A	JSC 65829 Rev B	Notes
LD0045	Covered by LDR-011	
LD0046	Covered by LDR-011	
LD0047	LDR-014	
LD0048	LDR-015	
LD0049	LDR-010 and LDR-018	
LD0050	Covered by LDR-014	Should be addressed in the Loads Control Plan
LD0051	LDR-011	
LD0052	LDR-011	
LD0053	LDR-011	
LD0054	LDR-011	
LD0055	LDR-011	
LD0056	LDR-011	
LD0057	LDR-011	
LD0058	LDR-011	
LD0059	LDR-011	
LD0060	LDR-011	While rendezvous and proximity operations with ISS will not be performed, the intent is the same for CSS rendezvous/proximity operations with future crewed destination spacecraft
LD0061		CSS will not perform rendezvous and proximity operations with the ISS.
LD0062	LDR-011	While rendezvous and proximity operations with ISS will not be performed, the intent is the same for CSS rendezvous/proximity operations with future crewed destination spacecraft
LD0063		CSS will not perform rendezvous and proximity operations with the ISS.
LD0064	LDR-011	While rendezvous and proximity operations with ISS will not be performed, the intent is the same for CSS rendezvous/proximity operations with future crewed destination spacecraft
LD0065		CSS will not perform rendezvous and proximity operations with the ISS.
LD0066	LDR-011	While rendezvous and proximity operations with ISS will not be performed, the intent is the same for CSS rendezvous/proximity operations with future crewed destination spacecraft
LD0067		CSS will not perform rendezvous and proximity operations with the ISS.

JSC 65829 Rev A	JSC 65829 Rev B	Notes
LD0068	LDR-011	While rendezvous and proximity operations with ISS will not be performed, the intent is the same for CSS rendezvous/proximity operations with future crewed destination spacecraft
LD0069		CSS will not perform rendezvous and proximity operations with the ISS.
LD0070	LDR-011	
LD0071	LDR-011	
LD0072	LDR-011	
LD0073	LDR-011	
LD0074	LDR-011	
LD0075	LDR-011	
LD0076	LDR-011	
LD0077	LDR-030	
LD0078	LDR-031	
LD0079	LDR-032	
LD0080	Covered by LDR-032	Should be addressed in the Loads Control Plan
LD0081	LDR-033	
LD0082	LDR-034	
LD0083	Covered by LDR-034	Should be addressed in the Loads Control Plan
LD0084	LDR-035	
LD0085	Covered by LDR-035	Should be addressed in the Loads Control Plan
LD0086	Covered by LDR-035	Should be addressed in the Loads Control Plan
LD0087	LDR-036	
LD0088	LDR-037	
LD0089	LDR-038	
LD0090	Covered by LDR-038	Should be addressed in the Loads Control Plan
LD0091	LDR-039	
LD0092	LDR-040	
LD0093	LDR-041	
LD0094	LDR-042	
LD0095	LDR-043	
LD0096	LDR-044	

APPENDIX E
NASA-STD-5002A REQUIREMENTS TRACEABILITY MATRIX

This table shows the mapping of requirements in NASA-STD-5002A to requirements in JSC 65829 Rev B. While NASA-STD-5002A is not called out in HEOMD-003, this matrix is provided for reference and to demonstrate that the current document offers coverage for all requirements in NASA-STD-5002A, as well as the previous version of JSC 65829.

NASA-STD-5002A	JSC 65829 Rev B	Notes
LAR 1	LDR-008	
LAR 2	LDR-002	
LAR 3	Covered by LDR-002	Should be addressed in the Loads Control Plan
LAR 4	Covered by LDR-001 and LDR-008	Should be addressed in the Loads Control Plan
LAR 5	LDR-006	
LAR 6	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 7	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 8	Covered by LDR-023	
LAR 9	LDR-026	
LAR 10	Covered by LDR-002 and LDR-003	Should be addressed in the Loads Control Plan
LAR 11	LDR-004	
LAR 12	LDR-003	
LAR 13	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 14	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 15	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 16	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 17	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 18	Covered by LDR-007	Should be addressed in the Loads Control Plan
LAR 19	LDR-012	
LAR 20	Covered by LDR-027	
LAR 21	Covered by LDR-012	

NASA-STD-5002A	JSC 65829 Rev B	Notes
LAR 22	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 23	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 24	LDR-023	
LAR 25	Covered by LDR-023 and LDR-013	Should be addressed in the Loads Control Plan
LAR 26	LDR-013	
LAR 27	Covered by LDR-013	
LAR 28	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 29	Covered by LDR-011	
LAR 30	Covered by LDR-016, LDR-017, LDR-019, and LDR-020	
LAR 31	Covered by LDR-011	
LAR 32	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 33	Covered by LDR-005	
LAR 34	Covered by LDR-005	
LAR 35	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 36	LDR-024	
LAR 37	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 38	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 39	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 40	Covered by LDR-001	Should be addressed in the Loads Control Plan
LAR 41	Covered by LDR-003	
LAR 42	Covered by LDR-003	
LAR 43	Covered by LDR-003	
LAR 44	Covered by LDR-006	

NASA-STD-5002A	JSC 65829 Rev B	Notes
LAR 45	LDR-007	
LAR 46	Covered by LDR-007	Should be addressed in the Loads Control Plan
LAR 47	Covered by LDR-007	Should be addressed in the Loads Control Plan
LAR 48	Covered by LDR-003 and LDR-007	Should be addressed in the Loads Control Plan
LAR 49	LDR-014	
LAR 50	LDR-015	
LAR 51	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 52	Covered by LDR-014	Should be addressed in the Loads Control Plan
LAR 53	Covered by LDR-014	Should be addressed in the Loads Control Plan
LAR 54	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 55	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 56	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 57	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 58	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 59	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 60	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 61	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 62	Covered by LDR-018	Should be addressed in the Loads Control Plan
LAR 63	Covered by LDR-011	